1 Earth Observation History on Technology

Introduction

Prior to the space age (conventionally dated from 1957), humankind had never been able to take in the whole of a hemisphere in a single glance. In fact it had never had a global view of the world in which it lived. It was not until the first spacecraft went into orbit that our horizons expanded and we saw our planet as never before. During more than four decades of spaceflight, planet Earth has been rediscovered through the systematic collection and analysis of vast amounts of information. At the turn of the century/millennium, satellite-provided services in many fields of application (environmental monitoring, navigation, weather forecasting, communication, etc) are taken for granted. We’ve come to depend on the satellites in a way that would have been unimaginable a few decades ago.

Before the space age, remote sensing, although not named as such, was done exclusively with photographic cameras. The so-called aerial photo emerged in the 1850’s, a mere dozen years after the invention of photography, with pictures taken from a tethered balloon - the French photographer, Gaspard Félix Tournachon (1820-1910), alias Nadar, obtained the first aerial photographs over Paris (Oct. 23, 1858) from an altitude of about 80 m; Nadar also used his art for mapping the countryside. In 1859, Napoleon III ordered Nadar to obtain reconnaissance photography in preparation of the Battle of Solferino in northern Italy. Thereafter, tethered balloons were used a few times during the US Civil War (1861-1865) by General George McClellan, to study enemy positions using aerial photographs. 1) At the beginning of the twentieth century, the aeroplane proved its advantage as a civil and military observation/reconnaissance platform. Aerial photography was extensively employed during both World Wars for military reconnaissance. In 1947, a number of captured V-2 rockets were modified and instrumented by the US military to photograph the clouds from 110-165 km altitudes in New Mexico, USA. [In the same year (Oct. 18, 1947), the Soviet Union launched its first LRBR (Long Range Ballistic Rocket) based on the German rocket A4 (V-2)]. The photographs demonstrated the immense potential of observing weather. 2) After the wars and prior to 1960, the development of aerial color and color infrared film gave civilian remote sensing a distinct boost. The color infrared photography allowed some interpretation means for a rough classification of some vegetation types. High-speed cameras, combined with wide-angle lenses, provided greater opportunities to image Earth’s surfaces. A more detailed account of the early rocket development history in Germany, in particular before and during WW-II (World War-II), and in USA after WW-II, is provided in the following reference. 3) 4)

Earth observation covers a wide field of remote sensing as well as of other sensing methods (in-situ), it encompasses the study of the Earth system (in particular its outer surface) and also Earth’s environment, including the study of interactions with the outside. Earth observation (i.e. remote sensing) is based on the fact that information is available from the electromagnetic energy field arising from the Earth’s surface (or atmosphere, or both) and in particular from the spatial, spectral and temporal variations in that field. 5) Spaceage Earth observation (although not named as such initially) started with the launch of Russia’s first Sputnik satellite on Oct. 4, 1957 on the R-7 launch vehicle from Baikonur (satellite mass = 83.6 kg, diameter = 58 cm, perigee = 228 km, apogee = 947 km, inclination = 65.1°, period = 96 min, RF

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1) As early as 1783, when as US ambassador to France, Benjamin Franklin observed the first Montgolfier balloons in flight over Paris and predicted their use in “conveying Intelligence” about “an Enemy’s Army,” generals and spies have understood the power of aerial reconnaissance; the high-altitude surveillance possible from satellites promised both a revolution in surveillance and insurance against political embarrassments (see Ref. 40).


4) Note: The history of rocket development as primary propulsion is not within the scope of this documentation

frequencies: 20.005 MHz and 40.002 MHz). The chief designer and general manager of the Sputnik project was Sergei Pavlovich Korolev (1907-1966, also spelling of: Sergey Pavlovich Korolyov).

Sputnik-1 made measurements that permitted a first estimation of the density of the upper atmosphere. Sputnik-1 reentered the atmosphere on Jan. 4, 1958. In the following period each new spacecraft launch produced new discoveries. The first successful US satellite was Explorer-1 (launch Jan. 31, 1958 with a S/C mass of 5 kg; orbit of 384 km x 1859 km, inclination of 32.2°) of the US Army, built by the Army Ballistic Missile Agency and by JPL. Explorer-1 (instruments included a cosmic ray and micrometeorite package, a micrometeorite impact microphone, micrometeorite erosion gages, and internal and external temperature gages) provided preliminary information on the environment and conditions in space outside Earth’s atmosphere. It resulted in the discovery of the Van Allen radiation belts (James Alfred Van Allen, US physicist at the University of Iowa, *Sept. 7, 1914, †Aug. 9, 2006). Explorer-1 reentered the Earth’s atmosphere on March 31, 1970.

Some background on the early space race (this and next paragraph): The IGY (International Geophysical Year) was created May 16, 1952 by the ICSU (International Council of Scientific Unions) plenary meeting in Paris, France as a platform for international cooperation in studying the physics of the Earth. The IGY was planned for 1957/58, a year of expected maximum solar activity. In the preparation phase for IGY, various project scenarios were considered in international meetings; the US introduced information on the evolving potential for launching satellites and their unique capabilities as tools for geophysical research. On Oct. 4, 1954, in an ICSU meeting in Rome, Italy, a resolution to recommend the use of satellites during the IGY was adopted by the international body. The USSR, which only recently had announced IGY participation, had no comment on the subject. In reflection of the meeting, however, an atmosphere of suspicion and mistrust began to grow in both camps of the world (USA and USSR), each wondering of what the other side was up to with regard to their satellite plans.

Thus, the space race in post WW-II history had somehow started, generating a lot of activity and technology development, binding in turn many resources for the respective IGY satellite programs of each side. On July 29, 1955, President Dwight D. Eisenhower announced publicly the US intention to launch satellites during the upcoming IGY. The NRL (Naval Research Laboratory) was selected to build and launch the first satellite. The world was somehow stunned by the news that space endeavors were in planning and would soon become a reality. The Soviet Union followed with a similar announcement within a few days. Both announcements put even more pressure on the various teams from the East and the West, including the military organizations. The launch of Sputnik-1 on Oct. 4, 1957 happened to coincide with the plan outlined for IGY. For the Soviet Union, Sputnik-1 was an impressive technical achievement that caught the world’s attention, but for the US it was a stunning blow to fall behind in the race for space. — As a consequence, the US Congress passed the National Aeronautics and Space Act in July 1958, legislation that led to the creation of the National Aeronautics and Space Administration (NASA) on October 1, 1958.

The first successful operational flight within the US IGY program was Vanguard-2 (launch Vanguard vehicle on Feb. 17, 1959 from Cape Canaveral). The objective of Vanguard-2 was to measure the Earth’s albedo, the amount of sunlight reflected by the Earth’s surface and cloud layers. The spherical S/C of 50 cm diameter had a mass of 9.5 kg and carried two photovoltaic detecting units, a data recorder, a transmitter and a receiver. As the satellite spun, its photocells registered variations in albedo intensity.

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6) Sergei P. Korolev (Jan. 12, 1907 - Jan. 14, 1966), Chief Designer of the Soviet space program and head of Special Design Bureau-1 (Russian acronym OKB-1), ancestor of today's RKK Energia (until recently, NPO Energia). Korolev is the father of Soviet rocketry, they called him the “Grand Designer.” But more than that, he was the heart and sole of the Soviet space program. In March 1962, Korolev started the Soyuz program, the rocket with the most launches in space history.

The first spaceborne imaging sensors flown were the film cameras, looking downward on Earth and providing a “bird’s eye view” from space. Initial efforts concentrated on the most obvious phenomenon to study, namely the weather. However, the major goals of the early US and Russian space programs were set to explore outer space (looking out), and not to look at Earth. Strangely enough, Earth was somehow considered to be sufficiently known at the time. It is interesting to note that planning for a deliberate and systematic approach to Earth observation, i.e. the survey and research of the Earth’s surface (and many other items), did not start before the mid 1960s. The reason for the new interest in Earth was stimulated mainly by the study of some 1100 photographs (film imagery), taken of Earth by astronauts during the manned Mercury (1961-1963) and Gemini (March 1965 - Nov. 1966) missions and subsequently being used in preparation for the Apollo program (the objective was the study of possible lunar landing sites as seen from space). In any case, in trying to analyze and to interpret the Earth imagery at hand, it began to dawn upon some people (familiar with the basic physics of the electromagnetic spectrum) that these photographs might contain a wealth of information - worthy of systematic analysis. Quantitative interpretation schemes had to be developed to interpret the data! 8)

The planning for the first dedicated civil spaceborne Earth-surface imaging project was initiated at a press conference on Sept. 20, 1966 in Washington, DC. 9) At this conference, Stewart Udall, Secretary of the Department of the Interior (DOI), and William T. Pecora, Director of USGS (United States Geological Survey), announced plans for a program called Earth Resources Observation Satellites (EROS). 10) Fortunately, President Johnson, the US Congress, and the US public supported this idea, there were strong objections voiced by DoD and the State Department. 11) This was indeed a new direction in the US space program at a time, when young NASA’s foremost task was to get a man on the moon (a national goal), in the middle of the Cold War and a hot war (Vietnam). NASA was given the task to plan and build the newly designated ERTS (Earth Resources Technology Satellite) spacecraft (launch of ERTS-1 on July 23, 1972) that was later renamed to Landsat-1. 12) 13)

In the words of Stephen S. Hall (Ref. 40), the Landsat project was a political stepchild in the 1960s, sought by scientists but shunned by the military, claimed by the Interior Department but coveted by Agriculture, a nuisance to NASA and undermined at almost every step of the way by the Bureau of Budget (later the Office of Management and Budget). The military and the National Security Council didn’t like the idea of the civilian community looking at the Earth at all. - In the long run, the greatest benefits of the space program have come from those satellites that, year in and year out, steadily and unspectacularly help us understand

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8) If there were any lingering questions about the promise of space observation, they were dispelled - to everyone’s considerable surprise - by John Glenn, Wally Schirra, and Gordon Cooper. Despite cramped conditions, these astronauts took conventional (Glenn) as well as large-format cameras (70 mm Hasselblad) aboard America’s early space flights and came back with breathtaking photographs of the earth shot through the window of their Mercury and Gemini spacecraft. These were ordinary photos using visible light, not the information-rich spectral images pushed by the remote-sensing crowd, but the surprising amount of clarity and detail excited geologists. More important, the images excited the public (Ref 40). The Gemini photos were taken from flight altitudes of 160 km.

9) http://academic.emporia.edu/aberjame/remote/landsat/landsat.htm (Author: J. S. Aber)


11) Ironically, objections of the State Department and DoD against the distribution of civil high-resolution Earth imagery (in the optical and microwave regions) and the proliferation of space technology have been around ever since and continue to be a major issue in US space policy. Special rules (including shutter control) may be imposed in particular conflict situations to restrict US-based commercial remote-sensing firms from unauthorized distribution of their imagery. Special rules apply also to the export of space technology by US companies. However, with space-imaging technology readily available outside the USA, the US-internal control functions became more or less ineffective as of 2000. Note: the US military campaign in Afghanistan, launched in the wake of the terrorist attacks in New York and Washington D. C. (Sept. 11, 2001), led to US government action to purchase every high-resolution satellite image of Afghanistan produced by the Ikonos spacecraft. This was a purely commercial deal that should not be confused with a government-ordered denial of access. Of course, with such a good customer, Space Imaging had no need and desire to sell its Ikonos imagery from Afghanistan to anybody else.

12) The policies on US remote sensing technologies and their restrictions evolved from two primary sources: a) the secret capabilities first developed for the NRO (National Reconnaissance Office), and b) civil systems like the Landsat series instruments MSS and TM. Originally, commercial considerations were not a factor in either of these areas.

our planet better, improve lives, and, as in a recent program to identify breeding areas of the insect that causes sleeping sickness, even save lives. There is a place for manned flight, but over the long haul it can’t compete with the satellites. Former astronaut Walter Schirra admitted back in 1972, "We should start looking down instead of up."

The introduction of new technologies was and is fundamental and indispensable to all aspects of space flight. New types of instruments were developed and flown, many of them capable of detecting and measuring radiation (such as radiometers) in the visible to microwave region of the spectrum. The creativity of the space age generated in effect a revolution and an evolution in sensor technology resulting in a multitude of sensor types as well as in many other innovations. The concepts of these new instruments were based on such diverse fields as optics, solid-state electronics, pattern recognition, signal processing, computer technology, and communications. The history of humankind is in general characterized by an evolution of tools. At the start of the 21st century it can safely be stated that the space age was instrumental of initiating and fostering new and vastly improved measurement technologies, accompanied by the greatest instrument-development spree (tools) in the history of science.

A most important space-age achievement (along with parallel developments in the wide field of electronics) is the ability, to observe the Earth and its environment as well as the universe in the entire breadth of the electromagnetic spectrum. This in turn opened a new era in experimentation and discovery in virtually all fields of the Earth and space sciences. For instance, synoptic observations over wide regions of the Earth and the capability to communicate, process and interpret vast amounts of information, practically in real-time, has revolutionized the way we do things and in which scientists study the atmosphere, oceans, land, vegetation, glaciers, sea ice, and other environmental aspects of the Earth’s surface and their interactions. Earth observation has become the prime source of input for the considerable advances in the geosciences and many related disciplines, permitting research into the distant past, the presence, and into the future (by assessing environmental impacts). As a consequence, Earth itself assumed a new clarity and gave us a better awareness of its dynamic nature. In the Sun-Earth system, space exploration provided for the first time a perception and understanding of the electromagnetic state of the interplanetary space between the Sun and the Earth.

Beside the research benefits, Earth observation has also evolved to become a technology driver and a mature service provider for a large spectrum of useful applications, ranging from weather forecasting over monitoring and managing of Earth resources (crop surveys, mineral surveys) to navigation-aid systems and monitoring of international treaty compliance. Also, more emphasis is being placed on such fundamental issues as the global environment and its changes (global interconnectivity of weather phenomena, preservation of the bio-environment, etc.). The goal is to develop predictive environmental, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth. - At the turn of the century/millennium, the new concept of "formation flying" [a combination of Earth observation, navigation (onboard propulsion), intersatellite communication, onboard autonomy, and onboard processing functions] has the potential of revolutionizing the way the space community conducts Earth observation missions. The space community is just beginning to understand the potential and perspectives

14) Note: The term “radiometer” is a generic label for any instrument that quantitatively measures the EM radiation in some interval of the EM spectrum.

15) Note: The “First Symposium on Remote Sensing of Environment” took place in Feb. 1962 - when the Institute of Science and Technology at the University of Michigan, a research organization funded by the US military, invited seventy agronomists, agriculturists, foresters, geologists, hydrologists, land-use experts, photogrammetrists, and of course, cartographers. From that date, civilian remote sensing as a discipline began to come of age. On that same date, the two converging streams (military and civil) began to back up behind a dam of security and secrecy. Scientists complained about how the military scrambled to classify information about remote sensing. William Fischer, a photogeologist at USGS, who attended that first meeting, returned to Washington and suggested to his boss at the Department of the Interior, William T. Pecora, that the time might be right for a remote-sensing satellite. (Ref. 40).
of satellite formation flying. New distributed observation concepts of spaceborne bistatic and multistatic systems are in the planning stage that may eventually permit more affordable spacecraft constellations for interferometric imagery.

The utilization of solar energy from LEO or MEO space power stations and conversion of the electricity into microwave energy for transmission to Earth are other concepts being explored and investigated today (lasers are also under consideration for beaming the energy from space). Space solar power - a dream today - has a good chance of becoming a reality in the decades ahead. 16) 17)

In a long-term perspective, the past forty-five years of space flight at the start of the 21st century can be regarded as the “early or adolescence period” in the field of Earth observation and Earth science. The future requires truly concerted efforts to bring about solutions for such unsolved global problems as biosphere-climate-interactions, and much more. All indications on enabling technology developments lead to the conclusion, that the best is yet to come, leading to a better understanding of the total Earth System. - “Earth functions as a system - a large, complex, and dynamic one, but a system nonetheless. It is affected in measurable ways by external forces such as the sun and its variability, and by the internal forces that are shaped by variations in the atmosphere, oceans, continents, life, and the complex web of interactions among them.

We are the first generation with the ability to observe global-scale changes from the perspective of space and the scientific knowledge to link them with their causes and consequences. This ability to record and understand global change will be among the greatest gifts that we can offer our children and their children after them, for it will put in their hands the power to make informed decisions about the environmental challenges of the future.

The quest for a true predictive capability for Earth system changes requires a flexible and progressive space system architecture. That’s why we need to design and establish a smart, autonomous, and flexible constellation of Earth-observing satellites that can be reconfigured based on the contemporary science and specific issues at hand.” 18)

United Nations statistics in the 1990s reveal that less than half of the Earth’s exposed land has been mapped at scales suitable for economic development measures. The need is particularly great for Africa. The answer lies in satellite image maps, which are accurate and can be quickly compiled and systematically updated. Satellite image maps have become the mapmaker’s benchmark for small and medium scale mapping. Moreover, Earth observation satellites have become the precious allies of a new type of agriculture managed from the sky, especially in developing countries where agricultural management is still at an early stage. With a single glance they report on crop areas, identify soil types and inventory water resources. All of which can be used to plan future agricultural development. Likewise, as the season changes, they monitor crop changes and enable early detection of diseases. Today, Earth observation satellites are becoming an extremely valuable monitoring and decision-making tool for disasters and environmental hazards (assessment of the extent of destruction, etc.).

The term “Digital Earth” was coined by US Vice President Al Gore, presented in a speech at the California Science Center in Los Angeles, on Jan. 31, 1998. His vision of the proposed concept model of “Digital Earth” refers to a multi-resolution, 3-D virtual representation of Earth, into which geo-referenced data can be embedded. A “Digital Earth” (along with Digital Earth Models) offers, for instance, a mechanism for users to navigate and search for geospatial information, etc. The consistent combination of all of this information is only

18) Daniel S. Goldin, “NASA in the 21st Century,” Millennial Challenges Colloquium series, Oct. 10, 2000, the address was presented at JHU/APL, Laurel, MD
possible if the reference frame is provided by geodesy. - Obviously, such an objective is so vast, that only international standardization bodies can undertake such a project. But it has to happen! The benefits of such a seamless system are apparent to the entire Earth Observation community. Eventually, the data from “Digital Earth” may also contribute to a new genre of virtual reality applications.

Prior to Digital Earth, a number of technical challenges have to be addressed and solved in such areas as graphics, visualization, image processing, spatial data structures, computer cartography, and support of global and regional modeling. Geovisualization and 4-D simulation will require parallel-processing, high-performance (teraflop) computing architectures and advanced (100-plus terabyte) storage systems. Even the most powerful computers and storage devices will require optimization of software functions and maximal data compression. A new class of space/time/entity/process linkage systems must be invented to represent and analyze spatial phenomena across fields as diverse as medicine, biology, engineering and physics. 19)

Regarding to the activities on the research of Digital Earth, the most significant event was the “International Symposium on Digital Earth,” held in Beijing from Nov. 29 to Dec. 2, 1999. The symposium was organized by the Chinese Academy of Sciences (CAS), and attended by over 500 delegates from 27 countries. The meeting set up an International Steering Committee for ISDE (International Symposium on Digital Earth). 20)

During the 1990s, industry is gearing up as a commercial total system (space and ground segment owner and operator) service provider. 21) The global research community is still a very large user of remotely sensed data, but an increasing amount of Earth observation data (information) permeates also into applications for everyday use. This development into a wider base is indeed a good perspective for a maturing service and utility environment.

At the turn of the 21st century, first attempts are being made by space agencies to design and demonstrate optical instruments to permit “remote sensing applications” from GEO (Geostationary Orbit). Earth observation missions (with spatial resolutions in the range of 1-4 km in the optical region of the spectrum) from GEO are rather challenging due to their enormous distance from the Earth’s surface (about 36,000 km, or 45 times further away than from normal LEO altitudes of 800 km). Still, Earth observation missions from GEO are very attractive, offering the advantage of a continuous viewing capability, which so far has only been employed by GEO weather satellites (much better data resolutions). NASA plans to fly GIFTS (Geostationary Imaging Fourier Transform Spectrometer) in 2006.

The intent of this chapter on “Earth Observation Short History” is to put some events, pertaining to the wide field of Earth observation, into proper (thematic) context - the past has to be known and understood in order to plan for the future. The emphasis is on sensor technologies, system concepts, observation techniques, operational aspects, and navigation. Of interest is also the introduction/provision of general services and the start of international cooperation. 22) The select nature of this EO-history overview precludes any claim for completeness. The scope of Earth observation is so immense, I simply do hope that some of the most important achievements are properly covered or even mentioned. It should also be pointed out that there is plenty of room left, as well as considerable needs, for creativity and innovation to continue to change things for the better. - At the beginning of

the 21st century, a better understanding is emerging of the relationship between technology development and the ability to do science.

Of all satellite launches on a worldwide scale, 70-75% are commercial communication satellites, the rest are military and civil satellites for such services as surveillance, technology development, Earth observation and navigation. Hence, telecommunication is by far the most widespread application of space technology. 23) The field of Earth observation is in second place when compared by the number of spacecraft launches. Next to telecommunications, remote sensing may be the most significant commercial application in the space industry – one which, like satellite telecommunications, has the potential to fundamentally change the way certain industries operate.

Space programs, in particular high-risk technology demonstration missions, are by nature technology drivers, due to the high demands on their functional capabilities, performances, and services in system hardware and software (service includes operational aspects). The term technology driver implies also technology transfer opportunities. Technology development in virtually any space program of the world is mostly carried out by the space industry of a country (or in a number of member countries like those of ESA) in response to an agency’s need. Over the years, it has become increasingly necessary for the economy of any spacefaring nation to transfer and to share the enabling technologies as well as the knowledge/expertise to the industry in general. Technology transfer means that a technology developed for a particular application, turns out to be conceptually more general in its functionality and in its application range than originally identified, planned, or envisaged.

It is then used as a spin-off in sometimes totally different areas of applications, resulting in a benefit to all involved. Start-up companies are often set up in the wake of newly developed technologies (promising ideas and concepts), usually by the same people/experts involved in the particular development, to exploit them with marketable products. Technology transfer often implies also licensing of a product, and/or a process, and/or a service. Besides totally new technology developments, many space agencies, military establishments, institutions, and space industry, invested (and continue to invest) in particular in raising the available technologies of their programs to new levels of performance and functional capabilities. The range of these advanced applications - of new technologies and of improved (or advanced) technologies - is certainly enormous; hence, many organizations [NASA, ESA, JAXA (formerly NASDA), CNES, etc.] have established special programs to better facilitate technology transfer and commercialization.

*It is ideas (unusual and daring ones) and imagination, coupled with a considerable amount of determination and persistence, that bring about innovation and technology development.* 24) In 2001, I was somehow quite irritated when I discovered ESA’s decision to drop the proposed atmospheric mission CLOUDS (Cloud and Radiation Monitoring Satellite), an excellently defined project study (after all, it represented a real consistent approach, the best definition I had seen so far of any project), conducted by 12 European partners. Considerable investments of time and money had gone into the realization of this study. The main arguments for the non-selection of CLOUDS were that the payload complement lacked at least to some degree an element of daring concept introduction needed for future observations. Tight budgets were of course another reason. Eventually, the EarthCARE (Earth Clouds Aerosol and Radiation Explorer) proposal was considered as more advanced to fill the gap. Space research, in particular technology introduction into instrumentation and/or spacecraft, is by its very nature an inherently high-risk and also a high-payoff enterprise. Trying and failing is often far better than not trying at all. High-risk development projects require an aggressive approach; they are a necessary complement to those (conventional service)

missions, in which new ideas, approaches and technologies are more or less avoided to maximize the chances of success.

Yuri Gagarin, the first Soviet cosmonaut, the first human in outer space, reported: “Circling the Earth... I marveled at the beauty of our planet... Looking at our Earth from space, what strikes me is not only the beauty of the continents... but their closeness to one another... their essential unity. The different parts that make up the world all merge into one whole... How worthwhile life would be on our planet, if the people of all the continents were to really become aware of their closeness... their common interests... Let us safeguard and enhance this beauty - not destroy it!”

An American astronaut, Russell Schweickart, lunar module pilot on Apollo 9, had similar feelings. “You look down there and you can’t imagine how many borders and boundaries you cross again and again... and you don’t even see them. From where you see it, the thing is a whole and it is so beautiful... And there you are - hundreds of people killing each other over some imaginary line that you’re not even aware of, that you can’t even see... You realize that on that small spot, that little blue-and-white thing is everything that means anything to you - all history, and music, and poetry, and art, and birth, and death, love, tears, joy, games.”

All of humanity now shares that picture of the Earth from space. We are one human species; we live on one tiny, fragile planet suspended in the darkness of space; there is one life-support system that maintains us all. The borders and boundaries that separate us are artificial. Whatever our differences - however emotional they are, however intractable they have become, however inevitable they may seem - they are insignificant compared to what we share.

An Earth observation and scientific research program may answer some of the following questions of profound importance to humankind:

- How is the Earth changing and what are the consequences of life on Earth?
- How is the global Earth system changing?
- What are the primary forcings of the Earth system?
- How does the Earth system respond to natural and human-induced changes?
- What are the consequences of changes in the Earth system for human civilization?
- How well can we predict future changes in the Earth system?

Earth observation gives a new view and perception onto as well as into Earth - providing a new understanding of Earth system processes on a global scale; its information may also serve as a much improved assessment tool for decision support on all levels.

The ultimate challenge of Earth system science is to consolidate all scientific findings (observations) from the different disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land and biosphere system, including the sun-Earth connection. This involves nothing less than the development of high-resolution modeling of the Earth system and a continuous process of re-assessment and improvement of these models. Impressive models already exist within each individual Earth science discipline, the models incorporate many relevant components.

An important step into the direction of a unified Earth observation approach was done at the GEO (Group on Earth Observations) summit in Tokyo, Japan, on April 25, 2004 when GEOSS (Global Earth Observation System of Systems) was created. GEOSS is an international framework to develop a 10-year implementation plan (for the period 2004-2014), a comprehensive, coordinated and sustained system that will help to better understand Earth systems, including weather, climate, oceans, water cycle, geology, ecosystems, agriculture


and biodiversity, energy, disasters, etc.. Representatives of 47 countries and more than a dozen international organizations [UN (UNEP, FAO, UNESCO), ESA, EUMETSAT, EC, ECMWF, ISCU, WMO, IGOS-P, CEOS, WCRP, etc.] were present at the ad hoc GEO (Group on Earth Observations) summit, signing the document (the finalization of a draft implementation plan). The plan represents a useful step forward in turning the GEOSS idea into a reality. The aim behind GEOSS is to maximize the effectiveness of Earth Observation by minimizing data gaps, building capacity and exchanging information as fully and quickly as possible. Developed and developing nations alike will have access to all data gathered by the network, following the model of the World Meteorological Organization’s four-decade-old World Weather Watch, which coordinates the globe’s weather satellites along with in-situ climate stations. 28) 29)

Note: The ad hoc intergovernmental Group on Earth Observations (GEO) was created during the first “Earth Observation Summit” in Washington DC (July 31, 2003) and was made responsible for producing a 10-year program to coordinate space- and ground-based global monitoring systems, to be known as GEOSS.

GEOSS will be a distributed system of systems, building step-by-step on current cooperation efforts among existing observing and processing systems within their mandates, while encouraging and accommodating new components. Participating members will determine ways and means of their participation in GEOSS. 30)

For the success of GEOSS, interoperability among each system is mandatory.

- Standards and practices: For each observation type or system, it is essential that standards are being developed, shared and implemented internationally. Otherwise, the value of the Earth observation investments will be significantly reduced.
- Data quality: Data quality is at the heart of every step of data management. Data are processed automatically more and more, the impact of the ingestion of bad data will become more serious and costly.

The 10-year GEOSS program implementation plan was formally approved/adopted by government delegates at the 3rd Earth Observation Summit on February 16, 2005 in Brussels, Belgium. Nearly 60 nations and about 40 international organizations, including ESA, EUMETSAT, and the EC (European Commission), are working to establish the emerging network of Earth observation systems. The participants have also agreed to share their scientific data. The 10-year plan states: “The vision for GEOSS is to realize a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information.” The plan sets out a timescale for achieving certain objectives in the fields of improved Earth monitoring, understanding of Earth processes and prediction capabilities for the behavior of Earth systems.

The 10-year implementation plan prescribes a user-driven approach to the creation of GEOSS. 31) GEOSS interoperability arrangements are to be based on the view of complex systems as assemblies of components that interoperate primarily by passing structured messages over network communication services. The core in building and operating GEOSS is thus interoperability specifications established and adhered to by all contributing systems. Building on existing systems and initiatives points to the importance of using existing international standards organizations and institutes in the identification and adoption of standards to achieve GEOSS interoperability objectives.

1.1 Some background on policies of commercial high-resolution imagery

In the time frame 1960 to the early 1990s (the so-called Cold War period), spaceborne high-resolution imagery was the exclusive province of the two superpowers, the USA and the USSR (Union of Soviet Socialist Republics). Both of them used dedicated military reconnaissance satellite systems to collect strategic intelligence with film-based camera and capsule reentry systems.\(^{32}\)\(^{33}\) The level of secrecy was extremely high, and the technology was restricted to the military sector (in particular, national interests were of great priority). In the USA, no civilian applications were allowed for spaceborne imagery below 30 m GSD (Ground Sample Distance). This corresponded directly to the imagery provided by the Landsat series of NASA. All bands of LS-4/5 had a spatial resolution of 30 m (except band 6 with 120 m). LS-4 was launched July 16, 1982, LS-5 was launched March 1, 1984.\(^ {34}\)

The availability of high-resolution imagery on a commercial basis is a fairly recent event in spaceborne remote sensing history. The government restrictions began to erode in the mid 1980s, with the commercialization of the Landsat program and the response to the development/operation of the SPOT series by CNES (France). Escalating Landsat costs led to its commercialization in 1983, and in July 1984 the “Land Remote Sensing Policy Act” turned over Landsat operation to the Eosat corporation.\(^ {35}\)

Some of the events are enumerated:

- In the fall of 1987, the USSR made the images, taken by the KFA-1000, the MK-4, and the MKF-6 film-based camera systems (flown on the Resurs-F1 and -F2 system series as well as on other spacecraft), commercially available; these were panchromatic (i.e., black and white) as well as color images at spatial resolutions of 5-10 m. Then in 1992, two Russian companies began to sell selected high-resolution imagery acquired by the KVR-1000 camera of the Komet spacecraft series (film camera, spatial resolution imagery of 2 m). This panchromatic camera was designed for intelligence applications and is still being used by the Russian intelligence community.\(^ {36}\)

- The potential of commercial imagery gained considerable momentum in the late 1980s when the space agencies of several countries announced plans to develop and launch high-resolution commercial imaging systems. For instance, France started its very successful SPOT satellite series in Feb. 1986 with the launch of SPOT-1 providing a spatial resolution of 10 m (first long-term introduction of CCD detector technology). ISRO of India followed closely with its IRS series imaging satellites (launch of IRS-1A in 1988). Realizing these facts and the current practices of high-resolution imagery sales by Russia, the US government removed some of its restrictions in January 1988 to remain commercially competitive (on the international scene).

- In Oct. 1992, the Land Remote Sensing Policy Act (US Congress) was signed into law.\(^ {37}\) This law reversed the 1984 decision to commercialize the Landsat system and recognized the scientific, national security, economic, and social utility of “land remote sensing from space.” In addition, it streamlined the procedure for considering license applications for commercial imaging satellites, and eliminated many of the legal obstacles that had been imposed in 1972 to prevent approval of most such applications.

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\(^{34}\) G. T. Richardson, R. N. Merz, High-resolution Commercial Imagery and Open-Source Information: Implications for Arms Control,” Intelligence Note, May 16, 1996, URL: http://www.fas.org/irp/offdocs/acda.htm


• In 1993, after the commercialization of KVR-1000 imagery by Russia, the US Government implemented a new policy [Presidential Decision Directive (PDD) No 23] that encouraged the commercialization of high-resolution imagery into the international market. As a consequence, the DOC (Department of Commerce) granted the first US license in 1993 to DigitalGlobe’s predecessor, namely WorldView Inc. of Longmont, CO, allowing a private enterprise to build and operate a satellite system and to gather high spatial resolution digital imagery (1 m GSD) of the Earth for commercial sale. Under the new policy, a number of private companies have obtained licences for the operation of private satellite remote sensing systems.

• In Feb. 1995, the US government declassified over 800,000 images taken between the years 1960 and 1972 — making the imagery available to the civil community (execute order by President Bill Clinton). The second declassification occurred in the fall of 2002 when NIMA (National Imagery and Mapping Agency) cleared imagery for public release from the KH-7 and KH-9 programs.

• Since 1996, under the national space policy signed by President Bill Clinton (PDD No 49, Sept. 19, 1996), the U.S. government has been committed to using commercial imagery satellites to augment its capabilities, save money and help ensure the health of the domestic industry.

• Space Imaging Inc. of Thornton, CO, obtained also a license for high-resolution imagery. The first spaceborne 1 m spatial resolution panchromatic solid-state digital imagery with an optoelectronic imager (using a CCD detector — i.e., no film) was obtained by the commercial spacecraft Ikonos-2 (launch Sept. 24, 1999) of Space Imaging. This was followed with data at a resolution of 0.62 m delivered by the optical imager of the QuickBird-2 mission (launch Oct. 18, 2001) of DigitalGlobe Inc. — Prior to this time, both companies had suffered severe setbacks with launch failures in their commercial ventures: Worldview/Earthwatch with its EarlyBird (launch Dec. 24, 1997) and QuickBird-1 (launch Nov. 20, 2000) satellites, and Space Imaging with its Ikonos-1 spacecraft (launch April 27, 1999).

• In a significant shift in policy, the Bush administration has ordered US federal agencies to rely much more heavily on private satellite companies to provide high-resolution imagery from space (April 25, 2003). Obviously, the quality of commercial imagery has improved over the years to an extent that military interest in these commercial products is on the rise. Naturally, there are also hard economic reasons to change the policies toward dual-use by the civil and military communities.

• NIMA (National Imagery and Mapping Agency), Arlington, VA, a US government agency, was established in Oct. 1996. NIMA incorporates the Defence Mapping Agency (DMA), the Central Imagery Office, and the Defense Dissemination Office as well as CIA’s Photographic Interpretation Center. NIMA is also the principal buyer of commercial imagery for all DoD organizations. In Nov. 2003, NIMA was renamed to NGA (National Geospatial-Intelligence Agency).

• To assure availability of imagery from the next-generation of commercial, high-resolution imaging satellites, NGA awarded DigitalGlobe with the first “NextView” vendor contract in Oct. 2003 — implementing a new level of partnering between the federal government and the US commercial remote sensing industry. It provides NGA and its military customers with greater access to and priority acquisition of high-resolution imagery. It further allows NGA to participate in the development cycle for commercial next-generation imaging capabilities.

• The next high-resolution imaging satellite of DigitalGlobe (Longmont, CO) is called WorldView-1, a successor of QuickBird-2. A launch is scheduled for late 2007. The NGA requirements, a major sponsor of the system, call for imagery with a spatial resolution of 0.5 m panchromatic and 2 m MS (Multispectral) data. — The OrbView-5 satellite, under devel-
development by OrbImage of Dulles, VA, is planned for launch in 2007. OrbImage has also a NextView vendor contract of NGA; the requirements of OrbView-5 call for panchromatic imagery with a resolution of 0.41 m and multispectral imagery with a resolution of 1.64 m.

- Naturally, this doesn’t mean the end of military imaging (reconnaissance) satellites. The military establishments of the USA, Russia, China (ZY-2B), France (Helios-1, Helios-2), Israel (Ofeq), Germany (SAR-Lupe), Italy, Japan, Spain, etc. are operating high-resolution imaging systems (in the optical and/or microwave region) or are in the process to do so (Germany). There is no intention in the foreseeable future to offer the classified imagery to commercial users.

Table 1 gives a general chronological overview of spaceborne imaging missions on a global scale. A lot of things have changed since the 1990s on the remote sensing scene. In the meantime, high-resolution commercial imagery is also available by a lot of other nations.
1.2 Sensor/Technology Development

In the early years of Earth observation (in particular satellite meteorology) attention was focused on those phenomena which could be observed relatively directly in the visible and near-infrared bands of the spectrum. First images were obtained by photographic systems such as automated still or movie cameras, followed eventually by vidicon electronic imaging systems [a framing system of TV heritage - the image from the photoconductive surface (detector) is raster scanned by an electron beam; example: RBV (Return Beam Vidicon), AVCS], and later by optomechanical scanner systems [examples: M-7 an airborne multispectral mapper of ERIM (first flown in 1971) and MSS on Landsat-1, launch July 23, 1972 from VAFB, CA]. The TV cameras of the TIROS-I satellite (launch April 1, 1960) provided daily low-resolution black and white pictures in the visible spectrum (panchromatic) of cloud cover and the Earth’s surface where clear. A time sequence of these synoptic coarse-resolution images permitted a visual interpretation by the meteorological community of large weather patterns which moved slowly across a continent (inferring atmospheric motions) - a first application of the emerging field of Earth observation. The TV cameras of the very next TIROS satellites experimented already with the infrared spectrum. The resulting images permitted a first look at the Earth’s heat distribution. In addition to the TV cameras, TIROS-2 and its successors experimented with the infrared spectrum by adding, variously, medium-angle, omni-directional and scanning radiometers.

The first years in Earth observation were dominated by such overall requirements for repetitive coverage (frequent observations) and the need of an operational capability, in particular for meteorological satellites. But it was also recognized that to create the new remote sensing technology, and to begin its utilization, would require an interdisciplinary effort by all parties involved. The challenges were monumental for research and technology development on all fronts, to create an infrastructure and to come up eventually with operational services.

The success of initial large-scale weather sensing started a planning and development period for better sensor systems, in particular with improved spatial and spectral resolutions, capable of land-surface imaging. Spectral resolution meant parallel sensing and detection in several bands of the visible and near-infrared spectrum. This technique was referred to as multispectral sensing, enhancing considerably the value (interpretability) of imagery.

The MSS (Multispectral Scanner System) instrument of the Landsat series (for land surface imaging) is such an early multispectral instrument (1972), with the visible and near-infrared spectrum almost evenly divided into four bands (band specification for MSS was simply adopted from airborne photographic experience of films).

The imagery of the Landsat-1 MSS instrument was a sensation of the time. Stephen S. Hall of USGS recalls the situation and his feelings of first Landsat imagery availability in the following way (book 1992). Within days it had stunned geologists, rewritten the textbooks of forestry and land use, and revolutionized cartography. Its earliest transmissions revealed several dozen earthquake faults near Lake Tahoe and Monterey Bay in California, faults that had escaped the notice of geologists who had crawled over that same shifting seismic terrain for decades. Undiscovered lakes winked up at the camera. One early image of Alaska showed a forest fire eating through a forest north of Fairbanks; nothing unusual about that, except people in Fairbanks didn’t know about it. A ship stranded by chance in the Arctic Ocean received Landsat’s satellite maps of the ice pack and picked its way to freedom. Previously unseen terrestrial pat-

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38) Note: A photographic system is also referred to as a framing system. It means that all of the data in an image are acquired simultaneously.

39) RBV was a three-camera video system designed for what was then regarded as high accuracy cartographic mapping data. It was a successful proof-of-concept instrument, but one that was eclipsed in the science community by the more versatile and popular MSS.

tems took on the beauty of modern art and modern metaphor: there were peeling fragments of landscape around Elephant Butte, Montana, that reminded one of Clyfford Still, Cairo as it might be imagined by Helen Frankenthaler, a network of Russian roads imitating astrocytes in the mammalian brain. From those first heady days, Landsat images have graduated to the level of cultural artifacts with coffee-table status: the posters hang in offices and homes, the maps have generated entire atlases, the images fill year after year of calendars. The satellite taught us, NASA administrator James C. Fletcher said at the time, "a new way to look."

In this context: in the Soviet Union, a parallel development to MSS (on Landsat) took place with the development of the MSS Fragment instrument at IKI (Space Research Institute), an 8-channel imager with a spectral range of 0.4-2.4 \( \mu m \), flown on Meteor-Priroda-5 (launch June 18, 1980). Fragment operated successfully onboard the spacecraft for four years.

Starting with Landsat-4 in 1982, a more sophisticated multispectral imaging sensor with the name of Thematic Mapper (TM) began its operation. It featured seven spectral bands and a ground resolution of 30 m in the VNIR bands. The TM band-selection process was on the basis of a comprehensive study and analysis of spectral reflection features for a variety of vegetation types. - The rather successful Landsat instruments eventually spawned other spaceborne Earth-surface imaging systems. Some of them are: The MOMS sensor missions on Shuttle (MOMS-01 in 1983), the SPOT satellite series sensors HRV (High Resolution Visible) of CNES (SPOT-1 launch in 1986), the Resurs-O1 series of Russia with MSU-E and MSU-SK (launch of Resurs-O1-1 in 1985), the IRS series of ISRO (launch of IRS-1A in 1988), JERS-1 of NASDA with OPS (launch of JERS-1 in 1992), ADEOS of NASDA with AVNIR (launch Aug. 17, 1996). See Table 1. At the beginning of the 21st century, the data from the Landsat S/C series constitute the longest record of the Earth’s continental surfaces as seen from space. It is a record unmatched in quality, detail, coverage, and value.

Most of the instruments placed into orbit for the study of the Earth’s atmosphere and surface have been of the type passive sensors,\(^{41}\) imagers and sounders operating in the visible, infrared and microwave spectral regions. Passive detection can only work, when the naturally occurring energy is available. The sun’s energy is either reflected, as it is for visible wavelengths, or absorbed and then re-emitted, as it is for thermal infrared wavelengths. Detection of reflected solar energy, for example, can only proceed when the target is illuminated by the sun, thus limiting visible light sensor observations on satellites from being used during a nighttime pass. Technology developments over the past four decades have allowed the capabilities of the current generation of passive sensors to advance far beyond those of the first instrument on Sputnik-1 and also the TV cameras on TIROS-1. - Active sensors are devices providing their own energy source for illumination of the target. They offer the capability to obtain measurements anytime, regardless of the time of day or season. Active sensors need of course a fairly large amount more power to perform their observation application. The first spaceborne active sensors were radar systems on Skylab (the instrument was named S-193, a combination of passive microwave radiometer with an active scatterometer, and a radar altimeter) operated between May 1973 and Feb. 1974. The next radar altimeter was flown on GEOS-3 (launch April 9, 1975, E.7.3) of NASA.

Many items/instances of technology introduction\(^{42}\) \(^{43}\) \(^{44}\) (the emphasis is on civil Earth observation programs, military programs are considered only when enough published information is available) are presented below. The scope of description must be limited to abstract level detail due to the vast number of topics in the general field of Earth observation. The reader is invited to consult also the survey references of the published literature as

\(^{41}\) Note: A passive instrument is a sensing system that detects and measures incoming radiation emitted by the target. Such sensing systems do not emit any power to the target for purposes of measurement.

\(^{42}\) “Perceiving Earth’s Resources from Space,” Special issue of Proceedings of the IEEE, Vol. 73, No. 6, June 1985, pp. 947-1128

\(^{43}\) Special Issue on Remote Sensing for Environmental Research, Proceedings of the IEEE, Vol. 82, No. 12, Dec. 1994, pp. 1771-1929

\(^{44}\) Special Issue on Remote Environmental Sensing, Proceedings of the IEEE, Vol. 57, No. 4, April 1969
well as the bracketed references in the text, referring to descriptions in other chapters of the book..

1.2.1 Concepts in Optical Observations

The principal detection methods used in optical observations are photographic [e.g., (analog) film], photoemissive (photomultipliers), and photoconductive (semiconductor).

- The first low-resolution space photograph of the Earth’s full disk was taken and transmitted by the US satellite Explorer-6, a spin-stabilized S/C with a mass of 64 kg (launch Aug. 7, 1959 on a Thor vehicle from Cape Canaveral into a highly eccentric orbit, perigee = 237 km, apogee = 41,900 km, inclination = 47º, period = 765 minutes) in August of 1959. The camera system flown was a TV optical scanner, consisting of an optical unit containing a concave spherical mirror and phototransistor, a video amplifier, timing and logic circuits, and telemetry. The scanner’s optical axis was directed 45º away from the S/C spin axis, which was parallel to the orbital plane. The vehicle’s spin furnished the line scanning, and the spacecraft’s forward motion along its trajectory provided the frame scanning. The first “television” photo, received in Hawaii, took nearly forty minutes to transmit.

- On June 7, 1967 the first color image of the Earth from space was taken by the Molniya-1 spacecraft of the USSR. In the US, the first color picture of the Earth from a near-synchronous orbit was taken on July 25, 1967 by the Dual Vidicon Camera system of the DODGE satellite (see M.8).

- **Spaceborne photographic film imagery** for reconnaissance and mapping (also referred to as “perspective imagery”). 45) 46) 47) 48) The early US military program, endorsed by President Dwight D. Eisenhower in Feb. 1958, employed traditional camera technology for information gathering (to support SALT treaty verification). The US Discoverer-14 satellite [also known as the CORONA mission 9009 of NRO (National Reconnaissance Office), launch Aug. 18, 1960 with a Thor vehicle from VAFB, CA; perigee of 250 km] opened a new era in spaceborne photoreconnaissance by successfully returning the film product in a reentry vehicle (capsule) and subsequent mid-air recovery on Aug. 19, 1960 northwest of Hawaii by a JC-119 aircraft, representing the first successful aerial recovery of an object returned from orbit. A total of 95 successful CORONA missions took place over a period of 12 years, ending on May 25, 1972 with mission 1117 (D.10). The high-resolution Earth-surface imagery (5-12 m) of the programs CORONA, ARGON (12 missions between Feb. 17, 1961 and Aug. 21, 1964), and LANYARD (single mission in 1963) predated the imagery of the civil program Landsat.

The first declassification (i.e. availability to the civil community) of the imagery of the three programs took place in spring 1995 by the US government [Executive Order 12951, declassifying reconnaissance satellite images from the Corona program and two related subprograms - Argon (KH-5) and Lanyard (KH-6)]. This, in turn, extends the baseline for historical systematic Earth surface coverage backwards by more than a decade [some 866,000 images taken in the period 1960-1972 by KH-1 (Keyhole-1, a code name) through KH-6 were released].

The second declassification occurred in the fall of 2002 when NIMA (National Imagery and Mapping Agency) cleared imagery for public release from the KH-7 and KH-9 programs. At 1.2 m resolution initially and later at 0.6 m, the KH-7 imagery was very fine in its time [KH-7 was operational from July 1963 to June 1967; its imagery had a swath width of about

46) R. A. McDonald, “CORONA: Success for Space Reconnaissance, A Look into the Cold War, and a Revolution for Intelligence,” PE&RS, Vol. 61, No. 6, 1995, pp. 689-719
47) http://www.nro.odci.gov/index5.html
48) http://www.fas.org/spp/eprint/mckinley.htm
23.5 km with a scene length anywhere from about 8 km to 750 km in length, the camera could be turned (tilted) in the cross-track direction to extend the field of regard]. A KH-9 scene has a size of 130 km x 260 km at an initial resolution of 10 m and 6 m on follow-up missions. A total of 20 KH-9 satellites were launched from June 1971 until April 1986.

Note: The US military reconnaissance program gave up the concept of high-resolution film imagery (70 mm unperforated film) and film capsule recovery in the mid-seventies in favor of optoelectronic imaging (more practical for routine operations, but lower spatial resolution than film) with the launch of the KH-11 (Keyhole designation) spacecraft series. The KH-11-1 satellite was launched Dec. 19, 1976. The KH-12 (advanced KH-11) series have a spacecraft mass of about 18 tons (up to 7 tons of propellant for extended in-orbit maneuverability) providing observations in moderately elliptical orbits of about 250 km x 1000 km. The moderate elliptic orbit is of interest in a so-called “theater context” when coverage need is limited and concentrated, but revisit and resolution are paramount. KH-12-1 was launched Nov. 28, 1992 from VAFB, CA, on a Titan-4 vehicle. The KH-12-5 spacecraft was launched Oct. 5, 2001.

- The former Soviet Union started its photoreconnaissance satellite program in 1957 (Zenit-2 spacecraft based on the Vostok design). The entire program was launched under the cover of the “Cosmos scientific program” of “DS” satellites to disguise its true intentions. The very first Zenit-2 launch took place Dec. 11, 1961, but the spacecraft didn’t achieve a proper orbit. The first version designed consisted of an equipment section and a re-entry capsule. The equipment section included the camera, ELINT (Electronic Intelligence) receivers, and control systems for orbital flight. The conical re-entry capsule contained the film cassettes to be returned to Earth and the recovery systems. The capsule was deorbited by a separate braking rocket. - The second launch of a Zenit-2 satellite (built by NPO Energia) occurred on April 26, 1962 and was successful.

A film camera of considerable sophistication on this spacecraft was MKF-6 (Multi-Kanal-Fotografie-6) or “ multispectral film camera-6”, developed at VEB Carl Zeiss, Jena, German Democratic Republic (former East Germany). The camera employed a battery of six lenses (two rows of 3 lenses in parallel), all looking into the same footprint, each for a different spectral band and furnished with a special filter, in the spectral range of 0.45 - 0.90 μm. Thus, color imagery with a high degree of geometric and radiometric accuracy and resolution was obtained in six spectral bands by using different films for each band. Un-perforated 70 mm films of 120 m length were used (shutter speeds of 7-56 ms, image format of 55 mm x 81 mm). MKF-6 was initially flown on aircraft (Antonov-30). The so-called “data processing” consisted of an opto-analog image analysis using MSP-4 (Multispectral Projector-4). This instrument assisted in the human visual inspection process by generating a color-coded synthesis, using multiple negative imagery of a multispectral set (analysis by superposition). A first spaceborne demonstration of MKF-6 took place on Soyuz-22 (launch Sept. 1976) within the framework of a Kosmos experiment called “Raduga” and within the Intercosmos program. During the 8-day flight of Soyus-22, Soviet Kosmonauts took over 2,500 Earth images with the hand-held MKF-6 camera. Thereafter, MKF-6 was also utilized on the Salyut-6 and -7 space stations as well as on MIR. 49)

Note: The latest entry in Russian military surveillance is the Arkon-2 spacecraft with a launch on July 25, 2002 on a Proton vehicle from Baikonur. The satellite, built by Lavochkin (Lavochkina Scientific Production Association) of Khimki, is designed to produce imagery of 1 m resolution in the visible range. The telescope of the imaging instrument was built by LOMO of St. Petersburg; it has a focal length of 27 m (folded optics). Orbit of 1,506 km x 1,774 km, inclination of 63.4º. The Arkon-2 imagery is dual-use, i.e. for military and com-

commercial applications. Prior to this mission, Russia launched its first optoelectronic high-resolution imagery mission (Arkon-1) on Cosmos 2344 on June 6, 1997, 50)

Figure 1: Illustration of the Arkon-2 spacecraft (image credit: Maney Publishing, London, UK)

- TV camera observations. Among the very early imaging sensors in space were shutter-style TV cameras, used to collect meteorological data. These so-called RBV (Return-Beam Vidicon) TV cameras employed a frame-sensor technique (instantaneous scene), where an electron beam scans the image on a photosensitive surface (raster scan of a complete image, ground size of image: 185 km x 185 km, spatial resolution of 80 m). In this concept, the image is exposed by a shutter device and stored on a photosensitive surface within each camera. This surface is then scanned in raster form by an internal electron beam to produce a video signal (the image is focused onto a photoconductor which causes the intensity of the electron beam, discharged from the electron gun, to vary with the intensity of light radiation). The values of the video signal are converted into digital information. Such RBV cameras were flown in several early satellite series such as: TIROS (TIROS-1 launch April 1, 1960), ESSA (launch of ESSA-1 on Feb. 3, 1966), Landsat-1 to -3 (LS-1 launch July 23, 1972), DMSP (Block IV series started in 1965), and Meteor (Meteor-1-1 launch March 23, 1969). The pictures obtained in this fashion were relayed to the ground and required substantial signal processing, including oscilloscopes, to recover a satellite image.

- Spaceborne film cameras in civil Earth observations (western world): The Metric Camera of DLR, flown on the Spacelab -1 Shuttle mission of NASA and ESA (STS-9, Nov. 28 to Dec. 8, 1983), is considered to be the first civil spaceborne experiment dedicated to photogrammetry. The calibrated Metric Camera was demonstrating high-resolution space photography on a large film format (23 cm x 23 cm) for topographic and thematic mapping applications. The Metric Camera was a slightly modified aerial survey camera of Carl Zeiss, Oberkochen, Germany, of the type RMKA (Reihenmesskammer A) 30/23. It was mounted on the optical—quality window in the ceiling of the Spacelab pressurized module. The results of the analog (film) imagery obtained can be summarized as follows:

• Ground resolution: 10 – 15 m (pixel equivalent)
• Planimetric accuracy: \( \pm 10 \) m
• Height accuracy: \( \pm 15 \) m
• Due to the limited ground resolution the maximum map scale that could be derived was 1:100,000.  

The only calibrated mapping film camera which has been flown after the Metric Camera was the LFC (Large Format Camera) of NASA, which was operated on Shuttle flight STS – 41G, Oct. 5 – 13, 1984. This camera was equipped with a FMC (Forward Motion Compensation) system and a large image size of 46 cm x 23 cm (with the long size of the film in the flight direction) to improve the stereoscopic effect. It could be shown, that from these images, location accuracies of better than 10 m could be obtained for all three coordinates of a point target, and that compiling and revision of topographic maps at a scale of 1:50,000 and larger was possible.

### 1.2.1.1 Solid-state (digital) imaging - CCD detector technology

Solid-state imaging - a key technology in optical remote sensing capability - started a new era in quantitative information collection. The technique (introduced in the early 1960s) uses silicon-based photodetectors onto which radiation (photons) can be focused and an electronic readout scheme (scanner) for image capture. The new method, later referred to as an optomechanical system (and a later introduction of the optoelectronics system with CCD technology), converts incident photons directly into electrical current, offering many advantages [true space-point (pixel based) information, high dynamic range, low power dissipation, low voltage operation, no geometric distortions, sampled signal output, rapid response, etc.] over the conventional electron beam scanning vacuum tube technology, such as the vidicons, traditionally used in the RBV TV cameras. The new solid-state-oriented imaging technology provided considerable flexibility; in particular, it is suitable for digital processing, offering a variety of readout schemes [imaging arrays (1-D, 2-D) such as self-scanned photodiodes, CIDs, CCDs], permitting the use of many detector element types. CCDs, CIDs, analog film (silver-halide crystals in photographic emulsions), and even the human eye are “photon counters”. While CCDs are regular arrays of receptors of identical size, photographic emulsions consist of a random three-dimensional arrangement of receptors in size significantly smaller than CCD cells. In practical applications, CCD images can be built up one-dimensionally (line scanner) or two-dimensionally; all cells in the lightsensitive part of a CCD are biased in the integrating mode.  

The new solid-state radiation detection concept employs scanner systems (see chapter O.3) permitting the acquisition of imagery within and outside the VNIR spectral region of photographic films, offering also a strategy of separating the received radiation into a number of spectral bands. This key technology provides the only practical means for obtaining high-accuracy radiometric information. The early scanners form an image successively on a cell-by-cell basis by the process of scanning. The first scanners employed were optomechanical whiskbroom systems where imaging occurs on a cell-by-cell basis in the cross-track direction (later whiskbroom systems are using multiple parallel cells in the along-track direction to offset somewhat the disadvantage of cross-track scanning); these were followed by more efficient parallel line-scanned pushbroom (CCD) systems. Note: pushbroom scanners are also referred to as “along-track scanners” because they use the forward motion of the platform to record successive scan lines and build up a 2-D image perpendicular to the flight direction. However, instead of a mirror, they use a linear array of detectors, located in the

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focal plane, which are “pushed” in along-track to build up a ground swath; hence, “push-broom.”

The newly available scanner technology (whiskbroom/pushbroom) offered a means of making imagery quantitatively available to computer processing methods; it stimulated in turn the development of new sensor systems with greatly enhanced performance and observation capabilities, it permitted also a better modular design concept of imaging sensors. An imager based on solid-state technology consists of a suitable lens system (the optics subsystem), a scanner subsystem with the detector positioned at the focal plane, and operating electronics.

- Solid-state multispectral imaging in the 1960s. It signifies a great step forward in image interpretation capability, namely from visual or machine-sensed photointerpretation (analysis based on image characteristics) to quantitative interpretation of several bands of imagery (analysis based on spectral characteristics). The new quantitative approach relies on image processing methods of the evolving computer industry of the time.

The pioneering airborne instrument of spatially-registered multispectral scanners is M-5, developed by the Willow Run Laboratories of the University of Michigan. The M-5 whiskbroom scanner is based on solid-state technology, and developed around an optomechanical scanning system called the S-5 (built by HRB Singer for the US Army). The S-5 had two optical channels (not registered) and recorded its data on film. From 1963 to 1965, two of these instruments were flown in tandem, each in a DeHavilland Beaver aircraft, to obtain four unregistered bands (selectable from UV through LWIR). From June 1963 through June 1964, around-the-clock (every 4 to 6 hours) imagery was collected once a month over a local fifty mile flight path, selected for natural and cultural diversity. These data were manually analyzed to form the initial basis for an understanding of day-night-seasonal spectral imaging phenomena. The M-5 instrument provided support of the developing ERTS (Landsat) program, in particular for the design of MSS (Multispectral Scanner). The M-7 multispectral scanner was a direct successor of M-5, it became operational in 1971, was upgraded several times, and provided a long-term source of remotely-sensed multispectral imagery (P.82.2). A much later descendent of optomechanical whiskbroom technology was AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) of NASA/JPL (P.42). This early airborne hyperspectral imager was introduced in 1987 and became operational in 1989, the first sensor to contiguously cover the 0.4-2.5 μm region with narrow spectral bands. At the start of the 21st century, its data is still very much in demand. - The short dwell-time problem of these cross-track whiskbroom scanners was solved by introducing a parallel coverage arrangement of detector arrays in the along-track direction. In this way, the wide along-track coverage permitted sufficient integration time for all parallel cells in each cross-track scan sweep.

55) Note: The term “whiskbroom scanning” comes from the notion of sweeping a pathway in a side-to-side fashion by a small handheld broom. - Cross-track scanners use a rotating or oscillating mirror to scan contiguous series of narrow ground strips at right angles to the flight path.

56) Conventional photographic films with high resolution imagery were not amenable for direct processing and transmission methods in remote sensing. Film material was not suitable for quantitative radiation measurements, only a small spectral range (VNIR, SWIR) could be covered with film.


58) Note: Realizing the value of multispectral data, there were a number of implementations in the early 1960s to obtain multispectral data (i.e. photographs) by special cameras. Spectral separation was accomplished by using photographic filters with multi-objective camera systems, each for a separate spectral range. This left the photointerpreter with a dozen or so photos of the same scene, each at a different spectral band. The human eye finds it difficult to keep track of tonal variations over 16 or more levels of gray for even a modest number of different scene objects. - The discrimination problem was eventually solved with the availability of data from multispectral scanners and the development of proper algorithms for computer interpretation of imagery.

59) Information provided by B. Horvath of ERIM, who operated the M-5 imager and analyzed the data.

60) Note: In 1973 the Willow Run Laboratories team separated from the University of Michigan and became ERIM (Environmental Research Institute of Michigan). In 2000, ERIM became part of Veridian ERIM International
The electronic imaging concept converts incident photons on a silicon-based detector (such as a photodiode, CCD, CID, CMOS) directly into electrical current offering such features as: true space-point (pixel-based) information, high dynamic range, low power dissipation, low voltage operation, little or no geometric distortions, sampled signal output, and rapid response times. These are real advantages over the previous electron beam scanning vacuum tube technology of vidicons.

The technology provides a new unit of measurement: the pixel (picture element). An image is made up of a series of spatially-fixed pixels providing a unique location reference of the data of each element along with the target radiation measurement. Thus, the technique provides a firm concept of spatial resolution.

The solid-state radiation detection concept offers a strategy of separating the received radiation into a number of spectral bands. This key technology provides the only practical means for obtaining high-accuracy radiometric information by the parallel collection of multispectral or of hyperspectral imagery. The use of a dense detector array provides the capability of high-resolution spatial and spectral imagery. This offers very extensive interpretation capabilities for many applications.

The data is available in digital form, quantified at the instrument level - providing a great deal of flexibility by offering all the capabilities of digital processing, storage, and communication.

The concept signifies a great step forward in image interpretation capability, namely from visual or machine-sensed photo interpretation (analysis based on image characteristics) to quantitative interpretation of several bands of imagery (analysis based on spectral characteristics).

The electronic imaging concept permits the collection of imagery in a wide region of the optical spectrum (from UV, VIS, NIR, SWIR, MWIR, TIR, to FIR). This represents a vast improvement over the (analog) photographic film technology which is basically limited to the VIS and NIR regions of the spectrum.

Two solid-state electronic imaging concepts were developed in the 1960s starting a new era in remote sensing - with so-called scanner systems, based on serial and parallel imaging techniques, respectively:

1) **Whiskbroom scanning technique** — an optomechanical design where imaging occurs serially on a cell-by-cell basis in the cross-track direction of the spacecraft orbit using an oscillating mirror for each scan sweep. The first spaceborne whiskbroom imager, MSS (Multispectral Scanner), developed at SBRC (Santa Barbara Research Center of Hughes Aircraft Company (now Raytheon), was flown on Landsat-1 of NASA (launch July 23, 1972). Silicon-based photodiodes became first available in 1961 at Bell Labs.

2) **Pushbroom scanning technique** — an optoelectronic design where imaging occurs in parallel for all line detector cells in the cross-track direction with the use of CCD (Charge-Coupled Devices) detectors. The first spaceborne pushbroom imager (MSU-E) was flown on Meteor-Priroda-5 (launch June 18, 1980) satellite of the former Soviet Union. The CCD technology was invented in 1969 by Bell Labs.

In remote sensing terminology a line scanner is a (nonphotographic) device that forms instantaneous exposure geometries between a target and a detector, with the sensor optics in between, thus forming an image by the successive addition of picture elements (effectively a 1-D configuration to build up a 2-D image by the S/C forward motion).
Note: In some instances, preference is given to a whiskbroom imager design (the older imaging technology) because the optics for pushbroom operation must always cover FOV (the total field of view - meaning the full swath width) while the optics for whiskbroom operation deal with IFOV (instantaneous field of view) which is much smaller than FOV. Hence, there are less distortions at the swath edge for whiskbroom systems. 61)

Figure 3: Illustration of the Landsat–1 MSS whiskbroom scanning geometry (image credit: SBRC)

- Spaceborne scanners. In 1968, SBRC (Santa Barbara Research Center) of Hughes Aircraft Company proposed to NASA to place a new type of imaging device on the planned ERTS spacecraft, namely a “scanner system” in combination with a photodiode detector system. At the time, scanners were viewed with great skepticism by most scientists for two reasons. First of all, the scanner employed a moving part, an oscillating mirror, which was considered unreliable. Secondly, the scanner was not a full-frame imaging device; it created images from strips. Cartographers were suspicious of the scanner’s geometric integrity.

Note: Silicon-based photodiodes had become available in 1961 [PIN (Positive Insulator Negative) type], the first high-speed avalanche photodiodes were formed in 1966. 62) In 1939, Russell S. Ohl, an electrical engineer at Bell Labs, stumbled on the first semiconductor p-n junction.

The scanner did have one important advantage, namely its multispectral capability. Agricultural research had demonstrated the value of multispectral imagery. For example, the

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61) Note: The requirement of very wide FOVs of CCD instruments is usually being implemented today with a double mount instrument design in cross-track to achieve a high-resolution wide swath observation coverage.
0.63 to 0.68 \( \mu m \) band measures chlorophyll absorption; the 0.79 to 0.9 \( \mu m \) band indicates water content in leaves; and the 1.55 to 1.75 \( \mu m \) band displays soil moisture. SBRC initially designed a six-band scanner for the satellite. However, NASA's small satellite could not house the large scanner, so a more modest four-band MSS (Multispectral Scanner) was built for ERTS-1. The spectral bands were chosen to simulate false-color infrared photography. NASA put RBV cameras as well as the new scanner system (MSS) onboard the ERTS-1 satellite (in 1975 ERTS-1 was renamed to Landsat-1) to compare imagery from both types of systems. Within hours after launch of ERTS-1 (launch July 23, 1972), the first MSS images created a sensation with their amazing clarity and synoptic views of the landscape. Spatially, both systems (RBV and MSS) provided a resolution of about 80 m. Spectrally, each of the three-camera RBV systems was designed to cover a band: the blue-green, yellow-red, and red/NIR. MSS provided a similar band set along with a fourth band to extend coverage into the infrared region. The imagery of MSS was in digital form. The scan mirror assembly of MSS was the key to providing wide-field and ‘high-resolution’ coverage.

The new technique of scanning had the promise of more things to come. Thus, on the spaceborne side, MSS (with a cross-track whiskbroom scanner) ushered in an era of previously unimaginable synoptic knowledge of the Earth. - By seeing the world in electromagnetic increments beyond the normal range of human vision, Landsat revealed whole new worlds hidden within the folds of a familiar world we thought we knew so well. It was no great surprise that Landsat, from an average altitude of 910 km in space, could discern the health of corn plants on a half-acre plot of land in Iowa, could determine which were suffering from corn blight and where a fungal infestation appeared to be gaining a foothold. That is exactly what it was designed to do.

- The TM (Thematic Mapper) sensor on LS-4 (launch July 16, 1982, end of LS-4 mission on June 15, 2001) is a much improved successor in spatial and spectral resolutions to MSS. A good portion of land-surface observation history is intimately connected with this pioneering sensor (TM) and program (Landsat). All TM sensors (including ETM+ of Landsat-7) employed the optomechanical whiskbroom concept with a two-axis gimbaled scan mirror. Other spaceborne optomechanical (whiskbroom or flying spot) instruments of note are:

VIRS flown on TRMM, AVHRR (on the NOAA/POES series, all three generations of instruments, since 1978 starting with TIROS-N, see Table 68), OLS (flown on DMSP series, first introduced in 1976 - OLS uses a flying spot design), ASTER (whiskbroom in TIR, pushbroom in VNIR and SWIR), MODIS (Terra, launch Dec. 18, 1999), and OSMI (Ocean Scanning Multispectral Imager, flown on KOMPSAT-1, launch Dec. 20, 1999). Note: Instrument designs like AVHRR and MODIS are of the optomechanical type because the extended focal planes, coupled with relatively short focal lengths, lead to unworkable field angles and geometric distortion problems (pushbroom designs are not well suited to moderate-resolution wide-field systems). The whiskbroom optomechanical scanner technology continues its usefulness in such next-generation instruments as JAMI (Japanese Advanced Meteorological Imager) of the MTSAT-1R mission of Japan (launch Feb. 26, 2005), IASI of the MetOp–A mission of EUMETSAT (launch Oct. 19, 2006), and VIIRS (Visible/Infrared Imager and Radiometer Suite) of the NASA/IPO NPP and NPOESS program (launch in 2009 and 2012); both instruments are developed by SBRS (Santa Barbara Remote Sensing) of Raytheon Electronic Systems, Goleta, CA (see E10.1 and G.10.5).

- Charge-transfer devices (see O.4.2). The CCD (Charge-Coupled Device) detector technology was invented in 1969 by Willard S. Boyle and George E. Smith and first demonstrated (one-line eight pixel detector) by Gil Amelio, Mike Tompsett and George Smith at the Bell Labs (Bell Telephone Laboratories of AT&T, since 1996 of Lucent Technologies, 63) A. M. Mika, “Three decades of Landsat instruments,” Photogrammetric Engineering & Remote Sensing, ASPRS, Vol. 63, No 7, July 1997, pp.839-852
Inc.) in Murray Hill, New Jersey, USA. The idea originated from research into magnetic bubble memories. **The silicon-based detector invention, along with the development of the planar process for integrated circuits (ICs), eventually led to a revolution in optical imaging capabilities (resulting in the birth of digital photography), providing in addition a wide forum for multi-disciplinary applications.** Early industry CCD manufacturers were: TI (Texas Instruments), RCA (Radio Corporation of America), Fairchild Semiconductor, GEC (General Electric Co., UK), and Thomson-CSF (France, since 1978). By 1970, the Bell Labs researchers had built the CCD into the world’s first solid-state video camera. 64) 65) 66) 67) 68) 69)

A **CCD** 70) 71) is a photosensitive solid-state silicon-based detector, consisting of many cells or pixels that are capable of producing an electrical charge proportional to the amount of light they receive. Typically, the pixels are arranged in either a single line (referred to as linear array or line array) or in a two-dimensional grid (area array CCDs). Each CCD cell CCD is essentially a MOS capacitor, of which there are two types: surface channel and buried channel. The device is typically built on a p-type silicon substrate with an n-type layer formed on the surface. The particular application will, in general, dictate the type of CCD that is being used. One of the fundamental parameters of a CCD is resolution, which is equal to the total number of pixels that makes up the light sensitive area of the device.

At the start of the 21st century, the CCD technology is still having profound effects in the fields of optical imaging, particle tracking, x-ray detection, as well as analog storage devices. The application spectrum ranges from security monitoring to high-definition television, from endoscopy to desktop videoconferencing, from Earth observation to astronomy.

In remote sensing, the CCD pushbroom concept permits simultaneous measurements of an entire scan line (detector line array over the full swath width) for each spectral band (and serial shift-register readout), thereby improving the dwell time (or sampling time) over whiskbroom systems. (Note: very short dwell times, in the order of a few microseconds, limit the number of photons that can be detected without using very large optics). Advantages of the digital CCD technology lie in the real-time processing capabilities of the data, the high accuracy potential, the good radiometric characteristics, and the availability of relatively inexpensive system components. 72) The first astronomical CCD ground observation (of Jupiter, Saturn and Uranus) was done in early 1976 at the Mount Bigelow observatory of the University of Tucson, AZ (CCD detector array built by Texas Instruments). 73) - The first experimental airborne optoelectronic instrument, featuring a pushbroom CCD detector li-

72) Note: The terms “optoelectronics” and “photonics” are being used as synonyms throughout the literature. The term optoelectronics is a contraction of ‘optical electronics’ and refers to all types of photon effects (interaction/ conversion, transmission) with a medium and vice versa, including magneto-optic phenomena. Optoelectronic or photonic devices are being used in a wide variety of applications in the fields of optical detection and imaging, communications, energy generation, and computing, to name just a few. Examples of optoelectronic or photonic devices include: CCD, CMOS/APS (Active Pixel Sensor), LED (Light Emitting Diode), all types of photodiodes, ILD (Injection Laser Diode), CRT (Cathode Ray Tube), IOC (Integrated Optical Circuit), photovoltaic cells also referred to as solar cells, fiber cables, and photonic links.
ne array, was EOS (Electro-Optical Scanner) of DLR (former DFVLR), designed and developed by EADS Astrium GmbH (formerly MBB) of Munich, Germany in 1977, and flown on a DLR aircraft (DO-28) in early 1978 (chapter P.79). MEIS (P128) of CCRS (Ottawa, Canada) followed in 1978, and TIMS of Daedalus in 1981. ISRO built a single-band CCD camera in the late 1970s and had it flight-tested on an aircraft in 1980.

Some performance characteristics of CCDs:

- Fill factor. The fill factor is basically the percentage of each pixel that is sensitive to light. Ideally, the fill factor should be 100%; however, in reality, it is often less than this. The net effect of reducing the fill factor is a lowering of the array sensitivity.

- Dark current noise. Dark current can be defined as the unwanted charge that accumulates in the CCD pixels due to natural thermal processes that occur while the device operates at any temperature above absolute zero. At any temperature, electron-hole pairs are randomly generated and recombine within the silicon and at the silicon-silicon dioxide interface. Some of the electrons may be collected in the CCD wells, appearing as unwanted signal charges (e.g., noise) at the output.

- Quantum efficiency (QE). QE is the measure of the efficiency with which incident photons are detected. Some incident photons may not be absorbed due to reflection or may be absorbed where the electrons cannot be collected. The QE is the ratio of the number of detected electrons divided by the product of the number of incident photons times the number of electrons each photon can be expected to generate. Visible wavelength photons generate one electron-hole pair, thus the QE for visible light is given by the ratio of the number of detected electrons divided by the number of incident photons. Back illumination of a CCD is a technique to improve the QE.

- Blooming is an effect that occurs when, during the integration period, a potential well becomes full of electrons; this is usually caused by the presence of a bright object in the scene being imaged (assuming that the overall exposure is correctly set). When a potential well overflows, the electrons flow into surrounding potential wells, thus creating an area of saturated pixels. If blooming isn’t controlled, the resultant image will suffer from large overexposed regions.

- Spaceborne CCD detector technology was introduced with the MSU-E (Multispectral Scanning Unit-Electronic) flown on the Meteor-Priroda-5 (launch June 18, 1980) spacecraft of the former Soviet Union. MSU-E was built at ISDE (Russian Institute of Space Device Engineering) in Moscow; it featured a CCD line array of 1024 pixels, three parallel line arrays, each of 1024 elements, provided pushbroom imagery in three spectral bands (visible and near-infrared range); the spatial resolution was 28 m on a swath of 28 km. The CCD line arrays were designed and manufactured in the “Pulsar” plant, Moscow. The results obtained with MSU-E confirmed the potential of CCD technology for use in high-resolution multispectral monitoring. The MSU-E pushbroom instrument was also introduced on the Soviet Resurs series, starting with Resurs-O1-1 (launch Oct. 3, 1985). 74) 75)

Further early CCD pushbroom instruments were: MOMS-01 (Modular Optoelectronic Multispectral Scanner) of DLR, built by EADS Astrium GmbH, and flown on Shuttle flights STS-7 in June 1983 and STS-41B in Feb. 1984), the HRV sensors on the SPOT series of CNES (launch of SPOT-1 on Feb. 22, 1986), and LISS on the IRS series of ISRO (launch of IRS-1A on March 17, 1988).

The UoSAT-1 (launch Oct. 6, 1981) and UoSAT-2 (launch March 1, 1984) microsatellites of the University of Surrey, UK, carried the first experimental 2D CCD Earth imaging snapshot cameras (area array detectors). – Other early spaceborne CCD area-array detector implementations were introduced in the TVS (TV System) instrument, a wide-angle TV camera [TVS, an IKI instrument (Moscow), developed in cooperation with France and Hungary) of the Soviet Vega interplanetary missions to Venus and later to Halley’s Comet.

75) Information provided and document translation: courtesy of Boris Zhukov, DLR and Ian Ziman, IKI, Moscow
in 1984 (launched Dec. 15 and Dec. 21, 1984, respectively). On June 9 and 13, 1985, each Vega S/C deployed a Venus capsule. In March 1986, each Vega S/C encountered Halley’s Comet. TVS provided color images of Halley’s coma and core (~ 500 images from Vega-1, ~ 700 images from Vega-2, each at closest approach (8000-9000 km) to Halley’s Comet). 76)

In the meantime CCDs have evolved to a sophisticated level of performance (high radiometric and spatial resolution). Starting with the 1990s CCDs have become the technology of choice for most imaging applications in remote sensing. The microelectronics industry provides CCD technology (area arrays) on a chip level. A high-resolution VNIR camera can be built around a CCD chip by combining it with a suitable lens system, a cooling method, and operating electronics. CCDs take the place of vacuum-tube based imagers and film in conventional cameras. They provide a wide field of applications in science as well as in the consumer market. An astronomical imaging system with the name of STIS (Space Telescope Imaging Spectrograph) on Shuttle flight STS-82 (launch Feb. 11, 1997) was installed aboard the orbiting Hubble Space Telescope (HST); 77) the key element of STIS is a very sensitive CCD array (developed by SITe) enabling faint radiation measurements of distant stars. Also in 1997 Philips Co. with several partners was testing a CCD area array of 9216 by 7168 detectors (pixels) on a chip. The pixel size is 12 μm x 12 μm, the chip size is 111 mm x 86 mm. The first application of the 7k x 9 k area array detector was in astronomy.- Some drawbacks of the CCD technology are: CCD’s provide good image quality, but they are expensive, power hungry, and rather bulky with the required accessory chips.

- **Introduction of the ILT (Interline Transfer) CCD architecture in spaceborne instruments.** The technology of the progressive scan ILT CCD image sensor (an area array detector type) was introduced in space with MFEX (Microrover Flight Experiment), also referred to as “Sojourner” (a 6-wheel vehicle of 11 kg), of NASA’s Mars Pathfinder Mission (launch Dec. 4, 1996 from KSC; arrival on Mars: July 4, 1997). Two separate Kodak area interline sensors (detectors) were aboard MFEX, the KAI-0371 monochrome sensor and the KAI-037M color sensor. In this imaging concept, separate area arrays for image capture and charge transfer are being utilized, allowing images to be read out while the next image is captured. These sensors perform a progressive three-step process to produce images. The first step converts light from the exposure into an electronic charge at discrete sites, making up pixels. Next, the packets of charge are transferred within the silicon substrate. Finally, the charge-to-voltage conversion and output amplification takes place. This concept enables the detector to detect light and deliver extremely clear and sharp imagery. The ILT technique provides in effect the fastest electronic shuttering performance possible. The progressive-scan technology permitted the sensors to deliver still/video imaging of fast moving objects without breakup. Additionally, the sensors were designed to continually capture images while simultaneously transferring the previous image out of the sensor memory. 78) 79)

Note: The progressive scan ILT technology was actually introduced in the early 1990s, mainly for the purpose of solving some industrial CCD imaging (machine vision, traffic control, and television) applications occurring with fast-moving targets. The time delay between the transmission of odd and even fields -- makes the image to appear blurred when an object is moving quickly compared to the CCD refresh rate. The best solution to this problem turned out to be the progressive-scan interline-transfer CCD detector featuring simultaneous integration of all pixels resulting in sharp imagery.

76) Halley’s Comet is named after the 18th century English astronomer Edmond Halley (1656-1742) who first calculated the comet’s orbit and predicted that it would reappear at regular intervals.

77) Note: HST is named after Edwin P. Hubble (1889-1953), an American astronomer. In 1924, he coined the word “galaxy,” referring to a large star system such as the Milky Way and the Andromeda Nebula. He devised the classification scheme for galaxies that is still in use today. In 1929, Hubble analyzed the speed of recession of a number of galaxies and showed that the speed at which a galaxy moves away from us is proportional to its distance (Hubble’s Law). This discovery of the expanding Universe marked the birth of the “Big Bang Theory.”


<table>
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<tr>
<th>Launch Date</th>
<th>Satellite Platform (Agency or Company)</th>
<th>Earth Imaging Sensors of respective Payload</th>
<th>Comment (ops = operations)</th>
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</thead>
<tbody>
<tr>
<td>Jul. 23, 1972</td>
<td>Landsat-1 (NASA)</td>
<td>MSS, RBV</td>
<td>MSS whiskbroom imaging End of service Jan. 6, 1978</td>
</tr>
<tr>
<td>June 18, 1980</td>
<td>Meteor-Priroda-5 (Russia) G.6</td>
<td>MSU-E, MSS Fragment</td>
<td>1st long-term use of CCD pushbroom technology</td>
</tr>
<tr>
<td>Nov. 3, 1985</td>
<td>RESURS-O1-1 (Russia)</td>
<td>2 MSU-E, 2 MSU-SK</td>
<td>Use of CCD technology</td>
</tr>
<tr>
<td>Mar. 17, 1988</td>
<td>IRS-1A (ISRO)</td>
<td>LISS-I, LISS-II A/B</td>
<td>Three CCD imagers S/C ops until 1992</td>
</tr>
<tr>
<td>Apr. 20, 1988</td>
<td>RESURS-O1-2 (Russia)</td>
<td>2 MSU-E, 2 MSU-SK</td>
<td>S/C ops until June 1, 1999</td>
</tr>
<tr>
<td>Jan. 22, 1990</td>
<td>SPOT-2 (CNES)</td>
<td>2 HRV</td>
<td>Operational as of 2000</td>
</tr>
<tr>
<td>Aug. 29, 1991</td>
<td>IRS-1B (ISRO)</td>
<td>LISS-I, LISS-II A/B</td>
<td>Ops until Aug. 2001 (10 years)</td>
</tr>
<tr>
<td>Oct. 5, 1993</td>
<td>Landsat-6 (NOAA)</td>
<td>ETM</td>
<td>Launch failure</td>
</tr>
<tr>
<td>Sept. 20, 1993</td>
<td>IRS-P1 (ISRO)</td>
<td>LISS-2, MEOSS (DLR)</td>
<td>Launch failure</td>
</tr>
<tr>
<td>Sept. 26, 1993</td>
<td>SPOT-3 (CNES)</td>
<td>2 HRV</td>
<td>S/C ops until Nov. 14, 1997 (loss of Earth lock)</td>
</tr>
<tr>
<td>Nov. 4, 1994</td>
<td>RESURS-O-3 (Russia)</td>
<td>2 MSU-E, 2 MSU-SK</td>
<td>Operational as of 2000</td>
</tr>
<tr>
<td>Dec. 28, 1995</td>
<td>IRS-1C (ISRO)</td>
<td>PAN, LISS-III, WiFS</td>
<td>Operational as of 2001</td>
</tr>
<tr>
<td>Mar. 21, 1996</td>
<td>IRS-P3 (ISRO)</td>
<td>WiFS</td>
<td>Operations ended in 2005</td>
</tr>
<tr>
<td>Aug. 17, 1996</td>
<td>ADEOS (NASA)</td>
<td>AVNIR</td>
<td>S/C operations terminated June 30, 1997 (loss of power)</td>
</tr>
<tr>
<td>Sept. 29, 1997</td>
<td>IRS-1D (ISRO)</td>
<td>PAN, LISS-III, WiFS</td>
<td>Operational as of 2000</td>
</tr>
<tr>
<td>Dec. 24, 1997</td>
<td>EarlyBird (EarthWatch)</td>
<td>EBP, EBM, 3 m resolution</td>
<td>Operational as of 2000</td>
</tr>
<tr>
<td>Mar. 24, 1998</td>
<td>SPOT-4 (CNES)</td>
<td>2 HRVIR, Vegetation</td>
<td>Operational as of 2005</td>
</tr>
<tr>
<td>July 10, 1998</td>
<td>RESURS-O-4 (Russia)</td>
<td>2 MSU-E, 2 MSU-SK</td>
<td>Operational as of 2000</td>
</tr>
<tr>
<td>April 15, 1999</td>
<td>Landsat-7 (NASA)</td>
<td>ETM+</td>
<td>Optomechanical (whiskbroom) imaging, operational</td>
</tr>
<tr>
<td>April 27, 1999</td>
<td>Ikonsos-1 (Space Imaging)</td>
<td>OSA (Optical Sensor Assembly)</td>
<td>Launch failure of commercial imaging mission</td>
</tr>
<tr>
<td>Sept. 24, 1999</td>
<td>Ikonsos-2 (SI) Identical backup satellite and payload to Ikonsos-1</td>
<td>OSA built by Kodak</td>
<td>A new era of 1 m spatial resolution imagery began for spaceborne instruments</td>
</tr>
<tr>
<td>Dec. 18, 1999</td>
<td>Terra of NASA</td>
<td>ASTER (NASA)</td>
<td>S/C operational as of 2005</td>
</tr>
<tr>
<td>Dec. 20, 1999</td>
<td>KOMPSAT-1 (KARI)</td>
<td>EOC</td>
<td>S/C operational as of 2005</td>
</tr>
<tr>
<td>Nov. 20, 2000</td>
<td>QuickBird-1 (EarthWatch of Longmont,CO)</td>
<td>BGIS-2000 (Ball Global Imaging System-2000)</td>
<td>Commercial imagery at 1 m GSD, Launch failure</td>
</tr>
<tr>
<td>Nov. 21, 2000</td>
<td>EO-1 (NASA)</td>
<td>ALI (Advanced Land Imager)</td>
<td>The Landsat-7, EO-1, SAC-C and Terra “morning constellation” train started in 2001</td>
</tr>
<tr>
<td>Dec. 5, 2000</td>
<td>EROS-A, ImageSat International, Cayman Islands</td>
<td>PIC (Panchromatic Imaging Camera)</td>
<td>Commercial imagery at 1.9 m GSD, swath=14 km</td>
</tr>
</tbody>
</table>
Table 1: Chronology of optical Earth-surface satellite imaging missions

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Satellite Platform (Agency or Company)</th>
<th>Earth Imaging Sensors of respective Payload</th>
<th>Comment</th>
</tr>
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<tbody>
<tr>
<td>Sept. 21, 2001</td>
<td>OrbView-4 (Orbimage of Dulles, VA)</td>
<td>OHRIS with Pan &amp; 4 MS bands, OHIS, 280 bands</td>
<td>Commercial imagery at 1 m Pan, 4 m MS, swath of 8 km 8 m resol., 5 km swath.</td>
</tr>
<tr>
<td>Oct. 18, 2001</td>
<td>QuickBird-2 (DigitalGlobe of Longmont, CO)</td>
<td>BGIS-2000 (Ball Global Imaging System-2000)</td>
<td>Commercial imagery at 0.61 m Pan, 2.5 m MS,</td>
</tr>
<tr>
<td>May 4, 2002</td>
<td>SPOT-5 (CNES)</td>
<td>2 HRG, HRS, Vegetation</td>
<td>5 m resolution for HRG PAN data, 2.5 m in supermode</td>
</tr>
<tr>
<td>June 26, 2003</td>
<td>OrbView-3 (OrbImage)</td>
<td>OHRIS (OrbView High Resol. Imaging System)</td>
<td>Commercial imagery at 1 m Pan, 4 m MS, 8 km swath, 8 m resolution for HRG PAN data, 2.5 m in supermode</td>
</tr>
<tr>
<td>Oct. 17, 2003</td>
<td>IRS-P6 (ISRO), also called: ResourceSat-1</td>
<td>LISS-IV, LISS-III, AWiFS</td>
<td>LISS-IV with 5.8 m GSD from SSO at 820 km altitude</td>
</tr>
<tr>
<td>Oct. 21, 2003</td>
<td>CBERS-2 (China/Brazil)</td>
<td>HRCC, IRMSS, WFI</td>
<td>ZY-1B (Chinese name)</td>
</tr>
<tr>
<td>May 20, 2004</td>
<td>FormoSat-2 – 2 (NSPO), Taiwan</td>
<td>RSI (Remote Sensing Instrument)</td>
<td>2 m GSD, 24 km swath 8 m MS data (5 bands)</td>
</tr>
<tr>
<td>May 5, 2005</td>
<td>IRS-P5 (ISRO)</td>
<td>PAN-F, PAN-A</td>
<td>Along-track stereo imagery 2.5 m GSD, 30 km swath</td>
</tr>
<tr>
<td>Oct. 27, 2005</td>
<td>TopSaT (QinetiQ, RAL), UK</td>
<td>RALCam1, 3 bands of MS, 1 Pan</td>
<td>Imagery at 2.5 m GSD Pan and 5 m MS, FOV = 15 km</td>
</tr>
<tr>
<td>Jan. 24, 2006</td>
<td>ALOS nicknamed Daichi (JAXA, formerly NASA)</td>
<td>PRISM, (stereo mapping) AVNIR-2</td>
<td>2.5 m GSD, 35 km swath 10 m MS, 70 km swath</td>
</tr>
<tr>
<td>Apr. 25, 2006</td>
<td>EROS-B (ImageSat International), Israel</td>
<td>PIC-2 (Pan Imaging Camera) with TDI capability</td>
<td>Commercial imagery at 0.7 m GSD, 13 km swath</td>
</tr>
<tr>
<td>June 15, 2006</td>
<td>Resurs-DKI, ISSKB-Progress, Samara (Volga), part of Russia’s space program</td>
<td>Geoton – 1 imager, PAN + 7 MS bands</td>
<td>1 m GSD all 8 VNIR bands, swath of 28.3 km (altitude 350 km), FOR = 448 km</td>
</tr>
<tr>
<td>July 28, 2006</td>
<td>KOMPASAT-2 (KARI), Korea</td>
<td>MSC (Multi-Spectral Camera) Pan and MS</td>
<td>1 m GSD for Pan, 4 m GSD for MS, 15 km swath</td>
</tr>
<tr>
<td>Jan. 10, 2007</td>
<td>CartoSat-2, ISRO</td>
<td>Pan Camera</td>
<td>&lt; 1 m GSD, swath of 9.6 km</td>
</tr>
<tr>
<td>2007 (launched)</td>
<td>RapidEye (RapidEye AG, Munich, Germany)</td>
<td>REIS, 5 bands MS</td>
<td>Commercial MS and Pan imagery at 6.5 m, 78 km swath</td>
</tr>
<tr>
<td>2007 (planned)</td>
<td>GeoEye-1 (GeoEye, Dulles, VA)</td>
<td>GIS (GeoEye Imaging System)</td>
<td>Commercial MS and Pan imagery at 1.64 m, 0.41 m</td>
</tr>
<tr>
<td>2007 (planned)</td>
<td>WorldView – 1 (DigitalGlobe) Longmont, CO</td>
<td>WV60 camera</td>
<td>Commercial imagery at 0.41 m (nadir) in Pan only</td>
</tr>
<tr>
<td>2007 (planned)</td>
<td>MACSat(RazakSat (ATSB, Malaysia)</td>
<td>MAC (Pan, 4 MS)</td>
<td>2.5 m GSD, 5 m MS, 20 km swath, Near-equatorial orbit</td>
</tr>
<tr>
<td>2007 (planned)</td>
<td>THEOS (GISTDA) Thailand</td>
<td>PAN camera</td>
<td>2 m GSD, 22 km swath 15 m GSD, 90 km swath</td>
</tr>
<tr>
<td>2007 (planned)</td>
<td>Diamant-1 (OHB System, Bremen, Germany)</td>
<td>MSRS, 12 bands of MS data in VNIR</td>
<td>Commercial imagery at 5 m GSD, 26 km swath</td>
</tr>
<tr>
<td>2008 (planned)</td>
<td>X-Sat (NTU, Singapore)</td>
<td>IRIS, PAN and 3 MS bands</td>
<td>10 m MS imagery, 50 km swath (technology test)</td>
</tr>
<tr>
<td>2008 (planned)</td>
<td>ALSat–2 (CNTS) Algeria</td>
<td>NAOMI</td>
<td>Pan: 2.5 m, MS: 10 m, 17.5 km swath</td>
</tr>
<tr>
<td>2008 (planned)</td>
<td>WorldView – 2 (Digital Globe) Longmont, CO</td>
<td>WV110 camera</td>
<td>Commercial imaging at 0.41 m Pan + 2 m MS (8 bands)</td>
</tr>
<tr>
<td>2009 (planned)</td>
<td>Pleiades-1 (CNES)</td>
<td>OHRI (Optical High-Resolution Imager)</td>
<td>Commercial imagery at 0.7 m Pan, 2.8 m for 4 MS bands</td>
</tr>
<tr>
<td>2010 (planned)</td>
<td>Pleiades-2 (CNES)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Chronology of optical Earth-surface satellite imaging missions

With regard to area array CCDs, there are the following basic architectures available: 80)

1) **Full Frame (FF)** CCDs consist of a parallel CCD shift register, a serial CCD shift register, and a signal-sensing output amplifier. In FF operation, the CCD must alternate between exposure and readout. In this support mode, the exposure is controlled by a mechanical shutter or strobe to preserve scene integrity, because the parallel register is used for both

scene detection and readout. This arrangement cannot be used for high frame rate requirements (due to serial readout configuration).

2) **Frame Transfer (FT) CCD.** This type of imager has a dedicated (radiation-shielded) storage (readout) area (of at least the same size as the imaging section of the array) separate from the imaging area with the following advantages:

- The collection of radiation is continuous, maximizing the fill-factor in the imaging region; the functions of image readout and radiation collection run in parallel
- This greatly increases the time available for the image integration period
- Better reliability is provided, in particular at higher frame rates that result from sub-imaging or binning
- The concept offers some electronic shuttering (prevention of smearing effects)
- The FT concept can be extended to multiple frames (also referred to as split frame transfer) by masking most of the parallel register and using only a small region as the image array.

3) **Interline Transfer (ILT) CCD.** The ILT has a parallel register which is subdivided so that the masked storage area fits between columns of exposed pixels. The electronic image accumulates in the exposed area of the parallel register, just as it does in the frame transfer CCD. At readout, the entire image is shifted under the interline mask. The masked pixels are read out in a fashion similar to the FT CCD.

The image collection mode of an area array sensor can be either “interlaced” or “progressive scan” (non-interlaced). The interlaced technique is used by the major broadcast standards PAL and NTSC and is done to reduce the bandwidth of the image for transmission. In this mode, the frame is divided into two fields: an odd field consisting of all the odd numbered rows, and the even field consisting of all the even numbered rows. Half of the frame is recorded by the odd field at time T1, and the other half of the frame is recorded by the even field at time T2.

![Figure 4: Spaceborne surface imaging resolution trends in the civil & military fields](image-url)
Earth Observation History on Technology Introduction

- **Spatial resolution.** The requirement of high spatial resolution (and with it the ability to discriminate between small objects), in particular to land surface imagery, has been around since the early days of remote sensing. In parallel, there are virtually always the needs for wide-swath coverage and high temporal resolution (i.e., frequent repeat coverage capability). High spatial resolution implies of course high data rates which conflicts in turn the wide-area coverage. An overview of major land-surface imaging missions (Figure 4, Table 2) demonstrates the trends and practical compromises taken with the best available technology of the time. - The first spaceborne 1 m spatial resolution panchromatic image with an optical imager was obtained by the commercial spacecraft Ikonos-2 (launch Sept. 24, 1999) of Space Imaging Inc. This was followed with a resolution of 0.61 m delivered by the optical imager of the QuickBird-2 mission (launch Oct. 18, 2001) of DigitalGlobe Inc.

- The high spatial resolution imagery of commercial satellite platforms led to new applications in cartography such as the fully automatic feature extraction of road networks in urban areas. The analysis method reported has its bases in a vegetation mask derived from coregistered multispectral Ikonos data (4 m resolution) and in texture derived from panchromatic Ikonos data (1 m resolution).

<table>
<thead>
<tr>
<th>Mission/Launch Date</th>
<th>Sensor</th>
<th>Spatial Resolution (best band)</th>
<th>Swath width</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-1 / Jul. 23, 1972</td>
<td>MSS</td>
<td>80 m</td>
<td>185 km</td>
<td>15 Mbit/s</td>
</tr>
<tr>
<td>Landsat-4 / Jul. 16, 1982</td>
<td>TM</td>
<td>30 m</td>
<td>185 km</td>
<td>85 Mbit/s</td>
</tr>
<tr>
<td>Resurs-O1-1 / Nov. 3, 1985</td>
<td>2 MSU-E</td>
<td>45 m x 33 m</td>
<td>80 km (total)</td>
<td></td>
</tr>
<tr>
<td>SPOT-1 / Feb. 22, 1986</td>
<td>2 HRV</td>
<td>10 m</td>
<td>117 km (total)</td>
<td>50 Mbit/s</td>
</tr>
<tr>
<td>IRS-1A / Mar. 17, 1988</td>
<td>2 LISS-II</td>
<td>36 m</td>
<td>2 x 74 km</td>
<td>2 x 10.4 Mbit/s</td>
</tr>
<tr>
<td>Resurs-F / (series)</td>
<td>KFA-1000</td>
<td>6-8 m</td>
<td>70 km</td>
<td>Film</td>
</tr>
<tr>
<td>IRS-1C / Dec. 28, 1995</td>
<td>PAN</td>
<td>6 m</td>
<td>70 km</td>
<td>125 Mbit/s</td>
</tr>
<tr>
<td>ADEOS / Aug. 17, 1996</td>
<td>AVNIR</td>
<td>8 m</td>
<td>80 km</td>
<td>60 Mbit/s</td>
</tr>
<tr>
<td>SPOT-5 / May, 4, 2002</td>
<td>2 HRG</td>
<td>5 m Pan (2.5 m in supermode)</td>
<td>120 km (total)</td>
<td>2 x 50 Mbit/s</td>
</tr>
</tbody>
</table>

**Table 2: Spatial resolutions of major land-surface imagers**

- Detector technology extension. The measurement of electromagnetic radiation in the various spectral ranges, in particular in the **infrared region**, is at the heart of the problem. The infrared sensor “Eye in the Sky” was the first successfully flown long wavelength sensor launched in 1967 (Corona military program of DoD). Significant advances in Earth observation capability have come from the development of on-chip detector circuitry (see chapter O.4).

- The directional pointing capability of a sensor (on command) in the cross-track direction was introduced in the SPOT series in 1986 with SPOT-1 (for imaging satellites in the civil domain) and continued until SPOT-5 (launch May 4, 2002). The new pointing technique introduced the term “FOR (Field of Regard)”, designating the angular coverage ca-

---

83) Note: In 1800, William Herschel (1738-1822) reported the discovery of light beyond the visible spectrum. He dispersed the solar spectrum with a prism and found thermal effects of invisible radiation beyond the red.  
capability beyond (and including) the swath - it allowed the imaging of nearby events of interest that happened to be outside the regular (nadir-centered) swath width. At the start of the 21st century, the capability of tilting -- either the imaging instrument by itself or the entire spacecraft with the imager (referred to as body-pointing) -- is being practiced by many optical imaging missions, in particular by the commercial imaging data providers. - On the military side, the KH-7 (Keyhole-7) reconnaissance satellite of DoD (launch July 12, 1963, operational until June 1967) featured a film camera (also by the name of Keyhole) with an instrument cross-track tilting capability (very probably the first instance in history on a spacecraft), to extend FOR.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Instrument Mass, Power</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-5 (launch Mar. 1, 1984), NASA</td>
<td>TM</td>
<td>285 kg, 385 W</td>
<td>Optomechanical instrument</td>
</tr>
<tr>
<td>IRS-1C (launch Dec. 28, 1995), ISRO</td>
<td>LISS-III</td>
<td>171 kg, 78 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>NEAR/Shoemaker (launch Feb. 17, 1996), NASA</td>
<td>MSI</td>
<td>7.7 kg, 6.9 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>DSI (launch Oct. 24, 1998), NASA</td>
<td>MICAS</td>
<td>12 kg,</td>
<td>CMOS/APS technology</td>
</tr>
<tr>
<td>Landsat-7 (launch Apr. 15, '99), NASA</td>
<td>ETM+</td>
<td>425 kg, 590 W</td>
<td>Optomechanical instrument</td>
</tr>
<tr>
<td>Ikonos-2 (launch Sept. 24, '99), SI</td>
<td>OSA</td>
<td>171 kg, 350 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>Terra (launch Dec. 18, 1999), NASA</td>
<td>ASTER</td>
<td>421 kg, 463 W</td>
<td>Optoelectronic and optomechanical instrument</td>
</tr>
<tr>
<td>QuickBird-1 (launch Nov. 20, 2000), Earthwatch</td>
<td>BGIS 2000</td>
<td>380 kg, 430 W</td>
<td>Optoelectronic instrument (launch failure)</td>
</tr>
<tr>
<td>EO-1 (launch Nov. 21, 2000), NASA</td>
<td>ALI</td>
<td>106 kg, 100 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>PROBA (launch Oct. 22, 2001), ESA</td>
<td>CHRIS</td>
<td>15 kg, 10 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>SMART-1 (launch Sept. 27,2003) ESA</td>
<td>AMIE</td>
<td>2.2 kg, 0.5 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>Diamant-1 (launch 2007), OHB-System</td>
<td>MSRS</td>
<td>64 kg, 120 W</td>
<td>Optoelectronic instrument</td>
</tr>
<tr>
<td>NPOESS (launch 2009)</td>
<td>VIIRS</td>
<td>160 kg, 134 W</td>
<td>Optomechanical instrument</td>
</tr>
</tbody>
</table>

Table 3: Mass/power reduction trends in typical spaceborne imaging instruments

<table>
<thead>
<tr>
<th>S/C</th>
<th>S/C Launch (End of Service)</th>
<th>Sensor Complement</th>
<th>Data Resolution (m)</th>
<th>Data Communications</th>
<th>Orbital Altitude</th>
<th>S/C Operator(s)</th>
<th>Revisit Time (days)</th>
<th>Data Rate Mbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-1</td>
<td>Jul.23, 1972 (Jan. 6, 78)</td>
<td>RBV MSS, DCS</td>
<td>80</td>
<td>DD (Direct Downlink) 2 WBVTR</td>
<td>907 km</td>
<td>NASA</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>LS-2</td>
<td>Jan. 22, 1975 (Feb. 25, 82)</td>
<td>RBV MSS, DCS</td>
<td>80</td>
<td>DD with 2 WBVTR</td>
<td>908 km</td>
<td>NASA</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>LS-3</td>
<td>Mar. 5, 1978 (Mar. 31,83)</td>
<td>RBV MSS,DCS</td>
<td>30</td>
<td>DD with 2 WBVTR</td>
<td>915 km</td>
<td>NASA</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>LS-4</td>
<td>Jul. 16, 1982 (standby Dec. 95)</td>
<td>MSS TM, GPS</td>
<td>80</td>
<td>DD TDRSS</td>
<td>705 km</td>
<td>NOAA (’83) Eosat (’85)</td>
<td>16</td>
<td>85</td>
</tr>
<tr>
<td>LS-5</td>
<td>Mar. 1, 1984</td>
<td>MSS TM, GPS</td>
<td>80</td>
<td>DD TDRSS</td>
<td>705 km</td>
<td>NOAA (’84) Eosat (’85)</td>
<td>16</td>
<td>85</td>
</tr>
<tr>
<td>LS-6</td>
<td>Oct. 5, 1993</td>
<td>ETM</td>
<td>15 (PAN) 30 (MS)</td>
<td>DD with recorders</td>
<td>launch failure (contact lost during launch)</td>
<td></td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>LS-7</td>
<td>Ap. 15, 1999</td>
<td>ETM+</td>
<td>15 (PAN) 30 (MS)</td>
<td>DD with recorders</td>
<td>705 km</td>
<td>NOAA</td>
<td>16</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 4: Overview of Landsat S/C series

- Size/mass/power/cost reduction of imaging instruments. 86) Miniaturization and the introduction of new technologies is the name of the game, in particular in the late 1990s and the early 21st century. The JHU/APL sensor MSI (Multispectral Imager) with a 537 x 244

CCD detector array, a spectral range of 0.4 to 1.1 µm, and a FOV of 2.9º x 2.25º (pixel resolution of 95 x 161 mrad), was flown on NEAR (Near Earth Asteroid Rendezvous/Shoemaker) of NASA (launch Feb. 17, 1996). A newer MSI design of JHU/APL with a lightweight reflective telescope, high-density solid-state memory and miniaturized on-chip-board electronics has a mass of 0.5 kg and a power of 1 W.

- In 1993, the US government (Department of Commerce) granted the first US license to DigitalGlobe’s predecessor, namely WorldView Inc. of Longmont, CO, allowing a private enterprise to build and operate a satellite system and to gather high spatial resolution digital imagery of the Earth for commercial sale.

1.2.1.2 Solid-state (digital) imaging - CMOS/APS detector technology

CMOS/APS (Complementary Metal-Oxide Semiconductor/Active Pixel Sensor) detector technology. In CMOS image sensors, the photo-voltaic conversion effect of silicon semiconductors, in this case diodes, is being exploited to make optical sensors that are sensitive to visible light. In the CMOS/APS design concept, the individual pixels do not only contain the actual photosensitive element, but also other (analog domain) processing circuitry, ranging from in-pixel buffers and amplifiers up to application-specific computational pixels. CMOS/APS represents an alternate approach to the proven CCD-imaging concepts, a second generation solid-state imaging sensor technology. The emerging CMOS/APS technology was first proposed at CSMT (Center for Space Microelectronics Technology) of NASA/JPL in 1993. Sabrina Kemeny and Eric R. Fossum were on the CSMT team who developed the APS technology. In 1995 JPL licensed the APS technology to Photobit Corporation of La Crescenta, CA, a JPL spin-off company.

The APS method basically provides a current as a function of the irradiance for each pixel. Normally, the output is proportional to the irradiance falling onto the APS detector. In CMOS/APS versions providing a logarithmic output of the irradiance. The CMOS/APS technology employs an amplifier at each pixel site, thereby eliminating the bus capacitance and resistance problems of CCDs or CID (newer APS technology utilizes active transistors in each pixel to buffer the photo-signal). It was not until sub-micron photolithography became available that APS imagers became useful. CMOS/APS imagers sense radiation (light) in the same way as CCDs. Both technologies convert incident photons into electronic charge (electrons) by the same photo-conversion process. However, in the CMOS/APS technique, the charge packets are not transferred, they are instead being detected by the charge-sensing transistors.

The CMOS/APS concepts take advantage of the microprocessor (CMOS) fabrication processes (mature and widely available manufacturing techniques) resulting in reduced manufacturing costs of APS detectors over similar CCD devices (down to 30% of the cost of a comparable CCD). Some performance advantages of the CMOS/APS technology are:

- TTL-compatible operation (0-5V), with low-power requirements (e.g. 10 mW at 1 M pixel/s; includes ADC)
- Only a single power supply is needed (at 3.3 V or at 5 V)

- Electronic shuttering (having on-chip control logic, smart functions such as automatic exposure control can be incorporated)
- Provision of high dynamic range and good functionality like readout windowing (the window-of-interest readout feature may be used to track objects in the image for machine vision; handling of simultaneous multiple windows)
- Variable integration time (timing control)
- On-pixel amplification, x-y addressability, and random access readout
- A single CMOS/APS system-on-chip can integrate image capture of 1 Mpixel
- A/D conversion and digital processing. In particular, APS can integrate analog and digital processing on the same die.
- APS detectors provide generally a considerably higher radiation hardness over CCD detectors since they can be manufactured with processes such as silicon-on-insulator.

Initial drawbacks of CMOS/APS with respect to CCD technology are seen in the relatively low pixel sensitivity (low quantum efficiency and non-uniformity), the relatively high noise levels of the small pixel arrays, and in reduced calibration capabilities of the array. Further, with CCDs up to 100% of a pixel’s area can be made sensitive to light (“fill factor”), where APS pixels by their very nature devote only a small portion of the total area to the actual photodiode or phototransistor function. The lower fill factors of APS result in longer exposure times for the same scene as compared to CCD concepts.  

--- Note: APS (Active Pixel Sensor) is also being referred to as APA (Active Pixel Array), both terms have the same meaning.

The CMOS/APS imager in silicon technology offers a spectral response in the UV/VNIR spectral regions. The CMOS/APS micro-technology implies low-power micro-instruments ( imagers and other devices) for near-future microsatellites. Other fields of CMOS/APS technology applications include:

- In the early the 21st century, replacement of CCD detector technology in AOCS (Attitude and Orbit Control System) pointing applications like in star trackers and in sun sensors (providing high-accuracy pointing performance of star trackers)
- Commercial camera market
- Optical communications
- Multimedia machine vision, and biomedical imaging.

<table>
<thead>
<tr>
<th>Description</th>
<th>CIF (Common Immediate Format) SOC</th>
<th>VGA (Video Graphics Array) SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel array size</td>
<td>352 (H) x 288 (V)</td>
<td>640 (H) x 480 (V)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 frame/s</td>
<td>30 frame/s</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>3.3 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>55 mW (typical)</td>
<td>&lt;100 mW (typical)</td>
</tr>
<tr>
<td>Output format</td>
<td>8-bit/10-bit color digital video (SRGB)</td>
<td>10-bit color digital video (SRGB)</td>
</tr>
<tr>
<td>Shutter</td>
<td>Electronic rolling snap</td>
<td>Electronic rolling snap</td>
</tr>
</tbody>
</table>

**Common features**
- On-chip: a) analog signal processing; b) 8/10-bit ADC; c) DACs (Digital-Analog Converter) for bias control; d) gain control (user programmable); e) Pan and zoom (user programmable); f) Timing and clock generator
- Standard digital output and control interface (I²C)
- Auto exposure control (user programmable)

Table 5: Specification of a typical CMOS/APS SOC (System-on-Chip)  

At the start of the 21st century, the CMOS/APS imaging concept is regarded a viable and complementary solid-state imaging technology to that of CCDs. However, it should be real-

--- Note: The APS noise problem is due to the so-called “fixed pattern noise,” a noise that results from small differences in the behavior of the individual pixel amplifiers. As of 1998, Bell Labs researchers developed circuits outside the sensor array that detect and cancel this noise - resulting in a patented camera-on-chip technology. The chip of 1 cm² in size contains over 100,000 active pixels. JPL built DIC (Digital Imaging Camera Experiment), a camera-on-chip containing an array of 1024 x 1024 pixels.

ized that the CCD technology has experienced three decades of advances and optimizations, specifically for imaging applications. They present today excellent performance and image quality, thanks to extremely low noise, low dark current, high quantum efficiency, and good fill factor efficiency. Due to these characteristics, the CCD concept will remain the technology of choice for high-quality imaging applications (in particular for hyperspectral applications). The general trend is to replace the older CCD technique by the more flexible, cheaper, and less power-hungry CMOS/APS technique. Several programs have been funded by ESA to support the development of APS technology, in particular for such applications as attitude sensors (smart sun sensors, star sensors, etc.) and vision cameras.

In the CMOS/APS image sensor, each pixel contains not only the photodetector element but also active transistor (amplifier) circuitry for readout of the pixel signal. In addition to the APS (Active Pixel Array) that detects photons and produces an analog voltage output, an ADC (Analog-Digital Converter) is an essential element of the CMOS/APS SOC (System-on-Chip) technology. The CMOS/APS SOC also contains an integrated timing generator for sequencing all operations, control registers for setting up the operation of the chip, on-chip generated bias voltages (that can be adjusted), and a rapid serial digital interface for controlling and verifying the operation of the chip. A typical realization (2002) of this architecture in a 0.5 μm standard CMOS technology is defined in Table 5.

Detector arrays can be monolithic or hybrid. Monolithic arrays, which are built from a single chip, are typically CMOS-based and are usually the cheapest alternative at least for large volumes. It is expected that image sensors operating at visible wavelengths will in the long run be almost completely CMOS-based. - When monolithic sensors cannot be made one has to resort to hybrid ones, where several chips are combined into a unit. The reason is usually that detectors cannot be based on silicon or materials compatible with silicon, and that more exotic materials are needed such as GaAs, InSb and MCT for infrared detection, and CdTe or GaAs for X-ray detection. In this hybrid case a chip consisting of the detector pixels is usually flip-chip bonded to a silicon CMOS chip, consisting of a ROIC (Readout Integrated Circuit) where multiplexing and conditioning of the electronic signals take place. An example of this hybrid detector technology is for instance a QWIP (Quantum Well Infrared Photodetector) array.

<table>
<thead>
<tr>
<th>Parameter (typical values)</th>
<th>CMOS/APS technology</th>
<th>CCD technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
<td>512 x 512 pixels</td>
<td>1024 x 1024 pixels</td>
</tr>
<tr>
<td>Pitch</td>
<td>5 - 20 μm</td>
<td>10-20 μm</td>
</tr>
<tr>
<td>Fill factor</td>
<td>15 - 43%</td>
<td>100%</td>
</tr>
<tr>
<td>SNR (Signal-to-Noise Ratio)</td>
<td>50 - 70 dB</td>
<td>75 dB</td>
</tr>
<tr>
<td>Non-uniformity</td>
<td>3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Dark signal</td>
<td>4000 e⁻/s</td>
<td>150 - 400 e⁻/s</td>
</tr>
<tr>
<td>Pixel rate</td>
<td>1 - 10 MHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Power consumption</td>
<td>20 - 200 mW</td>
<td>50 mW</td>
</tr>
</tbody>
</table>

Table 6: Comparison of typical CMOS/APS and CCD imagers

- Some early examples of CMOS/APS imaging technology demonstrations/implimentations are:
  - The first spaceborne demonstration of a camera with CMOS/APS technology was VTS (Visual Telemetry System), a joint project of: Matra Marconi Space, UK; DSS/OIP (Delft Sensor Systems/Optronic Instruments & Products), and IMEC, both of Belgium, and flown on TEAMSAT (M.45), an ESA low-cost satellite demonstrator mission, launched on Oct. 30, 1997 from Kourou (Ariane-502, 2nd qualification flight of an Ariane-5 vehicle). VTS, with a 512 x 512 pixel array for each of the three camera modules, performed visual post-launch monitoring of structure deployments. VTS used the FUGA15 random-access sensors, these chips were effectively the world’s first CMOS/APS imagers operational in space.

- The TMSat (renamed to Thai-Paht-1) microsatellite of Thailand, built by SSTL of Surrey, UK (launch July 10, 1998), carries a CMOS Video Camera with APS technology.

- APS (Active Pixel Sensor) technology is also part of MICAS (Miniature Integrated Camera Spectrometer) flown on DS1 (Deep Space 1, launch Oct. 24, 1998, M.9) of JPL.

- APS imaging technology is flown on ESA's XMM-Newton spacecraft (launch Dec. 10, 1999). Two cameras were mounted on the exterior of the spacecraft's focal plane assembly: a) the VMC (Visual Monitoring Camera), and b) the IRIS-1 (Integrated Radiation-tolerant Imaging System-1) color sensor, developed by FillFactory NV of Mechelen, Belgium (a spin-off company of IMEC, Belgium). About 5 hours after launch of XMM-Newton by an Ariane 4 launcher, these cameras took pictures of the left and the right solar array assemblies of the S/C. IRIS-1 characteristics: 640 x 480 pixels, 14 μm pitch; integrating photodiode pixel sensor, double sampling amplifiers; 8 bit digitization on-chip, 10 images/s; photo response of 2.05 x 10^{12} V/Ws; pixel response non-uniformity 2.27%; readout noise 63 e−; SNR (full range) 67 dB; power consumption 80 mA; 20 krad radiation tolerance. - During launch of the ESA Cluster-2 mission (launch Aug. 9, 2000), the IRIS-1 camera provided a color movie of the Cluster-2 satellite separation (a first in space). 97) A follow-up development at FillFactory resulted in the series of STAR-250 radiation-hardened CMOS/APS imagers for star and beam tracking as well as sun tracking purposes, introduced throughout 2001 [ESA funded project called ASCoSS (Attitude Sensor Concepts for Small Satellites). In 1999, this exercise produced a miniaturized CMOS/APS-based star sensor (detector by FillFactory) for ASCoSS according to Sira Electro-Optics specifications (thus, the first APS star sensor built by Sira included multi-chip module electronics and diffractive optics)]. The STAR-250 is a line-scan based integrating imager with provisions for versatile readout (windowing, electronic shuttering, etc.). – Note: In 2004, Cypress Semiconductor Corporation with HQ in San Jose, CA (USA) acquired FillFactory NV of Mechelen, Belgium.

- An early spaceborne CMOS/APS technology star sensor implementation is being flown on the SWIFT (Catching Gamma-Ray Bursts on the Fly) satellite, a NASA space science mission (launch Nov. 20, 2004). In this configuration, the FillFactory STAR-250 imager is being used in TAM (Telescope Alignment Monitor) as an alignment sensor in the calibration system of the SWIFT X-ray telescope (provided by Sira Electro-Optics, Chislehurst, UK). The sensor measures 68 mm x 69 mm x 28 mm, weighs 240 g, and consumes just 0.5 W of power.

- The ST-6 (Space Technology-6) “Compass” mission of NASA, is flying an APS star sensor package by the name of ISC (Inertial Stellar Compass), developed by CSDL (Charles Stark Draper Laboratory Inc.) of Cambridge, MA. The ISC attitude system employs a STAR-250 APS imager of FillFactory NV with a pixel pitch of 25 μm. The ISC has the following key performance features: 0.1º (1 σ) pointing accuracy in each axis; high-rate maneuver capability; self-initializing capability; mass of about 2.5 kg; power of about 3.5 W. ISC is composed of a wide FOV APS camera and a MEMS gyro assembly with associated processing and power electronics. 98) 99)

Note: While ISC was initially planned to be launched as a Hitchhiker payload on a Shuttle flight, NASA selected in Sept. 2003 a commercial ride on a solar sail mission, namely Team Encounter Flight One, of Team Encounter LLC, Houston, TX. The Team Encounter Flight One mission is expected to be launched in 2006 ??.
SSS (Smart Sun Sensor). With ESA funding, Galileo Avionica (of Florence, Italy) has developed SSS (validation phase as of 2002/3) consisting of an attenuation filter with a photoengraved pin hole, a CMOS/APS detector (STAR-1000 of Cypress/FillFactory, a 1024 x 1024 pixel chip) for sun spot imaging, proximity electronics for data processing (barycenter detection of the incident energy of the sun) and power interfaces. In acquisition mode, the entire FOV (128° x 128°) is searched for sun presence finding (sub-pixel sun position and housekeeping digital I/F). The sun angle resolution is 0.005° with a pointing accuracy of 0.02° (2 σ).  

Applications: SSS is to fly onboard the GOCE mission of ESA (launch in 2007). Furthermore, SSS will be part of the SOLAR payload, mounted on the external pallet of the ESA Columbus module of ISS, to keep the supported SOLAR payload instruments pointed toward the sun. SSS will also be flown on the SICRAL—1B military satellite of Italy, developed by Alcatel Alenia Space Italy.

- The 3CSat (Three Corner Satellite) constellation of UNP (University Nanosatellite Program), consisting of three cooperating S/C – built by CU (University of Colorado) at Boulder, ASU (Arizona State University), and NMSU (New Mexico State University) and sponsored by DoD, NASA and US industry – utilizes CMOS/APA (Active Pixel Array) imaging technology in a distributed observation concept. Note: The cluster launch of 3CSat took place on Dec. 21, 2004; however, the two microsatellites that were launched as secondary payloads, did not reach their proper orbit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device dimensions</td>
<td>110 mm x 108 mm x 45</td>
</tr>
<tr>
<td>Device mass</td>
<td>&lt; 330 gram</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-35 to + 70 °C</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 1 W with DC/DC</td>
</tr>
<tr>
<td>FOV (Field of View)</td>
<td>128° x 128°</td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt; 0.02° (2 sigma)</td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt; 0.005°</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>&gt; 100 krad</td>
</tr>
</tbody>
</table>

Table 7: Characteristics of SSS based on APS technology

- As of 2005, STAR-250 and STAR-1000 are monochrome, radiation hard CMOS/APS image sensors developed and validated under ESA contract. These sensors have a broad range of spaceborne applications, including star tracking, sun sensing and optical inter-satellite link beam tracking. Both sensors are designed using radiation-tolerant design techniques to allow a high tolerance against radiation effects. STAR-250 is a 250 k pixel sensor (512 x 512 with 25 μm pixel pitch), STAR-1000 is a 1 M pixel sensor (1024 x 1024 with 15 μm pixel pitch).  

The next generation CMOS/APS star tracker detector design is referred to as HAS (High Accuracy Star tracker) detector by the Cypress/FillFactory featuring a noise level sensitivity of < 1 arcsecond. The HAS device integrates a 1024 x 1024 pixel array with a pixel pitch of 18 μm, providing a dual addressable y shift register for rolling shutter operation, programmable offset and gain amplifier and an on-chip 12 bit pipelined ADC. The qualification work (ESA contract) has shown the feasibility of the HAS sensor technique to compete with...
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front illuminated CCDs in terms of performance for space applications. Hence, the HAS detector might very well become the APS detector of choice for future spaceborne AOCS applications. An essential objective of this HAS technology introduction is that it becomes eventually available as a COTS (Commercial-Of-The-Shelf) device being a space-qualified and low-cost detector. The HAS detector design is providing an accuracy comparable with those achievable so far only with the costlier CCD star trackers. See also chapt. 1.8.2.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HAS (High Accuracy Star tracker) detector</th>
<th>STAR-1000 detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector technology</td>
<td>CMOS/APS</td>
<td></td>
</tr>
<tr>
<td>Pixel structure</td>
<td>3-transistor active pixel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radiation-tolerant pixel design</td>
<td></td>
</tr>
<tr>
<td>Photodiode</td>
<td>High fill factor photodiode, using n-well technique</td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>0.35 µm CMOS</td>
<td>0.5 µm CMOS</td>
</tr>
<tr>
<td>Sensitive area format</td>
<td>1024 x 1024 pixels</td>
<td></td>
</tr>
<tr>
<td>Pixel size</td>
<td>18 x 18 µm²</td>
<td>15 x 15 µm²</td>
</tr>
<tr>
<td>Pixel output rate</td>
<td>5 MHz (nominal)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed can be exchanged for power consumption</td>
<td></td>
</tr>
<tr>
<td>Windowing</td>
<td>X- and Y- addressing random programmable</td>
<td></td>
</tr>
<tr>
<td>Electronic shutter</td>
<td>Electronic rolling shutter. Integration time is variable in time steps equal to the row readout time.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Possibility to have non-destructive readout (NDR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronic rolling shutter. Integration time is variable in time steps equal to the row readout time.</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Comparison of some HAS and STAR-1000 detector specification

- As of 2006, Galileo Avionica of Florence, Italy, is introducing the AA–STR (APS based Autonomous Star Tracker) device using the HAS detector technology. A first test flight is planned on PROBA–2 (launch 2007). The AA–STR is planned to be flown on the Alphabus series starting in 2010 as well as on EO missions. The HAS detector technology of Cypress/Fillfactory is also being used by the HYDRA multiple head Star Tracker of EADS Sodern. 106) 107)

- The “digital camera,” a commercial product of the photo industry (e.g., Kodak, Sony, Agfa, Canon, Fuji, Konica, Minolta, Nikon), is a natural application derivative of the CCD and CMOS/APS detector technologies, pioneered by the remote sensing and the electronics industry. The digital camera became a consumer product in the latter part of the 1990s when the detector densities (multi-megapixel detectors - approaching high-resolution quality) and storage capacities for image capture were sufficient and in addition economical for an evolving consumer market. - Since CCD detectors are inherently monochromatic, special filters are needed to separate the RGB radiation reflected by an object. A number of techniques are in use to capture color: a) RGB filter wheel (three exposures), b) tri-linear sensor (use of three linear sensors), c) multi-chip detectors, etc.

- A notable exception of the trend away from photographic film in spaceborne imaging technology was and is the RESURS-F satellite series of State Center Priroda, Moscow, Russia. The Resurs-F1 series (58 satellites in the time frame 1979-1993, Resurs-F2 series since 1995, see chapter D.37) onboard sensors are film cameras whose data (namely the films) are recaptured after the end of each mission. The film camera systems (examples: KFA-1000, TK-350, KVR-1000, KFA-200, MK-4) are returned to the ground in small spherical descent capsules which are reused an average of three times. The films are processed


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After each mission (average mission life is in the order of 14 to 30 days in orbits of 240 - 275 km altitude).

- At the start of the 21st century, film still holds the edge in spatial resolution over solid-state digital technology (CCD, APS, CID, etc.). However, digital technology can usually deliver images much faster while allowing greater flexibility in storage, manipulation and distribution. The real-time aspect of digital imagery is of considerable importance for many applications. In addition, the digital technology offers a much wider spectral coverage than film (for multispectral and hyperspectral applications).

**Overview of some detector types for digital imagery applications (as of 2004):**

- **CCD**s have been the dominant solid-state imagers since the 1980s, primarily because CCDs gave far superior images with the fabrication technology available.
  - CCDs offer superior image performance as measured in quantum efficiency (>90%) and noise, and flexibility at the expense of system size. They continue to rule in the applications that demand the highest image quality.
  - CMOS/APS imagers offer more integration (more functions on the chip), lower power dissipation (at the chip level), and smaller system size at the expense of image quality and flexibility.

- **ICCD** (Intensified Charge Coupled Device). An ICCD is a CCD that is fiber-optically connected to a MCP (Micro-Channel Plate) to increase the sensitivity. In ICCD cameras, a photo-cathode in front of the MCP converts photons to electrons which are multiplied by the MCP. In general, ICCDs are used in low-light (night-vision) environments. Besides the gain in sensitivity the possibility of gating the MCP also offers the possibility to gate ICCD cameras very fast. Therefore ICCD cameras are also used for range-gated imaging.
  - An example of a spaceborne ICCD detector implementation is SWUIS (Southwest Ultraviolet Imaging System), a payload (telescope) developed at Southwest Research Institute, San Antonio, TX, and flown on Shuttle flights STS-85 (Aug. 7-19, 1997) and on STS-93 (July 23-28, 1999). SWUIS was used to observe objects in the inner solar system, using a FOV of 0.3-0.6° (30 times that of Hubble).

- **EMCCD** (Electron Multiplying Charge Coupled Device), the on-chip multiplication technology was initially introduced in 2001/2 by Andor Technology, Belfast, Northern Ireland. An EMCCD is a CCD in which a gain register is placed between the shift register and the output amplifier. The electron multiplication register (provides gain) multiplies the electrons before they pass the output amplifier. With this gain the detected signal reaches an order of magnitude improvement so that the noise in the output amplifier is negligible. At a gain of about 100 single photon counting is possible.
  - The EMCCD can use several detection channels on the same device, reducing the amount of front end electronics. The device is immune against the ground echo saturation.
  - The EMCCD technique (or on-chip multiplication) offers single photon detection capability. When combined with back-illuminated sensor quantum efficiency for maximum photon conversion, it provides unequaled sensitivity for ultra low light imaging conditions.
  - First imagers (commercial cameras) with EMCCD technology were introduced in 2003. The WALES (Water Vapor Lidar Experiment in Space) mission of ESA, under definition as of 2004, is considering the use of EMCCD detector technology instead of the APD (Avalanche Photo Diode) technique of previous lidar implementations.

1.2.1.3 **Solid-state (digital) imaging - STJ detector technology**

- **STJ** (Superconducting Tunnel Junction) is a new type of optical radiation detector technology, first developments/demonstrations started in the 1990s. Initially, the STJ technology was only considered for x-ray detection, it is now also being used as single photon (or particle) detectors in the visible spectrum as well. A nobium-based STJ detector is
capable to detect radiation in the spectral range of 200 - 1000 nm with a spectral resolution of 45 nm. Unlike a silicon-based CCD detector, the STJ arrays record not only the position of incoming photons, but also their energy (one photon, depending on its energy, can generate thousands of electrons). This property eliminates the need for filters or diffraction gratings that lower the overall efficiency. The multispectral detection of colors of photons is of particular interest to astronomers and biomedical researchers alike.\(^{(108)}\)\(^{(109)}\)\(^{(110)}\)\(^{(111)}\)\(^{(112)}\)\(^{(113)}\)

An STJ device is a Josephson-type junction, consisting of two thin films of a superconducting metal such as niobium, tantalum or hafnium, separated by a thin insulating layer. When operated at temperatures well below the superconductor’s critical temperature (typically below 1 K), the equilibrium state of the junction is easily perturbed by any photon striking it. By applying a small bias voltage across the junction and a suitable parallel magnetic field to suppress the Josephson current, an electrical charge proportional to the energy of the perturbing photon, can be extracted from the device. Future STJ implementations will excel in particular in low-resolution spectroscopy applications. The STJ technology has the potential of offering “all-in-one” detectors, providing spectroscopy, imaging, photon timing, and high quantum efficiency in the spectral ranges from the \(\gamma\)-rays to the infrared. Some STJ characteristics are:

- STJ detectors combine the high energy resolution of wavelength dispersive spectrometers with the high count rate of energy dispersive spectrometers
- X-rays absorbed in a superconductor excite excess charge carriers across the superconducting gap in proportion to their energy.
- The small superconducting gap (\(\sim\) meV) translates into a large number of charge carriers and consequently high energy resolution (\(\sim\) 2 eV at 1 keV). Fast pulse decay times (\(\sim\) \(\mu\)s) allow high count rates (\(\sim\) 10 kHz).
- Energy-discriminate photon counting with tantalum has been demonstrated over a full decade in wavelength: 200 nm - 2000 nm (or 2 \(\mu\)m)
- By arranging a number of STJ detectors into a 2-D array, a true “3-D” detector can be constructed, whose output is not just the number of photons registered in each pixel of the image, but their distribution in energy throughout the UV, VIS and NIR spectral ranges. However, detector operation at cryogenic temperatures is required (typically below 1 K), to exploit the STJ-unique ability, namely to discriminate photons in wavelength without the use of filters or dispersive elements.

A first prototype STJ Camera (S-Cam) was developed at ESA/ESTEC and installed into a ground-based astronomical telescope (William Herschel Telescope, located on La Palma in the Canary Islands). The initial successful operation (first light) of S-Cam took place on Feb. 2, 1999. S-Cam employs a 6 x 6 array of tantalum devices (25 \(\mu\)m x 25 \(\mu\)m) and covers the 300-700 nm spectral range. As a photon counting system, STJ provides position and arrival time of each detected photon, along with the photon energy. Space-based instruments with STJ detectors are considered at the start of the 21st century for astronomical applications; Earth observation applications might follow soon.

\(^{108}\) Brian D. Josephson, a British physicist, predicted and discovered the phenomenon of superconductivity in 1962.\(^{109}\) http://astro.estec.esa.nl/SA--general/Research/Stj/STJ_main.html


1.2.1.4 Introduction of airborne digital frame cameras (photogrammetry)

- On the airborne side, conventional film-based (analog) photogrammetry is a mature process developed for nearly a century. These camera systems are still very much in use by commercial service providers at the start of the 21st century. The aerial analog systems provide discrete frame-type images with a very high geometric resolution. They are mostly being used for mapping applications with high-resolution photo scales between 1:5,000 and 1:15,000. Typical high-resolution aerial film camera examples are the RMK cameras of Carl Zeiss, Oberkochen (see P.178) and the Wild RC10, RC20 and RC30 systems of Leica AG, Heerbrugg, Switzerland (P.117).

In contrast, there are digital CCD mapping systems in spaceborne and also in some airborne applications, linear arrays with pushbroom technology, providing continuous strips of linescan imagery having a much lower geometric resolution than the discrete frame-type film imagery. The production of linear CCDs is straightforward and these detectors offer excellent features, such as defect-free linear arrays, electronic exposure control and multispectral sensing. However, from a photogrammetric data processing point-of-view, the use of linear imaging CCD arrays in aerial mapping applications has been difficult, since the orientation of every image line requires robust modeling of the data acquisition trajectory. In contrast, area array CCD imagers, completely analogous to the film-based imaging system in function, work with a standard frame camera model, which easily suits the current map-production practice.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>CCD model</th>
<th>Array size (pixel)</th>
<th>Pixel size (μm)</th>
<th>Data rate (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kodak</td>
<td>DCS-460</td>
<td>3,072 x 2,048</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Lockheed Martin</td>
<td>BigShot™</td>
<td>4,096 x 4,096</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Fairchild</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kodak</td>
<td>MegaPlus16.8i</td>
<td>4,096 x 4,096</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Philips</td>
<td>Icam28</td>
<td>7,168 x 4,096</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Reco/Optical/Dalsa</td>
<td>CA-260/50</td>
<td>10,080 x 5,040</td>
<td>10</td>
<td>48/64</td>
</tr>
<tr>
<td>Lockheed Martin</td>
<td>F-979F</td>
<td>9,216 x 9,216</td>
<td>8.75</td>
<td>160</td>
</tr>
<tr>
<td>Philips</td>
<td>FTF3020-C</td>
<td>3,072 x 2,048</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Some high-resolution CCD area arrays in the 1999 time frame

One of the major limitations in the introduction of the new aerial digital frame cameras has been the low spatial resolution or the availability of only fairly small pixel sizes of the CCD area arrays. In the mid-1990s, advances in semiconductor technology enabled the manufacturing of larger CCD area array detectors, the 4k x 4k (=16 Mpixel) arrays were the largest sizes used in experimental airborne digital cameras; examples are those instruments developed by IGN (Institute Geographique National), France; or AIMS™ (Airborne Integrated Mapping System) of CFM (Center for Mapping) at OSU (Ohio State University) built in 1996/8 with NASA support. In addition, a GPS/INS comes along with AIMS. In 1998 Philips Electronics N. V. produced a 7k x 9k (=63 Mpixel) array and Lockheed Martin an 8k x 8k array.

A performance comparison of the digital and analog imaging technologies with respect to spatial resolution shows that even the larger CCD arrays (start of the 21st century) fall way

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114) Note: The linescan (pushbroom) technique was initially confined largely to spaceborne systems due to the fact that atmospheric turbulence caused some gaps and double imaging. However, the use of modern fast-acting gyro-controlled mounts limits these effects. In addition, the development of integrated DGPS/INS systems provide location and attitude information needed to correct the imagery geometrically and to provide a photogrammetric solution on a line-by-line basis. An example of this solution is the ADS40 camera of LH Systems (P.3).


short with the 25k x 25k (= 625 Mpixel) imagery that can be produced by digitizing the (analog) film image of a standard 23 cm x 23 cm aerial film camera at the same pixel size. Aerial analog film cameras with 23 cm x 23 cm film format have been the mapping and reconnaissance instruments around the world for decades. Obviously, the digital area array CCD detector technology falls short in size, offering no more than 1/4 the imaging size (i.e. number of pixels per image) of the analog film technology. However, in spite of the smaller detector size, frame or area CCD arrays have other properties quite different or simply non-existent for analog film. Some of these special area array features include: 119) 120)

- CCDs with more than 10 million pixels usually cannot be manufactured without faults; hence, they come with a large number of inactive more malfunctioning pixels. However, the location of these bad pixels can be traced. Note: the manufacture of such large arrays lies at the very edge of current chip fabrication technology.
- The read-out rate of all the pixels from a CCD array can be substantial and is measured in seconds. Newer designs work with multiple output gates making this limitation less severe.
- The radiometric sensitivity of CCDs is around 100-200 ASA (American Standards Association) or higher (better than that analog film).
- In contrast to analog film, CCDs have a linear characteristic and thus are much more subject to saturation, in which case the charge from the saturated pixel map spill over to neighboring pixels (this phenomenon is called blooming).
- CCDs, especially cooled ones, can exhibit very good SNRs and can therefore typically produce pixel intensities with 10-12 bit resolution. This is much better than the currently realized 6-7 bit intensity resolution of scanned analog imagery.
- Unfortunately, electronic shutters, while easily incorporated into linear arrays, are not a feasible solution for large CCDs due to manufacturing complexities.
- CCDs provide immediate availability of the image data.

At the start of the 21st century, 121) 122) 123) 124) 125) 126) 127) developments in storage and compression technology have reached the point where large-format digital imagery can quite effectively compete with analog, film-based techniques in airborne applications. In particular, the fully digital workflow of CCD (digital) imagery offers numerous advantages, such as improved triggering, low noise level, no signal corruption during storage, and requirements for digitization. Also, several real-time processing tasks are possible while using digital imagery. These include:

- Signal conditioning (gain and offset control, color corrections)
- Image enhancements (real-time histogram collection and correction)
- Imprinting

119) A raster scan of the aerial film image of 23 cm x 23 cm with a pixel size of 9 μm amounts to about 625 Mpixel; while a state-of-the-art photogrammetric scanner with a pixel size of 7 μm produces an image of 32k x 32k = 1 Gpixel.
124) http://www.ziimaging.com/News/OtherDocs/Heier_DMC_Results_ASPRS_Jan02.pdf
• Image compression

The following examples illustrate the introduction of state-of-the-art ultra-high-resolution digital technology of large-format framing camera systems in aerial photogrammetry applications - resulting eventually in the replacement of the existing base of aerial film cameras (no film, no photo lab, no scanning, no noise from film grain and no cost of duplication).

1) **DMC** (Digital Modular Camera), an airborne digital photogrammetric camera of Z/I (Zeiss Imaging, Oberkochen, Germany). Note: As of Oct. 2002, Intergraph Corporation of Huntsville, ALA, acquired ownership of Z/I Imaging. Some of the instrument features/technologies are: 128)
   - DMC employs the CCD area array detector technology (i.e., a 2-D system consisting of a frame or matrix detector) for wide area coverage. The observed imagery has a known and precise geometry in x and y due the two dimensional area sensor. With regard to geometric accuracy, the CCD array (frame technology) has a clear advantage over the CCD line sensor (pushbroom technology).
   - The modular instrument concept employs an optics frame, referred to as CBU (Camera Base Unit), which consists of 8 cameras: 4 high-resolution panchromatic cameras (using a 7 k x 4 k CCD array), and 4 multispectral cameras (using a 3 k x 2 k CCD array), thus providing a reduced spatial resolution. The multi-camera configuration (four parallel cameras can generate multispectral (MS) imagery for the acquisition of color composites; four panchromatic images from converging cameras are mosaicked digitally to form a single high resolution image) resulting in a large FOV (Field of View). The MS cameras are collecting imagery in the red, green, blue and near infrared bands. A post-processing procedure (mosaicking) is used to transform four individual PAN images into one virtual image considered as normal central projection.
   - DMC is integrated into ASMS (Airborne Sensor Management System) to achieve the highest possible level of data flow during observations. The operator driven ASMS covers DMC and all auxiliary devices such as GPS, stabilization mount, IMU, FMC, etc.
   - Electronic FMC (Forward Motion Compensation) is used for acquiring a blur-free imagery under large-scale mapping conditions (wide FOV of 74º)
   - DMC is equipped with four 7k x 4k large area CCDs (PAN cameras), the resulting ground resolution of the system is 14,000 pixels in cross-track and approximately 8,000 pixel in along-track.
   - The electronics of the CCD matrix sensors can be operated in TDI (Time-Delay Integration) mode. This allows fully electronic FMC of the imagery (blur compensation). Note: FMC is not possible for pushbroom cameras, using the three-line sensor principle.
   - Each single camera module of the DMC is calibrated with regard to geometry and radiometry.
   - The imagery of such an advanced technology CCD digital aerial camera turns out to be of a higher quality and very cost effective compared to that based on analog film and scanning techniques. The reason is not only the higher radiometric sensitivity of CCD devices (as well as the potential of a larger spectral range), but in particular the elimination of film development and film scanning. These two steps of the film workflow are very sensitive and have to be maintained very carefully to avoid product degradation. The direct availability of digital imagery for all types of processing is also a great advantage for the user. 129)

2) **UltraCam-D** (Digital) of Vexcel Imaging GmbH, Graz, Austria (a unit of Vexcel Corporation, Boulder, CO), along with partners Wild Austria and GIP (Gesellschaft für Industriephoto grammie mbH), Aalen, Germany. A prototype system is available as

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of 2002/3. In addition to the sensor unit, there is SCU (Controller, Storage and Processing Unit) with a storage capacity of >1 TByte.\(^{130}\)\(^{131}\)

3) BAE Systems (formerly Fairchild) of Greenlawn, NY (with support from NRL) is developing a new digital framing camera incorporating an ultra high resolution CCD detector array comprised of 9,216 x 9,216 pixels which measures 8 cm x 8 cm and is fabricated on one silicon wafer. The new all-digital camera allows a very high framing rate (1 frame/s, later 2 frame/s) and differential image motion compensation for use with oblique imaging.\(^{132}\)

4) Leica Geosystems of Heerbrugg, Switzerland, introduced the first commercial digital airborne camera to the market in 2001, namely the **ADS40** (Aerial Digital Sensor 40). The ADS40 is a *pushbroom imager* capable of acquiring color and false color strip images at the same high resolution as the black and white stereo images. This high resolution of 12,000 pixels across the swath combined with 100% forward overlap in the three to six black/white image strips results in high-quality DSMs (Digital Surface Models). The ADS40 is capable of recording pan images of 5 cm GSD and larger and RGB images of 15 cm GSD and larger under normal lighting conditions.\(^{133}\)\(^{134}\)

<table>
<thead>
<tr>
<th>Specification of the UltraCam-D sensor unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panchromatic image size (2-D detector)</td>
</tr>
<tr>
<td>Panchromatic physical pixel size</td>
</tr>
<tr>
<td>Panchromatic lens focal distance (alternative exchangeable lenses)</td>
</tr>
<tr>
<td>Lens aperture</td>
</tr>
<tr>
<td>FOV (Field of View), cross track (along-track),</td>
</tr>
<tr>
<td>Color (multi-spectral capability) 4 channels --</td>
</tr>
<tr>
<td>Color image size</td>
</tr>
<tr>
<td>Color physical pixel size</td>
</tr>
<tr>
<td>Color lens system focal distance</td>
</tr>
<tr>
<td>Color lens aperture</td>
</tr>
<tr>
<td>Color field of view from vertical, cross track (along track)</td>
</tr>
<tr>
<td>FMC (Forward Motion Compensation),</td>
</tr>
<tr>
<td>Smallest pixels on the ground at flying height of 500 m (at 300 m)</td>
</tr>
<tr>
<td>Frame rate per second (minimum inter–image interval)</td>
</tr>
<tr>
<td>Analog–to–digital conversion</td>
</tr>
<tr>
<td>Radiometric resolution in each color channel</td>
</tr>
<tr>
<td>Physical dimensions of the camera unit</td>
</tr>
<tr>
<td>Weight, Power consumption at full performance</td>
</tr>
</tbody>
</table>

Table 10: Specification of the UltraCam-D sensor unit

<table>
<thead>
<tr>
<th>Specification of the ADS40 of Leica Geosystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panchromatic image</td>
</tr>
<tr>
<td>Multispectral image</td>
</tr>
<tr>
<td>Pixel size</td>
</tr>
<tr>
<td>Spectral bands (nm)</td>
</tr>
<tr>
<td>FOV (Field of View)</td>
</tr>
<tr>
<td>Focal length of camera</td>
</tr>
<tr>
<td>Stereo angles</td>
</tr>
<tr>
<td>Sensor Head SH40</td>
</tr>
<tr>
<td>Control Unit CU40</td>
</tr>
</tbody>
</table>


133) P.Fricker, A. Rohrbach, “Pushbroom scanners provide highest Resolution Earth Imaging Information in Multi-spectral Bands,” Proceedings of the ISPRS Hannover Workshop, Hannover, Germany, May 17–20, 2005

134) http://www.infra.kth.se/courses/1E1440/F2_05.ppt#2
Figure 5: Illustration of the DMC imager (image credit: Z/I Imaging)

Figure 6: Illustration of the ADS40 imager (image credit: DLR)
Solid-state imaging is based on the physical principle of converting incident light (photons) into a measurable quantity (electrical voltage, electrical current, density for photographic emulsions). The link between the photons at the input of an imager and the output of the device (voltages, metallic silver or color dyes) are the electrons. The collection and transport of those electrons is of great importance in this chain.

[It should be noted that the actual sensor is an analog device. It sends out a voltage or a current which is proportional to the intensity of the light that falls on it. This analog signal is converted into a digital signal by an analog-to-digital converter, also known as an A/D converter.]

When comparing film-based and solid-state (CCD) imagery, it should be remembered that film (as well as the human eye) respond to incident brightness levels nearly logarithmically. This is conveniently expressed in terms of densities (D), where $D = \log (1/\tau)$ and where $\tau$ is the transmittance of the detecting surface. Density ranges of about 0 – 3 (max) can be obtained. – CCDs, on the other hand, respond nearly linearly to incident energy, i.e. digital values obtained from initially measured analog values of the detector are actually transmittance (or reflectance) values. But the intensity of the reflected or transmitted light (radiation) in the image is proportional to the logarithmic density of the image.

- In an analog recording medium, the response of film is a continuum over its range of photographic density/exposure. The level of quantization possible with an image on film is subject to limitations due to resolving power, the MTF (Modulation Transfer Function), granularity and such considerations as the Wiener spectrum (after Norbert Wiener, 1894-1964) of the grain structure and wavelength of illumination used in scanning. All these characteristics being unique to a particular combination of camera, film and processing, as well as the scanner performance.

- Due to the logarithmic response relationship of film — a film negative can easily adopt to very large exposure ranges to obtain the desired density range for the image. By comparison, CCDs with their "linear range response" to brightness levels are much more susceptible to saturation in which case the charge from the saturated pixel map spill over to neighboring pixels (this phenomenon is called blooming).

![Figure 7: Qualitative performance characteristics of film-based and solid-state imagery](image)
At the start of the 21st century, there are three different data sources available in photogrammetry, resulting from: a) high-resolution analog airborne mapping cameras, b) digital airborne cameras, and c) high-resolution (digital) spaceborne instruments.

Automation of the map-making process is the ultimate goal of digital photogrammetry. The fundamental step of any data integration process is georeferencing or geometric fusion of data (time-space registration), most commonly provided by GPS/INS (see also photogrammetry in Glossary).

As of 2005/6 135) it looks like the high-resolution pushbroom digital airborne camera systems (DMC, ADS40, etc.) are outperforming their sister film (analog) frame cameras in many respects. In particular, the geometric quality of airborne digital pushbroom systems is excellent and fulfills all demands of the classical and modern photogrammetric work. Hence, the traditional distinction of airborne (film-based) and spaceborne (digital) remote sensing is slowly disappearing.

1.2.1.5 Stereoscopic imaging in the optical region

Stereoscopic imaging from a single S/C instrument in its orbital path requires a parallel observation geometry from at least two different angular positions of the same target area. A few seconds of time delay in the imaging sequence of multiple image viewing directions is of no consequence to the stereo concept (superposition of imagery). The technique is particularly suitable for topographic mapping applications (photogrammetry), it is also used for event coverage. Several observation schemes are in use:

- Along-track multidirectional target observation (successive viewing in one pass). A single imaging instrument provides two or three or more images of the same ground path (stereo line scanner implementation where each scan line is pointing into another along-track direction of the swath, like forward, nadir, backward). This technique provides continuous and contiguous long-term stereo observations.
- The imaging device has a cross-track tilting mechanism (thereby increasing its FOR (Field of Regard). This technique requires either a quick pointing capability (introducing possibly S/C vibrations), or two parallel instruments to perform stereo imaging. 
- Body pointing of an agile spacecraft with a single imager to obtain along-track or cross-track imagery from different positions (body-pointing implies the imager is pointed along with its platform (satellite) into the desired direction). This technique is more suitable for short event coverage applications, a function mostly provided in commercial imaging missions. Only small-mass spacecraft can provide sufficient agility.

Examples of spaceborne stereoscopic missions with along-track multi-line imaging instruments are:

- MOMS-02 (Modular Optoelectronic Multispectral Scanner), a three-line camera system of DLR on Shuttle flight STS-55 in April/May 1993, followed by a MOMS-02 relight on MIR/Priroda (launch of Priroda April 23, 1996). The MOMS-02 payload has a total of five optical systems: three are used for stereoscopic imagery, two are employed for multispectral imagery, one is used for high-resolution data. 136)

- OPS (Optical Sensor) of the JERS-1 mission of NASDA (launch Feb. 11, 1992, end of mission in October 1998). OPS offered a two-line stereoscopic along-track imaging capability in two spectral bands, both of the same wavelengths (760-860 nm). Band 4 is for off-nadir viewing (15.33 ° forward in flight direction); bands 3 (nadir) and 4 make a stereo pair.

136) Note: The three-line observation concept results in forward, nadir and aft views of the CCD pushbroom array. The imagery from each scan line is assembled into strips. Relief displacement in the line perspective geometry of the strip approach differs from conventional nadir perspective geometry. Every object appears on all three strips. In contrast, on film imagery only about 60% of the area of any one photograph is in a triple overlap.
The Terra mission of NASA (launch Dec. 18, 1999) with the NASDA/NASA cooperative instrument ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). ASTER is an along-track two-line system in the VNIR subsystem. VNIR features two telescopes, one nadir-looking with a three-spectral-band detector, and the other backward-looking with a single-band detector. The backward-looking telescope provides a second view of the target area in band 3B (0.76-0.86 μm) for stereo observations. The resolution is 15 m on a 60 km swath.

In addition, the NASA/JPL instrument MISR (Multi-angle Imaging SpectroRadiometer) is flown on Terra. MISR is an along-track nine-line camera system, offering multidirectional observations of each ground (or target) scene within a time scale of minutes. MISR uses nine CCD pushbroom cameras to observe the Earth at nine discrete viewing angles: one at nadir (0°), plus eight other symmetrical views at 26.1°, 45.6°, 60.0°, and 70.5° forward and aft of nadir. Images at each angle are obtained in four spectral bands centered at 0.446, 0.558, 0.672, and 0.866 μm. Each camera employs four independent line arrays (one per filter), 1504 active pixels per line. The swath width is 360 km. Ground sampling resolutions of 275 m, 550 m, or 1100 m are provided. MISR provides global maps of planetary and surface albedo (brightness temperature), and aerosols and vegetation properties. MISR provides new types of information for scientists studying Earth’s climate, such as the partitioning of energy and carbon between the land surface and the atmosphere, and the regional and global impacts of different types of atmospheric particles and clouds on climate. 137)

- The BIRD (Bi-Spectral Infrared Detection) mission of DLR (launch Oct. 22, 2001) with the WA OSS-B (Wide-Angle Optoelectronic Stereo Scanner, BIRD version). The along-track stereo imaging system of WA OSS-B is based on three lines (single optics and focal plate), operating in pushbroom mode, and taking images simultaneously in the forward-, nadir- and backward-pointing direction of the orbital ground track (spatial resolution of 183 m, swath of 527 km).

- SPOT-5 of CNES with HRS (High Resolution Stereoscopic) instrument, an along-track two-line camera system) with a launch May 4, 2002. HRS provides parallel forward and aft swaths (120 km width) in the along-track direction at fixed pointing angles of ±20°. A pixel size of 5 m (along-track) by 10 m (cross-track) is provided. The stereo acquisition mode can be sustained for scene lengths of up to 600 km. The panchromatic band (0.51 – 0.73 mm) of SPOT-1,-2,-3 is being reintroduced.

- The ALOS mission of JAXA (Japan Aerospace Exploration Agency, formerly NASA, launch Jan. 24, 2006) flies PRISM (Panchromatic Remote-sensing Instrument for Stere o Mapping), a three-line sensor with three independent catadioptric systems for nadir, forward and backward-looking (along-track stereoscopy). Each of the three telescopes employs a three-mirror type optics design (30 cm aperture diameter and 2 m focal length) and several CCD detectors for pushbroom scanning. Eight silicon CCDs (5000 pixels each) are physically aligned at each telescope’s focal plane. The nadir-looking telescope provides a swath of 70 km width (28,000 pixels per band), each of the fore and aft-looking telescopes provides a swath of 35 km (14,000 pixels per band).

- IRS-P5 (CartoSat-1, launch May 5, 2005) of ISRO flies a two-line camera assembly. PAN-F (Panchromatic Forward-pointing Camera) is tilted at 26° forward from nadir. PAN-A (Panchromatic Aft-pointing Camera) is tilted 10° aft. Each camera provides a spectral range of 500-750 nm, a spatial resolution of 2.5 m is provided on a swath of 30 km.

On the airborne side, DLR developed HRSC (High-Resolution Stereo Camera) which features three-line stereo imaging in color. The instrument is flown since Feb. 1997 (heritage of the HRSC instrument flown on the Russian Mars-96 mission with a launch Nov. 16, 1996 on a Proton vehicle from Baikonur - a malfunction of the third stage of the launch vehicle ended the mission prematurely). A completely automatic photogrammetric and cartographic

137) http://www—misr.jpl.nasa.gov/
processing procedure including digital image matching, digital terrain model (DTM) and ortho-image (orthophoto) generation, mosaicking and merging of multispectral data has been developed at DLR (P.101). A further HRSC instrument is flown on the Mars Express spacecraft of ESA (launch June 2, 2003, Mars insertion on Dec. 25, 2003), orbiting planet Mars and providing spectacular stereo imagery at 10 m resolution (and at 2 m super-resolution) of the Martian terrain.

Another airborne example of a three-line stereo pushbroom camera is DPA (Digital Photogrammetric Assembly) of DASA/MBB Ottobrunn (P.71). DPA has been operational since the end of 1992 and is a parallel development to MOMS-02. - JPL's “AirMISR” is flown since 1997 on NASA's ER-2 aircraft. Unlike the spaceborne MISR instrument, which has nine cameras oriented at various angles, AirMISR utilizes a single camera in a pivoting gimbal mount. A data run by the ER-2 aircraft is divided into nine segments, each with the camera slewed to a different MISR look angle. The gimbal rotates aft between successive segments, such that each segment acquires data over the same area on the ground as the previous segment. This process is repeated until all nine look-angles of the target area are collected.

- Example of a tilting camera scheme. The parallel HRV sensors of the SPOT series satellites (all SPOT missions, including HRG of SPOT-5) provide some degree of stereo capability with their individual side-viewing feature (up to 27º cross-track pointing capability).

- Examples of body-pointing spacecraft with an imager (boresight configuration of S/C and imager) to obtain along-track or cross-track imagery (pointing on a cyclic basis, slewing capability) collecting stereo pairs of imagery.
  - Ikonos-2 S/C of Space Imaging (launch Sept. 24, 1999) with the OSA sensor (along-track slewing capability of up to ±30º)
  - QuickBird-2 of DigitalGlobe Inc., with a launch Oct. 18, 2001 (orbital altitude of 450 km) is flying BHRC 60 (Ball High Resolution Camera 60). The instrument provides along-track stereo imagery (by S/C slewing).
  - MSRS (Multi-Spectral high Resolution System), built by ELOP (El-Op Electro-Optics Industries of Rehovot, Israel) in cooperation with OHB-System, Bremen, Germany. MSRS is planned to fly on Diamant of OHB-System with a planned launch in 2007. The spacecraft has an along-track slewing capability for stereo imaging.
  - The Pleiades spacecraft of CNES (launch in 2008 and 2009, 2 operational satellites in one orbital plane with a phase shift of 180º) permit a body-pointing capability with roll and pitch maneuvers, each up to 60º, within a period of 25 s. OHRI (Optical High-Resolution Imager) will be used for along-track stereo imagery and other support modes.

- DEMs (Digital Elevation Models) from optical satellite data. Since spaceborne stereo imagery is very suitable for topographic applications, there is a great demand for DEM or DTM (Digital Terrain Model) generation, in particular from along-track stereoscopy [a DTM or DEM forms the basic building block for combining other data for analysis; for instance, digitized spatial data (images) can be draped onto a DEM and analyzed using a GIS.]. Simultaneous along-track multidirectional imagery is not affected by the changes in radiometric variations that may occur in cross-track stereo image pairs collected on different satellite passes (possibly also over long time periods). On the other hand, cross-track stereo data has the advantage of more symmetrical view angles to the target area of interest.

138) Note: Digital orthophotos are scale correct aerial photographs.
as compared to along-track data collections (the stereo pairs are always at different angles). In the past 15 years, the long-term SPOT series imagery has been a frequently used source for stereoscopy and DEM extraction applications [superposition of multitemporal data in this analysis approach; a disadvantage is the multi-date imagery available reflecting the target changes during a growing season, etc.]. Alternative solutions are available at the start of the 21st century. The Terra mission of NASA is flying ASTER (launch Dec. 19, 1999). The stereo data is available to the public, it can be downloaded freely (http://asterweb.jpl.nasa.gov). This makes the ASTER data very attractive for the user community interested in DEM applications. SPOT-5 (launch May, 4, 2002) is also flying an along-track instrument HRS (High Resolution Stereoscopic); this capability adds to the normal cross-track capability of the SPOT series. In this scenario, PRISM of ALOS mission (launch Jan. 24, 2006) and PAN-F of the IRS-P5 mission (launch May 5, 2005) are further major entries for stereoscopic imagery applications, beside a number of commercial imaging missions. Naturally, DEMs (or DTMs) may also be generated from spaceborne stereo imagery in the microwave region, better known as SAR interferometry. 139)

1.2.2 Spectrometry, imaging spectrometry, and hyperspectral imaging

In remote sensing “spectrometry” or “spectroscopy” 140) refers to the detection and measurement of radiation spectra of a target (area or volume) in many bands of the medium (generally the atmosphere). In Earth observation, the measurement arrangement is that of a **sounding instrument**, i.e., measuring the medium of the incoming atmospheric spectra with a spaceborne (or airborne) instrument along the instantaneous field of view (IFOV), basically a straight line. 141) From a historic perspective, the information obtained by the first spaceborne sounders was that of “total column content,” i.e., only the entire spectrum measurement along the line-of-sight yielded a value (or a set of values). Later improved sounder versions [in particular with better radiometric performance (SNR)] permitted a more detailed analysis of the measured spectra, resulting eventually in the interpretation capability of pinpointing many measurements along an IFOV path in the atmosphere, and ending as a small area on the ground for the case of nadir observations. These improved results were referred to as **profile measurements** of various state parameters/constituents of the atmosphere that could be determined/extrapolated for various heights.

The data analysis approach of such a process is by its very nature iterative, requiring a comparison of intermediate results with atmospheric models until a suitable fit is reached. Also, it took a while to understand all the physics and various methods of interpretation, to develop the proper diagnostic tools for data analysis, and to develop suitable models. On hindsight, today’s (start of 21st century) arsenal of analysis tools and interpretation methods have reached a considerable level of sophistication, permitting also the extraction of “profiles” from the data sets of early space-age sounders (that provided only “total column content” at the time of first interpretation). This example demonstrates that improved interpretation capabilities (better algorithms, models, etc.) may eventually lead to a greater harvest (more parameters and/or better results) from observation data analysis without the added introduction of an improved instrument (measurement) technology.

The performance of early atmospheric sounders hinged in particular on the available detector technology of opto-mechanical systems. Practically all early instruments featured the following components: foreoptics, a grating, prism spectrometer, or filter spectrometer, a single detector element, and readout electronics. A mirror assembly was used in combination with the detector element to resolve the various components of the spectrum sequentially. In this fashion, a one-dimensional multi-spectral image was formed by the forward motion of the spacecraft (i.e., a sequence of measurement points, spectrally resolved, along the flight path for a nadir-viewing sounder).

Historically, the first spectrometers (e.g., sounders) on spacecraft were used to measure the atmospheres of the sun’s planetary system. The IRS (Infrared Spectrometer) instrument, developed at UCB (University of California at Berkeley), was flown on Mariner-6 (launch Feb. 24, 1969, Mars flyby mission) to measure the atmosphere of Mars. IRS (using a variable filter spectrometer) measured the infrared region 1.8-14.4 μm in approximately 1400 discrete measurements with a spectral resolution of 1%. IRS was also flown on Mariner-7 (launch Mar. 27, 1969). The Mars atmosphere showed hints of dust suspended in the atmosphere as well as: carbon dioxide ice, water ice clouds, carbon monoxide, ionized hydrogen, and ionized oxygen. Surface temperatures of 280-290 K were recorded near the equator.

In Earth observation, BUV (Backscatter UV Spectrometer) is an early spectrometer instrument flown on the NASA missions Nimbus–4 (launch April 8, 1970, see M.26.4) and

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140) Note: Both terms are used in the literature with the same meaning. Spectroscopy is the science of measuring the spectral distribution of photon energies (as wavelengths or frequencies) associated with radiation that may be transmitted, reflected, emitted, or absorbed upon passing from one medium (vacuum or air) to another (material objects).

141) The technical information of this chapter was obtained in discussions with Peter Haschberger of DLR, Oberpfaffenhofen, Germany

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AE-E (Atmosphere Explorer-E, Explorer 55) with a launch Nov. 20, 1975. BUV monitored the vertical distribution and total amount of atmospheric ozone by measuring the intensity of UV radiation backscattered by the Earth/atmosphere system during day and night in the spectral band of 250 - 340 nm. An improved version, SBUV/TOMS (Solar Backscatter Ultraviolet/Total Ozone Mapping Spectrometer), was later flown on Nimbus-7 (launch Oct. 24, 1978). The SAM (Stratospheric Aerosol Measurement) was flown on ASTP (Apollo-Soyuz Test Project), July 15-24, 1975, to perform the first successful solar occultation measurement of stratospheric aerosol. SAM was a single spectral instrument (sounder) measuring the aerosol extinction near the 1000 nm wavelength region.

**At the start of the 21st century**, Earth observation based on imaging spectroscopy has been transformed in less than 30 years from a sparsely available research tool into a commodity product available to a broad user community. Currently, imaging spectrometer data are widespread and they prove for example, that distributed models of biosphere processes can assimilate these observations to improve estimates of Net Primary Production, and that in combination with data assimilation methods, access complex variables such as soil respiration, at various spatial scales. 143)

Today, technological advances in the domain of focal plane development, readout electronics, storage devices and optical designs, are leading to a significantly better sensing of the Earth’s surface. Improvements in signal–to–noise, finer bandwidths and spectral sampling combined with the goal of better understanding the modeled interaction of photons with matter will allow for more quantitative, direct and indirect identification of surface materials based on spectral properties from ground, air, and space. Advances in sensor technology, electronics, and (pre–) processing have led to the development of a suite of new applications.

**The future:** Imaging spectrometer instrument technology will profit from true spectroscopy focal plane arrays, with improved quantum efficiency, several readout ports, a rectangular design and consistent readout in the spectral domain, eventually also being expanded to the emissive part of the spectrum. To achieve high spectral—spatial uniformity and high precision measurements advanced optical designs are required combined with enabling components (curved, high—efficiency dispersive elements and ultra—straight slits). Optomechanical designs must focus on spectral and radiometric stability. With stability, spectral, radiometric and spatial calibration can be readily established from the spectral features of the atmosphere as well as uniform/measured calibration targets on the Earth.

**1.2.2.1 Imaging spectrometry**

In literature, the terms “imaging spectroscopy”, “imaging spectrometry” and “hyperspectral imaging” are often used interchangeably in remote sensing. Even though semantic differences might exist, a common definition is: *simultaneous acquisition of spatially coregistered images, in many, spectrally contiguous bands, measured in calibrated radiance units, from a remotely operated platform.*

Imaging spectrometry is a scheme of combining the spatial and spectral information capture techniques into a common technique to obtain the best of both worlds, namely spatial information matched (or coregistered) with the corresponding multi-band spectral information. 144) See also “spectrometer” in Glossary and in chapter O.6. In general, there are three “image capture” technologies of imaging spectrometers in use (two are scanning types, one employs framing):

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1) **Whiskbroom line array** (band interleaved by pixel). Optical filtering of the incoming radiation into multiple bands can be provided by the following means:
   - Grating: an example instrument is AVIRIS (see Table 12)
   - Prism: an example instrument is HyMap

2) **Pushbroom area array** (band interleaved by line). Optical filtering of the incoming radiation into multiple bands can be implemented by:
   - Grating: an example instrument is AIS (see Table 12)
   - Prism: an example instrument is HYDICE
   - FTS (Fourier Transform Spectrometer): an example instrument is SMIFTS
   - Wedge-type variable filter spectrometers: an example instrument is WIS (Wedge Imaging Spectrometer)

3) **Framing camera** (band sequential). Optical filtering of the incoming radiation into multiple bands can be implemented by the following techniques:
   - AOTF (Acousto-Optic Tunable Filter)
   - LCTF (Liquid Crystal Tunable Filter)
   - FPI (Fabry-Perot Interferometer)

The availability of **line-array detector** and of **area-array detector** technology in the 1980s and 1990s changed the capabilities of Earth observation profoundly, offering new dimensions in the fields of imagery and spectrometry (i.e. in the spatial and spectral domains). The pushbroom imaging concept was introduced as a result of available **line-array detector technology**, permitting the simultaneous (parallel) observation of a cross-track line of spatial resolution cells (i.e., a large number of pixels providing a swath width). The 2-D image is formed by the forward motion of the spacecraft.

The pushbroom imaging concept had immediate consequences for the spectral data domain as well. It meant the introduction of “imaging spectrometry.” The straight-line measuring constraint of sounding could now be considerably enhanced over an extended area or scene (i.e., giving the spectral sounding data also the spatial dimensions of x and y). In comparison with the one-element detector sounding technology of 1-D observations, pushbrooming in combination with a rotating mirror (for sequential spectral sampling) offered now the capability of multiple-line (2-D) spectroscopy (all parallel in the cross-track direction) for nadir sounding observations. This resulted in a fairly close-grided observation pattern, contiguous in the cross-track, but discrete in the along-track direction due to the sequential sampling of the spectral domain.

The introduction of the area array detector technology provided finally the so-called contiguous “image cube” with two spatial dimensions and one spectral dimension. In this concept, the instantaneous spatial information is resolved in cross-track, while the corresponding spectral information for each spatial element is resolved by the along-track elements of the detector array. The second spatial dimension is obtained by pushbrooming, i.e., by the along-track motion of the spacecraft. Naturally, a fast area array readout technique is needed in this concept to free the array for the next detection/integration/read-out cycle.

Imaging spectrometry means that for every position in an observed target field, a spectrum is being obtained. The information content is a 3-dimensional “image or data cube” which contains radiometric information spatially and spectrally resolved.

Two techniques (instrument types) have been mainly applied in imaging spectrometry: the dispersive spectrometer and the interferometer. Both methods can only acquire two of the

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145) Note: A photographic system is an example of a “framing system” using either the conventional analog film or a digital 2D detector array system for instantaneous image format capture (referred to as “staring imagers”); it means that all of the data of an image are acquired simultaneously in a snapshot. A TV system employs also the framing technique with a rapid refreshment rate. However, motion compensation is generally needed with a staring imager (2D detector array) to correct for smearing effects on a moving platform. – In scanning systems (like whiskbroom or pushbroom type imagers) an image is acquired sequentially. A pushbroom imager with a 2D detector array is generally being used to collect spectral information in the second dimension (in parallel to the spatial information) such as in multispectral, hyperspectral or TDI support applications.
three dimensions of the data cube at any time. The third dimension has to be obtained sequentially: In the dispersive spectrometer case it is the second spatial dimension; in the case of the interferometer it is the wavelength dimension. See also chapters 1.2.8.4 and O.6.

1) **Dispersive spectrometer instrument technique:** This involves stepping the long slit of a dispersive (grating or prism) spectrometer across the target field. The basic system passes the incoming target radiation through a slit and onto a grating (or a prism) before illuminating a 2-D detector array. In this manner, one axis of the array corresponds to the spatial dimension and the other to the spectral. The second spatial dimension of the image is obtained by the forward motion of the spacecraft, thus producing an “image cube” with two spatial dimensions and one spectral dimension.

2) **Interferometer instrument technique:** Traditional FTS (Fourier Transform Spectrometer) imagers possess two major advantages over grating, prism, and circular variable filter (CVF) spectrometers. These are:

- **Time-multiplexing.** An interferometer’s (Michelson, etc.) single detector views all the wavelengths (within the sensor bandpass) simultaneously throughout the entire measurement period. This effectively lets the detector collect data on each wavelength for the entire integration time while staring at the target, measuring more photons and therefore, results in higher SNR (Signal-to-Noise Ratio) values, at best for situations where the source is stable.
- **Throughput advantage,** because the FTS does not need spatial filters (e.g. slit) in the optical light path.

The FTS (Fourier Transform Spectrometer) method generates an **interference pattern** as detector output (an intermediate product), also called the *interferogram*, which requires a Fourier transformation to obtain the measured radiance spectrum. The optical and detector system of the instrument can be devised in such a fashion that at any given OPD (Optical Path Difference) of the FTS, the image of the target is modulated spatially by the interferometer fringe pattern, which encodes the spectral information. Scanning the OPD generates the interferogram, representing the sum of all modulated waves. These interferograms are Fourier transformed individually yielding a spectral image data cube composed of the same spatial elements as the image.

However, a disadvantage of the conventional FTS imager concept is their optical delay by physically translating one or more optical components (the instrument has to go through all OPD positions to complete the measurement cycle of strokes). Such a mechanical translation mechanism reduces of course the performance of interferometer instruments. Over the course of a multi-year mission, millions of strokes are needed resulting in instrument wear or fatigue. Also, the moving optical elements may result in alignment problems.

The enormous information content provided by the technique of imaging spectrometry is of course very advantageous for analysis in many applications of Earth observation. In the past, imaging spectrometry had to overcome the technical challenges of available detector technology, computing power, and very large data volumes. These problems are somewhat alleviated with the available technology at the start of the 21st century. - In the 1980s, the potential of new and improved imaging spectrometer concepts lead eventually into the formulation of the term “**hyperspectral imaging.**” referring to a considerable number of spectral bands that could be observed by a single instrument.

- **Hyperspectral imaging** is an optical sensing technique breaking up the incoming radiation into numerous contiguous (i.e., adjacent and not overlapping) spectral bands (normally >20 - 200 narrow bands or many more). The technology was introduced with such pioneering airborne instruments as AIS (1982, 128 spectral bands) and AVIRIS (1989, 224 spectral bands), both of JPL. Another early airborne hyperspectral imaging spectrometer
was FLI (Fluorescence Line Imager), developed by Moniteq Ltd and Itres Ltd for the Canadian Department of Fisheries and Oceans. It was first flown in 1984, using pushbroom technology and 288 spectral bands (see P.93). Early hyperspectral imagery with airborne instruments demonstrated also the technique for mineral mapping applications. 146) 147) 148)

- The first spaceborne hyperspectral imagers launched were: a) UVISI on MSX of DoD (launch Apr. 24, 1996; b) HSI and LEISA, both on the Lewis spacecraft (launch Aug. 23, 1997; however, Lewis never became operational and reentered the Earth’s atmosphere on Sept. 28, 1997); c) FTHSI on MightySat II.1 of AFRL (Air Force Research Laboratory) with a launch July 19, 2000. FTHSI demonstrated the advantage of Fourier systems over dispersive hyperspectral imagers. FTHSI is the first spaceborne hyperspectral imager to record the full spectra without any time delay using the spatially modulated technique (de-coupling the spatial and spectral signatures). See also Table 36 in chapter 1.2.8.4.

The Hyperion and LAC (LEISA Atmospheric Corrector) instruments on EO-1 (NASA/GSFC), of HSI and LEISA heritage, respectively, were launched Nov. 21, 2000. 149) Hyperion is an imaging dispersive grating spectrometer in VNIR and SWIR (in this context, the ALI instrument on EO-1 is also an imaging dispersive-type grating spectrometer, but in the multispectral class). The PROBA mission of ESA (launch Oct. 22, 2001) is flying CHRIS (Compact High Resolution Imaging Spectrometer), a hyperspectral imager of the UK, funded by BNSC (see M.30). Note: The hyperspectral imagers are also known by the term of “imaging spectrometers.”

- As of 2007, planned missions with hyperspectral imagers are:
  - EnMAP (Environmental Monitoring and Analysis Program): A German spacecraft with a launch planned for 2010. The sensor, also named EnMAP, has a spectral range of 420 – 2450 nm with 96 bands in VNIR and 122 bands in SWIR. A swath of 30 km is provided with a GSD of 30 m.
  - ZASat – 003, a microsatellite mission of SunSpace and Stellenbosch University, South Africa. A launch is planned for 2010. The instrument is MSMI (Multi – Sensor Microsatellite Imager) with over 200 bands in the spectral range of 400 – 2350 nm, GSD = 14.5 m on a swath of 14.9 km.
  - HERO (Hyperspectral Environment and Resource Observer) is a potential mission of CSA (Canadian Space Agency) in the definition phase awaiting approval. The requirements call for a hyperspectral imager in the 400 – 2500 nm range (spectral resolution of 10 nm) with a GSD of 30 m and a swath of ≥ 30 km.

Typical examples of hyperspectral filter techniques include dispersive gratings or prisms, multi-order (mode) etalons, interference filters, Michelson interferometers 150), acoustooptic tunable filters (AOTF), and wedge-type variable filter spectrometers [an example is WIS (Wedge Imaging Spectrometer) see also 1.2.8]. The other key feature is focal plane detector array technology which allows multiple spatial and/or spectral samples through 1-D or 2-D arrays.

---

150) Note: The Michelson interferometer is named after the US physicist Albert Abraham Michelson (1852-1931) who is regarded the father of interferometry providing the first successful measurements in interferometry (see O.9). Also first successful measurements of the diameters of Jupiter’s moons in 1891. Michelson is the first American who received the Nobel Prize in physics in 1907.
<table>
<thead>
<tr>
<th>Sensor (Agency/Company)</th>
<th>No. of Bands</th>
<th>Spectral Range (nm)</th>
<th>Bandwidth at FWHM (nm)</th>
<th>IFOV (mrad)</th>
<th>FOV (°)</th>
<th>Data Product</th>
<th>Period of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAS (ASTER) (DAIS-2815) (GER)</td>
<td>1 3 20</td>
<td>760-850 3000-5000 8000-12000</td>
<td>90 600-700 200</td>
<td>1.0, 2.5, or 5.0</td>
<td>28.8, 65, or 104</td>
<td>Image cube</td>
<td>since 1991</td>
</tr>
<tr>
<td>AHS, Daedalus</td>
<td>48</td>
<td>440-12700</td>
<td>20-1500</td>
<td>2.5</td>
<td>86</td>
<td>Image cube</td>
<td>1994</td>
</tr>
<tr>
<td>AIS-1</td>
<td>128</td>
<td>990-2100 1200-2400 800-1600 1200-2400</td>
<td>8000-12000</td>
<td>9.3 10.6</td>
<td>1.91 2.05</td>
<td>Image cube</td>
<td>1982-85</td>
</tr>
<tr>
<td>AIS-2 (NASA/JPL)</td>
<td>128</td>
<td>990-2100 1200-2400 800-1600 1200-2400</td>
<td>8000-12000</td>
<td>9.3 10.6</td>
<td>1.91 2.05</td>
<td>Image cube</td>
<td>1986-87</td>
</tr>
<tr>
<td>AISA (Karelsilva Oy)</td>
<td>1-286</td>
<td>450-900</td>
<td>1.56-9.36</td>
<td>1</td>
<td>21</td>
<td>Image cube</td>
<td>since 1993</td>
</tr>
<tr>
<td>AMSS (GEOSCAN)</td>
<td>32 8 6</td>
<td>490-1090 2020-2370 8500-12000</td>
<td>170-240 430-440 550-590</td>
<td>2.1 x 3.0</td>
<td>92</td>
<td>Image cube</td>
<td>since 1985</td>
</tr>
<tr>
<td>ARES (AIP) (Lockheed)</td>
<td>75</td>
<td>2000-6300</td>
<td>25-70</td>
<td>1.17</td>
<td>3 x 3</td>
<td>Image cube</td>
<td>since 1985</td>
</tr>
<tr>
<td>ASAS upgraded ASAS (NASA/GSFC)</td>
<td>29 62</td>
<td>455-873 400-1060</td>
<td>15 11.5</td>
<td>0.80 0.80</td>
<td>25</td>
<td>25</td>
<td>Image cube</td>
</tr>
<tr>
<td>AVIRIS (JPL)</td>
<td>224</td>
<td>380-2500</td>
<td>9.7-12.0</td>
<td>1</td>
<td>30</td>
<td>Image cube</td>
<td>since 1989</td>
</tr>
<tr>
<td>CASI (Itres Research)</td>
<td>288 19</td>
<td>400-1000 (nominal)</td>
<td>650</td>
<td>1.3, 1.6</td>
<td>37.8 44.7</td>
<td>Profile image</td>
<td>since 1990</td>
</tr>
<tr>
<td>CIS (China)</td>
<td>64 24 1 2</td>
<td>400-1040 2000-2480 3550-3940 10500-12500</td>
<td>10 20 410 1000</td>
<td>1.2 x 3.6 1.2 x 1.8 1.2 x 1.2 1.2 x 1.2</td>
<td>80</td>
<td>Image cube</td>
<td>since 1993</td>
</tr>
<tr>
<td>CHRISS, SAIC AAHIS, (SAIC)</td>
<td>40 288</td>
<td>430-860 440-880</td>
<td>11 3</td>
<td>0.05 1.0</td>
<td>10 11.5</td>
<td>Image cube</td>
<td>1992 1994</td>
</tr>
<tr>
<td>DAIS-7915 (GER/DLR)</td>
<td>32 8 32 1 6</td>
<td>400-1010 1500-1788 1970-2450 3000-5000 8700-12700</td>
<td>10-16 36 36 2000 600</td>
<td>3.3, 2.5, or 5.0</td>
<td>64-78</td>
<td>Image cube</td>
<td>since 1994</td>
</tr>
<tr>
<td>DAIS-16115 (GER)</td>
<td>76 32 32 6 12 2</td>
<td>400-1000 1000-1800 2000-2500 3000-5000 8000-12000 400-1000</td>
<td>8 25 16 333 333 stereo</td>
<td>3</td>
<td>78</td>
<td>Image cube</td>
<td>since 1994</td>
</tr>
<tr>
<td>DAIS-3715 (GER)</td>
<td>32 1 2 1 1</td>
<td>360-1000 1000-2000 2175-2350 3000-5000 8000-12000 400-1000</td>
<td>20 1000 50 2000 4000</td>
<td>5</td>
<td>±45</td>
<td>Image cube</td>
<td>since 1994</td>
</tr>
<tr>
<td>FLI/PMI (Moniteq)</td>
<td>≥ 288</td>
<td>430-805</td>
<td>2.5</td>
<td>1.3</td>
<td>70</td>
<td>Profile image</td>
<td>1984-90</td>
</tr>
<tr>
<td>FTVHSI (Kestrel)</td>
<td>256</td>
<td>440-1150</td>
<td>67 cm⁻¹</td>
<td>0.8</td>
<td>15</td>
<td>Image cube</td>
<td>1996</td>
</tr>
<tr>
<td>GER-63 Channel Scanner (GER)</td>
<td>24 4 29 6</td>
<td>400-1000 1500-2000 2000-2500 8000-12500</td>
<td>25 125 17.2 750</td>
<td>2.5, 3.3, or 4.5</td>
<td>90</td>
<td>Image cube</td>
<td>since 1986</td>
</tr>
<tr>
<td>HYDICE (NRL/ERIM)</td>
<td>206</td>
<td>400-2500</td>
<td>7.6 - 14.9</td>
<td>0.5</td>
<td>8.94</td>
<td>Image cube</td>
<td>since 1994</td>
</tr>
<tr>
<td>ISM (DESPA/IAS/OPS)</td>
<td>64 64</td>
<td>800-1600 1600-3200</td>
<td>12.5 25.0</td>
<td>3.3 x 11.7</td>
<td>40</td>
<td>Image cube</td>
<td>since 1991</td>
</tr>
<tr>
<td>ISM (DESPA/IAS/OPS)</td>
<td>64 64</td>
<td>800-1600 1600-3200</td>
<td>12.5 25.0</td>
<td>3.3 x 11.7</td>
<td>40</td>
<td>Image cube</td>
<td>since 1991</td>
</tr>
</tbody>
</table>
Table 12: Summary of some early hyperspectral airborne imaging spectrometers

<table>
<thead>
<tr>
<th>Sensor (Agency/Company)</th>
<th>No. of Bands</th>
<th>Spectral Range (nm)</th>
<th>Bandwidth at FWHM (nm)</th>
<th>IFOV (mrad)</th>
<th>FOV (º)</th>
<th>Data Product</th>
<th>Period of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAS (Daedalus)</td>
<td>50</td>
<td>547-14521</td>
<td>31-517</td>
<td>2.5</td>
<td>85.92</td>
<td>Image cube</td>
<td>since 1992</td>
</tr>
<tr>
<td>MISI (RIT)</td>
<td>60</td>
<td>400-1000</td>
<td>10</td>
<td>2</td>
<td>±45</td>
<td>Image cube</td>
<td>from 1996</td>
</tr>
<tr>
<td>MIVIS (Daedalus)</td>
<td>20, 64, 10</td>
<td>433-833, 1150-1550, 2000-2500, 8200-12700</td>
<td>20, 50, 8, 400-500</td>
<td>2.0</td>
<td>70</td>
<td>Image cube</td>
<td>1993</td>
</tr>
<tr>
<td>MUSIC (Lockheed)</td>
<td>90</td>
<td>2500-7000, 6000-14500</td>
<td>25-70, 60-1400</td>
<td>0.5</td>
<td>1.3</td>
<td>Image cube</td>
<td>1989</td>
</tr>
<tr>
<td>ROSIS-03 (DLR/GKSS)</td>
<td>115</td>
<td>430-830</td>
<td>4</td>
<td>0.56</td>
<td>16</td>
<td>Image cube</td>
<td>since 1993 ROSIS-03 since 1998</td>
</tr>
<tr>
<td>SFSI (CCRS)</td>
<td>115</td>
<td>1200-2400</td>
<td>10.4</td>
<td>0.4</td>
<td>9.4</td>
<td>Image cube</td>
<td>since 1994</td>
</tr>
<tr>
<td>SMIFTS (U. of Hawaii)</td>
<td>75, 35</td>
<td>1000-5200, 3200-5200</td>
<td>100 cm⁻¹, 50 cm⁻¹</td>
<td>0.6</td>
<td>6.0</td>
<td>Image cube</td>
<td>since 1993</td>
</tr>
<tr>
<td>TRWIS-B</td>
<td>80</td>
<td>400-640</td>
<td>10-14</td>
<td>1</td>
<td>31.5</td>
<td>Image cube</td>
<td>Test phase 1994</td>
</tr>
<tr>
<td>TRWIS-II</td>
<td>80</td>
<td>400-640</td>
<td>10-14</td>
<td>1</td>
<td>31.5</td>
<td>Image cube</td>
<td>Test phase 1994</td>
</tr>
<tr>
<td>TRWIS-III (TRW)</td>
<td>30</td>
<td>440-640</td>
<td>10-14</td>
<td>1</td>
<td>31.5</td>
<td>Image cube</td>
<td>Test phase 1994</td>
</tr>
<tr>
<td>Hybrid VIFIS (U. of Dundee)</td>
<td>30</td>
<td>440-640</td>
<td>10-14</td>
<td>1</td>
<td>31.5</td>
<td>Image cube</td>
<td>Test phase 1994</td>
</tr>
</tbody>
</table>

The passive remote sensing technique of hyperspectral imaging offers an unparalleled spectral interpretation capability of the data (quantitative monitoring) for many applications, including land, water and atmospheric parameters [detection/discrimination of spectral fingerprints of matter (solids, liquids, gaseous or particulate matter) that cannot be derived from coarser multispectral imagers]. Land applications include vegetation studies (species identification, plant stress, leaf water content), soil science (erosion), geology (mineral identification and mapping, detection of underground/camouflaged structures), and hydrology (liquid/solid water differentiation, snow/grain size). Water applications include monitoring of water quality, bathymetry, etc. Atmospheric applications include the measurement of water vapor, trace gases, aerosols, and cloud characteristics. - A disadvantage of the technique is the generation, communication, processing, interpretation and storage of immense data volumes.

1.2.2.2 Spectral dispersion methods

There are three mainstream instrumental dispersion approaches to spectral imaging (SI): a) filter/interferometer (FSI), b) wavelength/dispersive (WDSI), and c) a hybrid of FSI and WDSI (hybrid). The main properties of the three dispersion techniques are given in Table 13. 151)

- The FSI (Filter/Interferometer Spectral Imaging) method images a fixed FOV sequentially through a series of filters, each of which has a certain bandpass and center wavelength. The filtered image is then focused onto a CCD camera. Electronic methods used to gener-

ate the filters include LCTF (Liquid Crystal Tunable Filters), AOTF (Acousto-Optic Tunable Filters), and interferometry. Overall, the spectral acquisition process is slow in hyperspectral applications due to the sequential acquisition approach of many channels.

<table>
<thead>
<tr>
<th>Parameter/instrument technique</th>
<th>Filter/interferometer (FSI)</th>
<th>Wavelength/dispersive prism/diffraction grating</th>
<th>Hybrid/PMT (Photomultiplier Tube)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength acquisition</td>
<td>Sequential</td>
<td>Simultaneous</td>
<td>Limited simultaneous</td>
</tr>
<tr>
<td>FOV (Field of View)</td>
<td>Simultaneous over a fixed FOV</td>
<td>Sequential over an unlimited FOV</td>
<td>Point-by-point confocal over a fixed FOV</td>
</tr>
<tr>
<td>Spectral acquisition</td>
<td>Bandpass</td>
<td>All contiguous wavelengths</td>
<td>Bandpass</td>
</tr>
<tr>
<td>Spectral discrimination</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Relative spectral acquisition time</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Time-resolved fluorescence with the lanthanide series</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 13: Comparison of performance characteristics of FSI, WDSI, and hybrid systems

- The WDSI (Wavelength/Dispersive Spectral Imaging) technique (the most common in imaging) uses an imaging spectrometer that incorporates a diffraction grating or prism as the dispersive device to split the radiation into all its component wavelengths. The CCD detector is positioned to intercept focused diffracted light at all contiguous wavelengths simultaneously. The design of the spectrometer enables the user to know the location on the sample that emits a particular spectrum. The CCD presents one spectrum per row of pixels. If there are 240 rows of pixels, then a slice of the sample will be characterized by 240 spectra. Software automatically classifies the spectra obtained, so that all spectra that are the same can be similarly pseudo-color-coded. – Because each CCD row of pixels acquires a complete spectrum in one shot, data processing can begin immediately after one acquisition. This is in direct contrast to the FSI approach, where it is necessary to wait until a FOV has been acquired through a series of filters and each pixel has accumulated a full spectrum. All wavelength/dispersive imaging spectrometers abide by the following rules:

1) Light must pass through an entrance aperture (ES) that is almost always a slit.

2) An image of the slit is focused at different locations in space as a function of wavelength and the dispersive properties of the spectrometer. Hence, the term “spectral lines” is derived from the slit image produced at various wavelengths. A detector array or CCD is in focus when it records spectral lines at their narrowest. Each row of pixels provides a spectrum associated with a particular point in the slice.

3) The width of the detector determines the wavelength dispersion; for example, spectral range: 360-800 nm; wavelength range: 440 nm (800-360 nm); detector: 8 mm active length; and pixel size: 8.5 µm. Therefore, the average wavelength dispersion is 55 nm/mm (440 nm/8 mm). A prism presents nonlinear wavelength dispersion, with significantly greater dispersion in the blue compared to the red.

4) The spectral bandpass is a function of dispersion of the spectrometer, the entrance slit width, and the detector size, so that: Bandpass = FWHM = (effective slit width x dispersion) where the effective slit width is the greater of the width of the detector elements or the image of the slit. In this case, the detector elements are the pixel dimensions of the CCD.

5) The spectral resolution of a spectrometer is defined as the limiting bandpass for an emission source of infinitely narrow natural line width, such as a single-mode laser, the narrowest possible slit width, and the finite dimensions of the detector elements.
6) A slice of the FOV is defined by the projected width of the ES on the sample following the microscope objective (MO). For example, if the magnification of the MO = 10x, and ES = 0.025 x 5.0 mm, then the slice will be 0.0025 x 0.5 mm at the sample.

7) Spatial resolution is determined either by the projected width of the slit through the microscope objective or by the projected image of the object, whichever is smaller.

- Hybrid spectral imaging. One of the most sensitive detectors is the photomultiplier tube (PMT). This device contributes very low noise and a high dynamic range ($10^6$), compared to $10^3$ with a CCD, with good efficiency (from 185 to 700 nm). A PMT is the detector of choice with almost all laser confocal imaging systems. New developments in PMT technology include the IPMT (Imaging PMT) of Hamamatsu. Unlike a typical PMT that has only one detector element, the IPMT has a linear array of detector elements on 1 mm centers and an active area of 800 µm.

1.2.2.3 ETF (Electronically Tunable Filter) systems and technologies

The capture of reflectance information (i.e., reflective solar radiation observation from the Earth’s surface using imaging devices, extraction of color-light interactions in computer vision, etc.) in spectrally higher dimensions (multispectral or hyperspectral imagery) generally improves image analysis. To acquire spectrally and spatially high-dimensional images, one has to employ specialized image acquisition devices [a spaceborne hyperspectral imager builds an image cube (x, y, $\lambda$ dimensions) in a pushbroom fashion, by capturing typically one spatial and all spectral dimensions simultaneously in each camera frame, while the second spatial dimension is captured displaced in time]. Electronically tunable filters offer the fastest, most accurate and flexible color filtering techniques that are currently available.

Background on reflective optical instruments: 152) Reflective optical systems for imaging spectrometry have a number of advantages for use in spaceborne applications. They operate over a broader wavelength band than refractive systems. In particular, a single foreoptic and (sometimes) spectrometer optic can be made to work over the full wavelength band (400 to 2500 nm) of interest for remote sensing of solar reflected radiation. The optics can be aligned using visible light, and the result will hold at all wavelengths. Reflecting systems are inherently more radiation hard than refractive ones, and reflective systems can be designed and built to have a stable optical performance over a wider temperature range than refractive systems.

An ETF is a filter device whose spectral transmission can be electronically controlled through the application of voltage or acoustic signal, etc. There are no moving parts and no discontinuity in the spectral transmission range, thus a fine spectral sampling is provided as well as rapid and random switching between the various spectral bands. 153) 154)

There are three prominent classes of ETFs to achieve wavelength selectivity in imaging applications (generation of hyperspectral imaging cubes) in combination with framing cameras for sequential wavelength scanning:

1) AOTF (Acousto-Optical Tunable Filter)
2) LCTF (Liquid Crystal Tunable Filter)
3) FPI (Fabry-Perot Interferometer) tunable filter.

The ETF technology is sensitive to polarization so that the imagery can be used to discern polarization information about a scene in addition to spectral information. The light trans-

mission through an AOTF, LCTF, or an interferometer is always wavelength dependent and typically polarization dependent. It is difficult to reach even 50% transmission efficiency, especially as most biological samples present randomly polarized light.

<table>
<thead>
<tr>
<th>Attributes/System</th>
<th>LCTF (Liquid Crystal Tunable Filter)</th>
<th>AOTF (Acousto-Optical Tunable Filter)</th>
<th>FPI tunable filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunability time</td>
<td>~ 50 ms</td>
<td>~ 15 ms, ~ 30 ms</td>
<td>~ 40 ms FPI ~ 4 ms DE-FPI</td>
</tr>
<tr>
<td>Operating spectral range</td>
<td>0.4 - 1.7 μm</td>
<td>0.2 - 5 μm</td>
<td>0.4 - 1.55 μm</td>
</tr>
<tr>
<td>Max width of tunable range</td>
<td>450 nm (VNIR) 950 nm (SWIR)</td>
<td>700 nm (VNIR) 3900 nm (SWIR, MWIR)</td>
<td>100 nm</td>
</tr>
<tr>
<td>Min output bandwidth</td>
<td>5 nm</td>
<td>0.4 nm</td>
<td>0.05 nm</td>
</tr>
<tr>
<td>Max output bandwidth</td>
<td>30 nm multispectral 100 nm trichromatic</td>
<td>50 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>Mean error in central wavelength</td>
<td>0.5 nm</td>
<td>1 nm (varies with λ)</td>
<td>1 nm (varies with λ)</td>
</tr>
<tr>
<td>Average transmission rate</td>
<td>20-50%</td>
<td>98%</td>
<td>20-50%</td>
</tr>
<tr>
<td>Transmission rate over wavelength</td>
<td>increases with wavelength</td>
<td>constant</td>
<td>increases with wavelength</td>
</tr>
<tr>
<td>Out of band transmission</td>
<td>0.01-0.05%</td>
<td>0.05-0.1%</td>
<td>0.5-1%</td>
</tr>
<tr>
<td>Range of aperture sizes</td>
<td>20-35 mm</td>
<td>3-10 mm</td>
<td>15-76 mm</td>
</tr>
<tr>
<td>Incident light limitations</td>
<td>None</td>
<td>Requires collimated light</td>
<td>None</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Low</td>
<td>Low</td>
<td>Low (FPI) High (DTFPI)</td>
</tr>
</tbody>
</table>

Table 14: Typical tunable filter characteristics

1.2.2.4 Acousto-Optic Tunable Filters (AOTF)

- Acousto-Optic Tunable Filters (AOTF) in acousto-optic imaging systems (O.4,5). The AOTF technique is based on diffraction of an acoustic wave of electromagnetic radiation traversing a transparent medium. An AOTF consists of a crystal in which radio frequencies (RF) acoustic waves are used to separate a single wavelength of light from a broadband source. The wavelength of light selected is a function of the frequency of the RF applied to the crystal. An acousto-optic cell is a transparent birefringent crystal excited by a radio frequency transducer. Propagating acoustic waves inside the crystal create regular spatial variations of the refractive index. Under phase-matching conditions, light of a particular linear polarization and wavelength, incident on the crystal at a very specific angle, is diffracted by the moving grating produced by the acoustic wave.

In the 1990s AOTF devices are based on solid-state technology, they are RF-tunable and random access devices, offering the important capability of spectral agility. When combined with a 2-D CCD array, the complete spectral, spatial, and polarimetric characterization of a scene can be measured with an imaging system that has no moving parts. An AOTF device, can switch from one spectral range to another in the time that it takes an acoustic wave to traverse the crystal, (typically in the μs range). By making the AOTF part of an imaging system [i.e. an AOS (Acousto-Optic Spectrometer)], and projecting the diffracted light onto a 2-D array, it is possible to form an image extracted from the particular spectral component of the incident radiation. CCD arrays have been utilized for this purpose. - Be-

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causethecrystalisbirefringent,thepolarizationofthelightincidentonthedeviceaffects theangleatwhichthelightisdiffracted. Diffraction changes the polarization of the incident radiation so that some of the initially ordinary polarization emerges from the device with extraordinary polarization, and some of the initially extraordinary polarization emerges from the device with ordinary polarization. The result of this sensitivity to polarization is that an AOTF imager can be used to discern polarization information about a scene in addition to spectral information. Because the two polarizations of incident light are diffracted differently, it is possible to use two CCD arrays in order to capture separately the image generated by each polarization. The birefringent material of TeO₂ (Tellurium dioxide) is frequently used due to its high acousto-optic figure of merit, and good transmission in the UV, visible and infrared (range of application 0.25-4.5 μm).

- Some airborne precursor instruments with AOS (Acousto-Optic Spectrometer) technology, leading toward AOTF capabilities are: POLAS (Polarization-sensitive Acousto-optic Spectrometer) of Russia introduced in 1989, AHSTRA (Airborne Heterodyne Spectrometer THz Astronomy) of the Max-Planck-Institute for Radio Astronomy, Bonn; AMSOS (Airborne Millimeter & Submillimeter-wave Observing System) since winter 1997/98, Univ. of Bern, Switzerland; SUMAS/ASUR (Submillimeter Atmospheric Sounder/Airborne Submillimeter SIS Radiometer), Institute of Environmental Physics at the University of Bremen, Germany; THOMAS (THz OH Measurement Airborne Sounder), DLR (Institute of Optoelectronics, Oberpfaffenhofen, Germany).

- In the field of spaceborne Earth observation, the Russian instrument Trasser with AOTF technology was first flown on Okean-O1-N2 (or Cosmos 1869) with a launch on July 16, 1987. The instrument was operational until 1990. Another Trasser-O instrument was flown on Okean-O-1 (launch July 16, 1999, end of mission fall 2000). All Trasser instruments were designed and built by STCU (Scientific Technological Center of Unique Instruments), Moscow. The Swedish SMR (Submillimeterwave Radiometer) instrument on ODIN (launch Feb. 20, 2001) features an AOS detector provided by France. The Japanese instrument SMILES (Superconducting Submillimeter-wave Limb-Emission Sounder) employs two acousto-optical spectrometers (AOS) with the objective to observe submillimeter-wave radiation (monitoring of trace gas distribution in the atmosphere). SMILES is an ISS payload planned to be launched in 2006 (L.2.15).

- In spaceborne science, the NASA SMEX mission SWAS (Submillimeter Wave Astronomy Satellite) with a launch on Dec. 5, 1998 carries the instrument AOS (Acousto Optical Spectrometer), provided by the University of Cologne, Germany, to investigate the composition of dense interstellar clouds. AOS on SWAS is used as a backend in combination with a heterodyne receiver to analyze the intermediate frequency signal. Inside AOS, the RF signals are converted to acoustic waves within a crystal causing pressure waves to travel through the crystal. When illuminated by laser light, the alternating patterns of compression and expansion within the crystal act like the finely spaced lines of a grating causing the laser light to be dispersed along one dimension with intensity variations along this direction that are proportional to the intensities within the input 1.4 to 2.8 GHz band.

### 1.2.2.5 LCTF (Liquid Crystal Tunable Filter)

A liquid crystal tunable filter is a bandpass filter technique that allows selection of the wavelength of the transmitted light by varying an electrical input voltage, and also functions as a linear polarizer. LCTFs use electrically controlled liquid crystal elements to select a specific visible wavelength of light for transmission through the filter at the exclusion of all others. The method relies on constructive and destructive interference effects in a multi-

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159) http://www.ph1.uni--koeln.de/spec.html
160) Note: The term “bandpass” is defined as the FWHM (Full Width Half Maximum) spectral response measured from the peak maximum if the line shape is Gaussian. The half-power width of a response is easier to describe than true resolution because the concept does not involve the contrast of the target.
layer stack of quarter-wave reflective layers and half-wave spacer layers. This type of filter is ideal for use with electronic imaging devices, such as CCDs (Charge Coupled Devices), because it offers excellent imaging quality with a simple linear optical pathway.

In simple terms, an LCTF is something like an optical filter wheel - featuring a large aperture, large field of view, and good optical quality. But being electronic, there are no moving parts and no distortion of the image between wavelengths; therefore, it is ideal for automation. Being continuously tunable, a wider range of colors (bands) is available, beyond the conventional three fixed colors (RGB). A typical wavelength-selective liquid crystal tunable filter is constructed from a stack of fixed filters consisting of interwoven birefringent crystal/liquid-crystal combinations and linear polarizers (Lytotype birefringent design consisting of multiple cells of increasing retardance). A single Lyot stage of the LCTF system is a “sandwich” of birefringent liquid crystal, glass, quartz, and sheet polarizers. The spectral region passed by LCTFs is dependent upon the choice of polarizers, and the liquid crystal characteristics (nematic, cholesteric, smectic, etc.). In general, visible-wavelength (VIS) devices of this type usually perform quite well in the 400 to 700 nm region. To achieve monochromatic throughput in the LCTF, a series of these “sandwiches” are stacked horizontally in order of increasing retardance. The bandwidth of the LCTF is constant in frequency space.

![Figure 8: Schematic principle of an LCTF cell](image)

An LCTF is based on two principles: **birefringence** and **polarization**. Birefringence is the phenomenon exhibited by some crystalline substances which display two different indexes of refraction. Polarization is related to the geometry of light wave propagation. It is associated with the plane of oscillation of the electric field of a light wave. Light waves can have no preferred oscillation plane (unpolarized light) or have all rays oscillate on a single plane (polarized light). The process of converting from unpolarized to polarized light is called polarization and the optical device that achieves this is a polarizer. Once light is polarized, its plane of vibration can be rotated through a process called retardation. The corresponding optical device is called a retarder. Some birefringent materials (e.g. calcite, quartz) can be used as retarders.

Background: The working principle of the AOTF technique, namely the diffraction of an acoustic wave of electromagnetic radiation traversing a transparent medium, was first recognized and discovered by L. Brillouin in 1921.\(^{161}\) In the 1990s the LCTF technology was first introduced in the medical field. Things not visible to the human eye can often be imaged using the LCTF and multispectral techniques. Separate images are prepared at different parts of the visible or infrared spectrum, and the images of their differences and con-

\(^{161}\) L. Brillouin, Ann. de Physique, Vol.17, p. 103, 1921
Trasts are combined to prepare a new image. This technique has been applied to fingerprint recovery and for the detection of forgeries in altered documents. JPL illustrated the power of multispectral imaging techniques using an LCTF when legible images of the Dead Sea Scrolls were obtained. Little contrast existed between the ancient papyrus and the ink, making it unreadable to the unaided eye. However, in the spectrum’s near—infrared band, the parchment becomes more reflective while the carbon—based ink remains dark. An LCTF made it possible to quickly scan the spectrum for the best imaging frequency.

At the start of the 21st century, the LCTF technology is being used in airborne applications and is also considered a viable and potential technique for spaceborne imaging applications. Example: 162)

- NASA/JPL is using the LCTF technology in the design of an EOIFTS (Electrooptical Imaging Fourier Transform Spectrometer), a new type of interferometer, for hyperspectral measurements in the infrared region (1-2.5 μm), but without any moving parts as experienced in traditional Michelson interferometers. This approach takes advantage of fast switching ferroelectric or dual-frequency nematic LC modulators to quickly vary the time delay in order to implement fast-acquisition of the time-series data. This project addresses also the need by reducing the weight, size and power consumption of FTS (Fourier Transform Spectrometers) by eliminating all moving parts. The mechanical scanning mechanism of conventional FTS technology is being replaced with a solid-state time delay design using optoelectronic components. EOIFTS is a low-mass instrument to permit hyperspectral imaging of atmospheric constituents and many other applications. 163)

1.2.2.6 FPI (Fabry-Perot Interferometer) tunable filter

The FPI (etalon) functions like a tunable interference filter by varying the gap between the two reflective plates, changing the wavelengths that undergo constructive interference. Some of the most important properties of an FPI filter are the in-band transmittance at the design wavelength, its bandwidth or its full width half maximum (FWHM) and the tunable spectral range. The concept may be used for a number of applications such as in imaging spectroscopy (to disperse the frequency components), Doppler wind measurements, and in optical communications for WDM (Wavelength Division Multiplexing). Prototype implementations are:

- Physical Sciences Inc. (PSI) of Andover, MA, developed AIRIS (Adaptive Infrared Imaging Spectroradiometer) for DoD. The operation of AIRIS from an airborne platform was demonstrated in 2002. In contrast to other approaches to multispectral and hyperspectral infrared imaging, e.g., pushbroom spectrometers and FTIR (Fourier Transform Infrared) spectrometers, AIRIS may be commanded to collect data at only those wavelengths which facilitate target detection. This capability can reduce data volume and data processing requirements for many multispectral imaging applications. The patented AIRIS concept employs an FPA (Focal Plane Array) which which views the far field through a tunable Fabry-Perot interferometer (etalon). The tunable etalon is the critical enabling technology. Some features of AIRIS are: 164)
  - Continuous coverage of MWIR (λ ~ 3 - 5 μm) or TIR (λ ~ 8 - 12 μm) atmospheric transmission windows
  - High spectral resolution (λ/Δλ > 100) imagery
  - Random wavelength access


- Etalon tuning time is 10 to 20 ms
- Etalon easily integrated with commercial IR cameras or operated as a stand-alone device
- Tunable bandpass filter for differential absorption LIDAR receivers

Note: FTIRs as well as FPI instruments involve moving parts which must be accelerated and decelerated (linear mechanical motion is required), which dramatically limits the speed of acquiring a spectrum, typically to a maximum of ~1 frame/s. Real-time spectroscopic imaging (30 frames/s) cannot be done with the FTIR technology.

- NASA/LaRC is developing the TTSS-FPI (Tropospheric Trace Species Sensing Fabry-Perot Interferometer) instrument within IIP (Instrument Incubator Program). The TTSS-FPI instrument concept employs a double-etalon FPI (DE-FPI) to achieve the necessary high-resolution (0.068 cm⁻¹), narrow-band infrared emission measurements within the strong 9.6 μm ozone band. The technology will first be demonstrated on an airborne instrument while the intended implementation for future science missions is a geostationary-based measurement of tropospheric ozone and other trace gas species (application considered for the post-Aura time period). The goal is to provide a new measurement capability intended for geostationary Earth orbit (GEO)-based observation of tropospheric ozone.

1.2.3 Microwave Region, Active Observations (Radar)

The term RADAR (Radio Detection and Ranging) was probably first suggested by S. M. Taylor and F. R. Furth of the U.S. Navy and became in November 1940 the official acronym of equipment built for radio detecting and ranging of objects. The acronym was by agreement adopted in 1943 by the Allied Forces of World War II and thereafter received general international acceptance. The term “radio” refers to the use of electromagnetic waves with wavelengths in the so-called radio wave portion of the spectrum, which covers a wide range from $10^4$ km to 1 cm in wavelength (ELF to SHF). The microwave region with wavelengths generally considered from 1 m to 1 mm, happens to be the most frequently used spectrum range for radar instruments within the radio spectrum; this is the reason why “radar” is mostly equated with “microwave.”

- The following list provides some background on the early history of radar developments. Most of the chronology was compiled by BBC of London, UK. It should be said that all countries involved in an aspect of radar technology invention state somewhat different claims as to their contributions (examples: a) there are several claims to the coining of word “radar”, b) there is a claim that SAR and a chirp radar existed in 1945).

- In 1904, the German engineer Christian Hülsmeyer (1881-1957) of Eydelstedt in Lower Saxonia received a German patent (patent Nr. 165 546, plus others in the UK, the USA and some more countries) for the so-called “Telemobiloskop” or Remote Object Viewing Device. The device achieved ranges of up to 3000 m against ships, even before amplifier tubes were invented. It was offered for an application to prevent ship collisions, but didn’t find the interest of any customer and fell into oblivion.

- R. C. Newhouse of Bell Labs received a patent in 1920, and his experiments performed throughout the decade eventually led to the radio altimeter which became operational in 1937.

- In 1922, the Italian inventor/physicist Guglielmo Marconi ((1874-1937)) held a speech which showed that he had a clear idea of detecting remote objects by radio signals. But it was not before 1933 that he was able to show a first working device.

- In 1924/26, the American physicists Gregory Breit (1899-1981) and Merle A. Tuve (1901-1982) as well as the British researchers Edward V. Appleton (1892-1965) and Samuel Barnett performed measurements of the Earth’s ionosphere, using a pulse-modulated (or simply pulsed) radio transmitter which could be called a radar. Appleton received the 1947 Nobel Prize in physics for his discovery of the F layer of the ionosphere in 1924.

- It was 1928 when H. M. Signal School of the UK received the first patent on Radio Location, credited to L. S. Alder.

- In 1930, a team of engineers from the US Naval Research Lab performed measurements of a radio antenna, and more or less by serendipity - they independently discovered radar. Their radio link happened to stretch across an aircraft landing strip, and the signal quality changed significantly when an aircraft crossed the beam.

- In 1933 when Hitler took over power in Germany, the German Kriegsmarine (Navy) started research into what they called “Funkmesstechnik,” or remote radio measuring technology.

- Research in USSR/Russia began in 1934, but was somewhat hindered by quarrels between different authorities. However, one of the earlier radar devices was a success, with 70 km detection range against aircraft. RUS-1 (Radio Ulavlivatel Samoletov – Radio Catcher of Aircraft), a bistatic CW (Continuous Wave) radar, was introduced by the Red Army in 1939. Transmitting and receiving stations were separated by 35 km, the wavelength was 4 m (VHF). The first pulse-modulated radar, Redut (in production RUS-2), was adopted by the Red Army in 1940. It was bistatic as well, though with a shorter baseline (up to 1000 m).

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166) http://windfall.evsc.virginia.edu/~class/Jeremy/drhist.htm
167) “The History of Radar,” http://www.bbc.co.uk/dna/h2g2/A591545
It provided not only aircraft detection (as CW radars) but range and angle coordinate measurement. First Soviet aircraft VHF radars (1.5 m wavelength) were introduced in 1943.

- In the fall of 1934, the German company GEMA [of Hans Erich Hollmann (born in 1899 in Solingen, Germany) 169] 170 and his partner Hans-Karl von Willisen] built the first commercial radar system for detecting ships. Operating in the 50 cm wavelength range, it could detect ships up to 10 km away. In the summer of 1935, a pulse-modulated radar was developed with which they could spot the ship, the Königsberg, 8 km away, with an accuracy of up to 50 m. The same system could also detect an aircraft at 500 m altitude at a distance of 28 km.

- In 1935, the British physicist Robert A. Watson-Watt (1892-1973) successfully demonstrated the detection of an aircraft by a radio device, during the so-called Daventry Experiment. An order for full scale development of radar was issued later that year, after it was realized that sound locators (which at the time were the only means of detecting inbound bombers) could not provide adequate reaction time. This was the starting point of the world’s first operative radar network, called “Chain Home” or CH in short. The Chain Home became operational in 1937, well before the war broke out. Bombers could be detected at ranges of 150 km and more. Sir Watson Watt is often being addressed as the ‘father’ and ‘inventor’ of radar, the latter of which must now be debated. He was elected a Fellow of the Royal Society in 1941 and Knighted in 1942 for his role in the development of radar.

- Also in 1935, a French ship was equipped with a collision avoidance device of local fabrication. A land-based device, the “barrage electronique” was tested in 1936 and found application in the early days of World War II.

- By 1939, the following countries had more or less rudimentary, but operational radars in their inventories: Britain, France, Germany, Hungary, Italy, Japan, the Netherlands, Russia, Switzerland, and the USA. To some extend the technology behind these devices can be described in terms of todays buzzwords, such as continuous wave Doppler, conical scan, bistatic, and spread spectrum radars.

- On Dec. 7, 1941, radar missed a chance to significantly change history. There was a first system deployed on a hill on the Pacific island of Hawaii, close to Pearl Harbor. The operators actually detected the Japanese attack squadrons and reported their observation, but none of their superiors believed them because they were deemed unexperienced. 171) Had the reports been acted upon, then the whole attack could have been turned into a failure.

- During the war, higher and higher frequencies of the electromagnetic spectrum were put to use. Researchers started with the first experiments at some 10 MHz, the Chain Home operated around 20 MHz (with later extensions up to 70 MHz), and the bulk of air surveillance and tracking radars worked between 200-800 MHz. The cavity magnetron transmitter device was invented by A.W. Hull of the General Electric Co. in 1921, 172) no practical use was found for it at that time (the practical and efficient magnetron tube gathered world interest only after Kinjiro Okabe proposed the divided anode-type magnetron in 1928). In 1939/40 the British physicists John T. Randall and Henry A. H. Boot invented the resonant-cavity magnetron; the new technology represented a significant breakthrough. This new efficient high-power (10 kW) multi-cavity pulsed magnetron (oscillator), referred to as H2S 173) and invented/developed at the University of Birmingham, became quickly the heart of the American H2S bombing radar which operated at 3 GHz (10 cm wavelength). 174) 175) In

169) In 1935, H. E. Hollmann wrote the first comprehensive two-volume books on microwaves entitled: "Physik und Technik der ultrakurzen Wellen," (Physics and Technique of Ultrashort Waves), published in Berlin, 1936. Hollmann is considered as one of the “Fathers of Modern Radar and Microwave Technology.”

170) http://www.radarworld.org/hollmann.html

171) Note: Other sources state that the blips were misinterpreted as a weather front or an American squadron.


173) Note: The acronym H2S (or H2S) stands for Hydrogen Sulfide (meaning Stink bombs!)


September 1940 the British military decided to share its radar technology with the United States. The Americans moved quickly and opened the Radiation Laboratory at MIT under the leadership of Lee DuBridge. - The H2S plan position indicator (PPI) screen showed a map of the underlying terrain with a resolution that was hitherto unheard of. This type of magnetron wasn’t known in Germany, and 3 GHz was far beyond the frequency range of Germany’s intercept and warning devices. - But then in the spring of 1943, an American bomber was shot down near Rotterdam and the H2S radar with its magnetron was a big surprise for the German military. Significant effort went into repair, study and reproduction of the device, but only a few examples became operational by the end of 1944.

- At the end of the war, most of today’s technologies had already been put to use, although they relied on contemporary technical means. There was a chirp radar in production, the monopulse principle was invented and even a Synthetic Aperture Radar (SAR) already existed. The Chain Home was used to detect the V2 rockets after they left their launch sites, hence it can also be called the world’s first Anti Ballistic Missile (ABM) radar system. Among the few ideas which were born later than 1945 are the phased array antenna technology and the concept of multistatic radar.

- The radar technology was kept highly secret throughout World War II, and only in 1946 was it published that an American device had successfully measured the distance to the moon, which is a round trip of some 770,000 km. Much later it became known that a Hungarian device had already done the same measurement in 1944.

- Most early radar applications involved simply echo measurements of a pulsed signal that bounced back from a target to the receiver. By the end of WW-II, radar was able to pick up the placement of naval shells being fired from ships, and gave the navy the ability to correct their fire.

1.2.3.1 SAR (Synthetic Aperture Radar) concepts

Active microwave instruments (providing their own illumination) of the type SLAR (Side-Looking Airborne Radar), RAR (Real Aperture Radar) and SAR (Synthetic Aperture Radar) were developed and flown. In the SAR imaging scheme, a microwave signal at known frequency is sent out from a SAR transmitter on a platform located above the target zone. That signal travels through the atmosphere, reflects off a target (generally the surface of the Earth), and returns back to the receiving antenna (receiver). The resultant signal is measured as a combination of phase and amplitude data that, after processing, form a single-look complex radar image of the ground surface (the information content of a radar system originates at the target and requires interpretation). Originally discovered in the 1950s, SAR uses high-range resolution waveforms and synthetic aperture techniques to produce images of objects. Rather than depending on a large physical (real) aperture, a SAR forms a large virtual aperture in the processor when operating on an ensemble of received signals. In this way, an antenna only about 10 m in length on the S/C leads to image resolutions comparable to those of very large real antennas (several km in length). First radar systems for range measurements (tracking of aircraft, ships, etc.) were developed during World War II.

In USA, the first RAR instrument, developed initially for military use in the early 1960s, became available for civilian use in 1965 with the airborne instrument AN/APQ—97, developed by the Westinghouse Corp. (Baltimore, MD). The multi-polarized Ka-band (35 GHz) RAR provided imagery with a resolution of 7.5 m in cross-track (range resolution) and 1.1 R m along-track (azimuth resolution), where R is the range (distance in km) from the radar instrument to the target. Thus, at a range of 10 km, the airborne RAR instrument produced imagery with a resolution of 7.5 m x 11 m. The AN/APQ—97 instrument is the

Note: RAR systems are usually much simpler than SAR systems in design and data processing. RAR-pulse-modulated signals, based on the range-Doppler principle, are not required to be coherent (only the signal amplitude information is recovered and processed), representing and displaying backscatter characteristics from the surface sweep.
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best—known dual—polarized side—looking RAR imaging radar. In this radar, image data seen through the like—polarized and the cross—polarized channels were recorded directly onto photographic film. Hence, extensive, unclassified SLAR coverage of the United States was acquired under the NASA radr program.\(^{177}\)\(^{178}\)

**Aperture synthesis** is a processing technique of generating high spatial resolution imagery by dividing the collection area of an antenna [(in the microwave region), or of a telescope (in the optical region)] into smaller subapertures spread out in a pattern covering several baselines. An active microwave antenna is restricted to wavelength ranges in which reasonable intensities of radiation must be generated and transmitted by the remote sensing device in order to obtain a measurable return echo radiation. Conceptually, each SAR instrument is by definition an aperture synthesis device. A real (but relatively long) SAR antenna system, pointed into the cross-track direction of a flight path, is synthesized through the motion of the antenna relative to the target with either the antenna, or the target, or both moving. A synthesized antenna can be thought of as a number of independently radiating elements (i.e., the real aperture), whose separation is established by the pulse repetition frequency (PRF) and the platform velocity. The change of the phase with respect to time is the Doppler angular frequency. The azimuth resolution is determined by the Doppler bandwidth of the received signal. - In LEO spaceborne SAR missions or with aircraft—mounted SAR antennas, this relative motion to the target area is provided simply by the forward motion of each system in its flight path. The signal (echo) received by the antenna is processed coherently over an integration time. The synthesized antenna length is given by the trajectory traversed by the antenna relative to the target during the coherent integration time.\(^{179}\)

An active microwave antenna system measures not only the **intensity** (phase and amplitude) of received radiation, but also:

- The time taken for the emitted pulse of radiation to travel from the satellite to the ground and back. Conceptually, in a pulsed-modulated radar system, the radar platform is assumed to be stationary during the transmission and reception of a pulse.
- The Doppler shift in the frequency of the radiation echo as a result of relative motion of the satellite orbit with respect to the target area
- The polarization of the radiation (note: polarization can also be measured by passive devices)
- The nature of the information content of an observation in the microwave region differs from that in the visible and infrared region (optical region) of the electromagnetic spectrum. Scattering in the optical region depends very much on the molecular properties of the surface layer of the vegetation or soil, while microwave scattering depends on the largescale surface roughness (roughness in the cm range) and volume scattering (e.g. within a forest canopy).

The range resolution (in the direction normal to flight path)\(^{180}\) of a pulse-modulated radar system is limited fundamentally by the bandwidth of the transmitted pulse (the wider the bandwidth, the better the range resolution). A wide bandwidth can be achieved by a short duration pulse. However, the shorter the pulse, the lower the transmitted energy (for a fixed—peak power limitation), and the poorer the SNR, resulting in a lower radiometric resolution.

\(^{177}\) “Development and Application of Small Spaceborne Synthetic Aperture Radars (1998),” SSB (Space Studies Board), URL: http://darwin.nap.edu/books/N1000S02/html/12.html


\(^{179}\) Note: The side—viewing orientation from spacecraft of conventional flat antenna screens turned out to be the most simple and efficient way to obtain a well—defined observation swath. Conventional imaging SARs use a series of pulses instead of a continuous signal. Each transmitted wave front hits the target surface at near range and sweeps across the swath to far range. Successive sweeps are produced to form a continuous observation coverage in the long—track direction. The pulse bandwidth determines the cross—track or range resolution. The echos are sensed coherently.

\(^{180}\) http://envisat.esa.int/instruments/asar/descr/concept.html
The azimuth resolution (oriented into the flight direction) of a real aperture radar system is a function of the antenna length (the larger the antenna, the better the azimuth resolution). It can be shown that a spaceborne real aperture radar, giving a useful azimuth resolution for points on the Earth’s surface, would require an impractically large antenna. Aperture synthesis, therefore, offers a means of greatly improving the azimuth resolution.

The first ever Earth-orbiting civilian spaceborne imaging radar instrument (SAR) was flown on Seasat (NASA/JPL, L-band SAR, launch June 27, 1978, see D.43). Unfortunately, Seasat suffered a malfunction 106 days later (ending the mission abruptly); still, during its brief life, Seasat, considered to be the first oceanography mission, collected more information about the oceans than had been acquired in the previous 100 years of shipboard research. It pioneered satellite oceanography and proved the viability of imaging radar for studying our planet. The SAR instrument provided a wealth of information on such diverse ocean phenomena as surface waves, internal waves, currents, upwelling, shoals, sea ice, wind, and rainfall (first global view of ocean circulation).

Beyond the oceans, Seasat’s synthetic aperture radar instrument provided spectacular images of Earth’s land surfaces. The antenna of the planar antenna array had a size of 11 m x 1.2 m. LMSS (Lockheed Missiles and Space Systems), of Sunnyvale, CA, was the prime contractor of the mission. The SAR instrument provided an analog source data stream of 20 MHz requiring a special downlink and ground station design (implemented by JHU/APL). The received radar echoes were downlinked in S-band (analog data link at 2.265 GHz) to a total of five ground receiving stations in real-time (no onboard high-rate recording capability was possible at the time) located at: Goldstone, CA, Fairbanks, AK, Merrit Island, FL, Shoe Cove, Newfoundland (provided by CCRS), and Oakhanger, UK (provided by ESA). A side-looking spaceborne RAR instrument with the name of RLSBO was first flown on the Cosmos-1500 satellite (launch Sept. 28, 1983), later also on the Okean series of the former Soviet Union (launch of Okean-O1-1, July 5, 1988).

The standard or conventional architecture of a spaceborne SAR instrument features a SAR antenna (analogous to a telescope of an optical instrument), mounted in a side-looking configuration (see O.8.2 and Glossary) and tilted at a look angle, usually between 15-60º, into the swath. As the platform moves in its orbit, a continuous strip of swath width is mapped in the along-track direction of the satellite ground path.

SAR instruments provide high-resolution imagery (typically 1-30 m spatial resolution) of selected polarization and frequency in the microwave region (typical wavelengths from a few cm to about 1m). The active SAR observation technique is transparent to cloud coverage and rain, and does not need any sun illumination.

<table>
<thead>
<tr>
<th>Sensor Name</th>
<th>Sensor Provider</th>
<th>Introduction</th>
<th>Microwave Band</th>
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<td>1976</td>
<td>X-band</td>
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<td>NIT</td>
<td>IKI RAN, Soviet Union</td>
<td>early 1980s</td>
<td>Ku-band</td>
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<td>SLAR (part of MSS)</td>
<td>SSC, Sweden</td>
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<td>R-SLAR</td>
<td>RRL (CRL), Japan</td>
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<td>SLAR</td>
<td>TNO/NLR, The Netherlands</td>
<td></td>
<td>X-band</td>
</tr>
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</table>

Table 15: Some early SLAR (Side-Looking Airborne Radar) instruments

- Some background on early SAR developments: The earliest statement that Doppler frequency analysis could be used to obtain fine cross-range resolution is attributed to Carl

Wiley of the Goodyear Aircraft Corporation in June 1951. Wiley observed that a one-to-one correspondence exists between the along-track coordinate of a reflecting object (being linearly traversed by a radar beam) and the instantaneous Doppler shift of the signal reflected to the radar by that object. In 1953, the Doppler-frequency technique was studied by the US Army in the Project Wolverine at the University of Michigan, resulting in an Army project to further develop the range-Doppler radar principle (the pulsed Doppler radar is an example of an extension of the basic pulsed radar system). Part of the program was to develop a practical data processor which could accept wideband signals and carry out the required Doppler-frequency analysis at each resolvable range interval.

A group at the Willow Run Laboratories at the University of Michigan (ERIM since 1973) was assigned the problem of developing an optical computer for the purpose. In the summer of 1957, the Willow Run researchers constructed an X-band radar and built an optical computer. The first fully focused SAR map was produced in August 1957. Soon afterwards, the Willow Run group, in cooperation with Texas Instruments, constructed the first demonstration system, AN/UPD-1, on Army request. Five radar systems were built and various demonstration flights on aircraft were conducted in early 1961.\(^\text{184}\)\(^\text{185}\)\(^\text{186}\)

The first fielded phased-array radar, called ESAR (Electronically Scanned Array Radar), was designed by MIT/LL and built by Bendix Corp., completed in 1960 for the DoD. ESAR had IF analog phase shifters and an IF beamformer. This beamforming technique was bulky and required good temperature control.\(^\text{187}\)

On the civilian side, a three-wavelength SAR instrument was developed and flown by NASA on the Apollo-17 lunar mission (launch Dec. 7, 1972, moon landing on Dec. 11, return to Earth on Dec. 19, 1972). The objectives of ALSE (Apollo Lunar Sounder Experiment) were to detect subsurface geologic structures (“sounding”), to generate a continuous lunar profile, and to image the moon at radar wavelengths. The ALSE instrument, aboard the Apollo-17 CSM (Command and Service Module), operated at the wavelengths of 60 m, 20 m, and 2 m (corresponding to 5, 15, and 150 MHz). The instrument consisted of two distinct coherent radar subsystems, one operating at two frequencies in the HF-band and the second at a single VHF frequency. The combined HF/VHF radar had a mass of 49 kg and required 103 W of power. The radar data were recorded on 70 mm photographic film (optical recorder - CRT film type) in a conventional SAR format, and returned to Earth for processing. The HF-1 system (5 MHz) was capable of the deepest exploration. The HF-2 system (15 MHz) was operated simultaneously with the HF-1 system to provide partial overlap in the depth of exploration, trading off for improved resolution. The VHF system (150 MHz) was designed for shallow sounding and for surface imaging. All three frequencies were capable of surface profiling. Separate transmit/receive antenna systems were provided for the HF and VHF ranges. The returned data were optically processed and provided good profiles of the lunar surface/subsurface.\(^\text{188}\)\(^\text{189}\)

The first high-quality images (from a ground-based instrument) of near-Earth space objects were obtained in the early 1970s with ALCOR (ARPA, Lincoln Laboratory, C-band, Observables Radar). The data of ALCOR were processed by Lincoln Laboratory of MIT (MIT/LL) and Syracuse Research Corporation. Successful results were made possible by the range resolution of 50 cm, by the coherent recording, and by sufficient sensitivity to image low-altitude satellites. In the late 1970s, LRIR (Long-Range Imaging Radar), an X-
band instrument, was an ALCOR successor system, built at MIT/LL. The objective: imaging of satellites at geosynchronous range. In particular, significant image processing developments were achieved with LRIR such as ECP (Extended Coherent Processing).

NASA/JPL started its coherent radar test program in 1968, resulting in the development of an airborne L-band SAR instrument, flown on the CV-990 aircraft of NASA/ARC since 1971. The objective was to observe ocean surface patterns and to study the relationships between the image and the surface effects by using synthetic aperture techniques. The L-band SAR (1.215 GHz, bandwidth of 10 MHz) featured a phased array antenna with HH and HV polarization. This airborne instrument was a predecessor to the L-band SAR on SEASAT. - Star-1 (of Inter, Canada, developed by ERIM) was another early civilian airborne SAR instrument in 1983.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch</th>
<th>Spatial Resolution (m)</th>
<th>Swath Width (km)</th>
<th>Freq. GHz (Band)</th>
<th>Polarization</th>
<th>Look Angle</th>
<th>Data Rate M bit/s</th>
<th>Altitude, Inclina. (km,°)</th>
<th>Instrument, Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEASAT</td>
<td>27.6.78</td>
<td>25</td>
<td>100</td>
<td>1.28 (L)</td>
<td>HH</td>
<td>20°</td>
<td>110</td>
<td>800, 108°</td>
<td>SAR</td>
</tr>
<tr>
<td>SIR-A</td>
<td>12.11.81</td>
<td>40</td>
<td>50</td>
<td>1.28 (L)</td>
<td>HH</td>
<td>47°</td>
<td>N/A</td>
<td>260, 38°</td>
<td>SAR, Shuttle</td>
</tr>
<tr>
<td>SIR-B</td>
<td>5.10.84</td>
<td>25</td>
<td>30</td>
<td>1.28 (L)</td>
<td>HH</td>
<td>15-60°</td>
<td>34</td>
<td>225, 57°</td>
<td>SAR, Shuttle</td>
</tr>
<tr>
<td>Kosmos 1870</td>
<td>25.7.87</td>
<td>25-30</td>
<td>20-35</td>
<td>3.125(S)</td>
<td>HH</td>
<td>25-60°</td>
<td>270, 72°</td>
<td>EKOR</td>
<td></td>
</tr>
<tr>
<td>Almaz-1</td>
<td>31.3.91</td>
<td>13-20</td>
<td>2 x 172</td>
<td>3.125(S)</td>
<td>HH</td>
<td>25-60°</td>
<td>100</td>
<td>350, 72°</td>
<td>EKOR-A</td>
</tr>
<tr>
<td>ERS-1</td>
<td>17.7.91</td>
<td>30</td>
<td>100</td>
<td>5.3 (C)</td>
<td>VV</td>
<td>23°</td>
<td>105</td>
<td>785, 98.5°</td>
<td>SAR, Shuttle</td>
</tr>
<tr>
<td>JERS-1</td>
<td>11.2.92</td>
<td>18</td>
<td>75</td>
<td>1.27 (L)</td>
<td>HH</td>
<td>35.21°</td>
<td>60</td>
<td>568, 97°</td>
<td>SAR</td>
</tr>
<tr>
<td>ERS-2</td>
<td>21.4.94</td>
<td>30</td>
<td>100</td>
<td>5.3 (C)</td>
<td>VV</td>
<td>23°</td>
<td>105</td>
<td>785, 98.5°</td>
<td>SAR, Shuttle</td>
</tr>
<tr>
<td>SIR-C/X-SAR</td>
<td>4.11.94</td>
<td>15-25</td>
<td>30-100</td>
<td>1.28, (L) 9.6 (X)</td>
<td>VV, HH, HH</td>
<td>15-55°</td>
<td>46/Ch.</td>
<td>225, 57°</td>
<td>SAR, Shuttle</td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>4.11.95</td>
<td>25-100 (12x9)</td>
<td>100-170</td>
<td>5.3 (C)</td>
<td>HH</td>
<td>20-60°</td>
<td>110</td>
<td>800, 98.6°</td>
<td>SAR, Scan/SAR</td>
</tr>
<tr>
<td>Priroda</td>
<td>23.4.96</td>
<td>50</td>
<td>50</td>
<td>1.28, (L) 3.28 (S)</td>
<td>HH, VV</td>
<td>35°</td>
<td>16</td>
<td>400, 52°</td>
<td>SAR Travers</td>
</tr>
<tr>
<td>SRTM</td>
<td>11.22.2000</td>
<td>30</td>
<td>225</td>
<td>5.3 (C) 9.6 (X)</td>
<td>VV, HH, HH</td>
<td>45° 52°</td>
<td>180</td>
<td>225, 57°</td>
<td>SAR, Scan/SAR</td>
</tr>
<tr>
<td>Envisat</td>
<td>1.3.2002</td>
<td>&lt;30</td>
<td>100</td>
<td>5.33 (C)</td>
<td>Polari-metric</td>
<td>15-45°</td>
<td>100</td>
<td>800, 98.5°</td>
<td>A SAR, Scan/SAR</td>
</tr>
<tr>
<td>ALOS</td>
<td>24.01.2006</td>
<td>10</td>
<td>70</td>
<td>1.27 (L)</td>
<td>HH or VV</td>
<td>9-60°</td>
<td>240</td>
<td>700, 98°</td>
<td>PALSA R, Scan/SAR</td>
</tr>
<tr>
<td>Condor-E</td>
<td>2005??</td>
<td>1-5</td>
<td>20-150</td>
<td>3.13 (S)</td>
<td>HH, HH, VV</td>
<td>20-55°</td>
<td>61</td>
<td>600, 98°</td>
<td>SAR-10</td>
</tr>
<tr>
<td>SAR-Lupe (5S/C)</td>
<td>19.12.20</td>
<td>&lt;1-5</td>
<td>5.5 x 5.5 60 x 8</td>
<td>9.6 (X)</td>
<td></td>
<td>300</td>
<td>515, 97.44°</td>
<td>TSX-SAR</td>
<td></td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>2007</td>
<td>15-30 (100 km)</td>
<td>9.6 (X)</td>
<td>Polari-metric</td>
<td>20-60°</td>
<td>300</td>
<td>515, 97.44°</td>
<td>TSX-SAR</td>
<td></td>
</tr>
<tr>
<td>TecSAR (israel)</td>
<td>&lt;1-20</td>
<td>100 km</td>
<td>9.6 (X)</td>
<td>Polari-metric</td>
<td></td>
<td>550;</td>
<td>XSAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>2007</td>
<td>15-30</td>
<td>150</td>
<td>5.3 (C)</td>
<td>Polari-metric</td>
<td>10-50°</td>
<td>105</td>
<td>800, 98.6°</td>
<td>SAR, Scan/SAR</td>
</tr>
<tr>
<td>COSMO-SkyMEd</td>
<td>2007-8</td>
<td>1, 3-15, 30, 100</td>
<td>10, 40</td>
<td>20-60°</td>
<td>HH, VV</td>
<td>2 x 150</td>
<td>620</td>
<td>SAR-2000</td>
<td></td>
</tr>
<tr>
<td>RISAT (ISRO)</td>
<td>2007</td>
<td>3-50</td>
<td>10-240</td>
<td>5.3 (C)</td>
<td>multi-polariz.</td>
<td>609, 98°</td>
<td>SAR, Scan/SAR, spotlight</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Earth Observation History on Technology Introduction

Table 16: Chronological survey of spaceborne imaging radars (SAR instruments)

<table>
<thead>
<tr>
<th>Mission, Instrument</th>
<th>Launch Date</th>
<th>Spatial Resolution (m)</th>
<th>Swath Width (km)</th>
<th>Freq. GHz (Band)</th>
<th>Polarization</th>
<th>Look Angle</th>
<th>Data Rate Mbit/s</th>
<th>Altitude, Inclina. (km,º)</th>
<th>Instrument, Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>TanDEM-X</td>
<td>2009</td>
<td>1 - 6</td>
<td>15 - 30 (100 km)</td>
<td>9.6 (X)</td>
<td>Polari-metric</td>
<td>20-60º</td>
<td>300</td>
<td>515, 97.44º</td>
<td>TSX-SA R</td>
</tr>
<tr>
<td>TerraSAR-L</td>
<td>2009</td>
<td>5 x 9 50 x 50</td>
<td>40-70 200</td>
<td>1.25 (L)</td>
<td>Polari-metric</td>
<td>20-36º 20-45º</td>
<td>300</td>
<td>629, 98º</td>
<td>L-SAR</td>
</tr>
</tbody>
</table>

- Tilting capability of a SAR antenna. The SIR-B Shuttle mission (launch: Oct. 5, 1984) provided for the first time the ability to mechanically tilt the antenna over a range (15º - 55º) so that radar imagery from multiple angles of incidence could be obtained.

- First onboard recording of high-rate SAR data. The USSR missions Kosmos-1870 (launch July 25, 1987) and Almaz-1 (launch March 31, 1991) were the first to record and dump SAR data during station passes, followed by JERS-1 (launch Feb. 11, 1992). JERS-1 is regarded as the first long-term mission which provided an onboard SAR-recording capability for its user community on a regular basis. This enabled extended observations beyond the limits of available ground stations. JERS-1 is also the first S/C carrying two types of imaging instruments, namely a microwave imager (SAR) and an optical imager (OPS).

- Until 1978, SAR images were formed using analog techniques, incorporating optical lenses and photographic film (initially, over 95% of the SEASAT data was processed in a survey mode using optical laser techniques). Also in 1978, the first reconstruction of a SAR image was formed on a digital computer (a slow process at the time with the available computer power, but good quality imagery was generated with this technique). This SAR processor was developed by MDA (MacDonald Dettwiler and Associates Ltd.) of Richmond, BC, Canada, for the purpose to manage SEASAT SAR data. These early digital SAR processors required all the processing power available of a system; they were installed on main-frame computers or on large dedicated hardware. - On the other hand, today’s SAR images (since the late 1990s) can be formed on relatively inexpensive equipment like a workstation or a PC. (192) (193)

Hybrid solution of SAR data processing in the 21st century. For the future, SAR processing technology may come full circle. Important breakthroughs in acousto-optic and piezoelectric modulators, and very large format image collection planes make it possible to consider designs using the benefits of compact, power efficient, fast optical computers. Considering the continuing improvements of both the digital and optical technologies, it is not unreasonable to expect that a high performance onboard SAR processor, capable of providing a direct-downlink compressed data stream to operational users, will become a reality within the next decade. (194)

- A limitation and drawback in the analysis of SAR data (195) from conventional (single-frequency or single wavelength) SAR instruments is of course the availability of data at only one frequency (or single wavelength) with a fixed polarization. It means that only one component of the total surface scattering matrix is being measured, while any additional information contained within the reflected radar signal is being lost.

191) Note: The two Shuttle imaging radars, SIR-A and SIR-B, had recorders, but data was collected only for select sites due to the short mission duration of one week each.


193) Note: The SEASAT SAR analog radar echo data were downlinked in S-band (analog data link at 2.265 GHz) and recorded at the receiving stations on film using a cathode ray tube. The data were then processed to pictures using analog Fourier Optical techniques in what is known as an "Optical SAR Processor." - SAR echo data is effectively a microwave hologram of the illuminated area, so by recording this data on film, optical processing becomes the natural approach to forming an image of the ground.


<table>
<thead>
<tr>
<th>Instrument - Agency</th>
<th>Frequencies/Band (GHz)</th>
<th>Polarizations</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRSAR - NASA/JPL</td>
<td>0.45/(P), 1.26/(L), 5.31/(C)</td>
<td>H, V, full polarimetric</td>
<td>since 1987</td>
</tr>
<tr>
<td>TOPSAR - NASA/JPL</td>
<td>5.288/(C)</td>
<td>VV</td>
<td>AIRSAR configuration</td>
</tr>
<tr>
<td>CARABAS - FOA Sweden</td>
<td>20-90 MHz UWB, (VHF center frequency)</td>
<td>H</td>
<td>foliage/ground penetration</td>
</tr>
<tr>
<td>CASSAR - CAS/ISRA China</td>
<td>9.375/(X)</td>
<td>HH, VV, HV, VH</td>
<td></td>
</tr>
<tr>
<td>C-band polarimetric</td>
<td>9.66/(X)</td>
<td>VV</td>
<td>C-band interferometry</td>
</tr>
<tr>
<td>DO-SAR (Dornier, Germany)</td>
<td>3.2/(S)</td>
<td>VV, VH, HH, HV</td>
<td>polarimetric</td>
</tr>
<tr>
<td>DCS, ERIM</td>
<td>9.65/(X)</td>
<td>HH</td>
<td>SAR single-pass interferometer</td>
</tr>
<tr>
<td>EMISAR - EMI/ TUD Denmark</td>
<td>5.3/(C)</td>
<td>full polarimetric</td>
<td>since 1993</td>
</tr>
<tr>
<td>E-SAR - DLR, Germany</td>
<td>1.3/(L)</td>
<td>HH</td>
<td>E-SAR since 1989</td>
</tr>
<tr>
<td>FOLPEN - SRI, CA</td>
<td>100-500 MHz/(VHF/UHF)</td>
<td>HH</td>
<td>foliage/ground penetration</td>
</tr>
<tr>
<td>FOLPEN - SRI, CA</td>
<td>9.5 (X)</td>
<td>HH</td>
<td>interferometric mapping SAR</td>
</tr>
<tr>
<td>INGARA, Australia</td>
<td>9.375 (X)</td>
<td>HH</td>
<td></td>
</tr>
<tr>
<td>MMW-SAR - MIT</td>
<td>33.56/(Ka)</td>
<td>V, H, full polarimetric</td>
<td></td>
</tr>
<tr>
<td>NASA R ( NASA/ EORC)</td>
<td>1.291 (L-band)</td>
<td>full polarimetric</td>
<td>operation starting in fall 1996</td>
</tr>
<tr>
<td>NEC-SAR - NEC Jap.</td>
<td>9.53/(X)</td>
<td>HH</td>
<td>Interferometric mode</td>
</tr>
<tr>
<td>P-3/SAR - ERIM,Navy</td>
<td>0.350/(UWB)</td>
<td>VV, VH, HH, HV</td>
<td>UBW added in 1994, existing, polarimetric</td>
</tr>
<tr>
<td>PHARUS - TNO-FEL Delft, The Netherlands</td>
<td>5.25/(C)</td>
<td>full polarimetric</td>
<td></td>
</tr>
<tr>
<td>PI-SAR, CRL, NASDA</td>
<td>9.55 (X), 1.27 (L)</td>
<td>full polarimetric in X,L interferometric in X</td>
<td>since 1996, initially also called CLR-SAR</td>
</tr>
<tr>
<td>SAR Travers - Vega, Moscow</td>
<td>3.0/(S)</td>
<td>VV or HH</td>
<td></td>
</tr>
<tr>
<td>SASAR U. of Cape Town, South Africa</td>
<td>5.3/(C), 0.141 (VHF)</td>
<td>VV or HH</td>
<td>under construction, July 1996 first flight</td>
</tr>
<tr>
<td>RAMSES - ONERA France</td>
<td>1.6/(L), 3.0/(S), 6.2/(C)</td>
<td>VV, HH, VH, HV</td>
<td></td>
</tr>
<tr>
<td>STARS - VEGA</td>
<td>9.375/(X)</td>
<td>HH</td>
<td>since 1983</td>
</tr>
<tr>
<td>IMARC - Vega Moscow</td>
<td>118 MHz/(VHF)</td>
<td>HH, VV, HV, VH</td>
<td></td>
</tr>
<tr>
<td>Sandia SAR (SNL)</td>
<td>14.850 (Ku)</td>
<td>VV</td>
<td></td>
</tr>
<tr>
<td>IFSAR (SNL)</td>
<td>15 (Ku)</td>
<td>interferometric</td>
<td></td>
</tr>
</tbody>
</table>

Table 17: Overview of some early airborne SAR systems

- SAR observations from ocean surfaces (see Ref. 6534). Initial applications of ocean surface SAR observations were already reported in 1980. Ocean backscatter has increasing sensitivity with increasing frequency, particularly in the relation of backscatter to wind speed. In general, C-band is preferred over L-band for most SAR ocean applications. In
terms of power, lower-frequency SARs have lower power requirements. For a given signal-to-noise ratio, for example, L-band is easier to accommodate on a satellite than C- or X-bands. Next, ocean backscatter falls off rapidly with increasing viewing angle as compared with backscatter from other surfaces. This results in a comparatively narrow range of viable SAR viewing angles over which the ocean produces backscatter sufficiently above a reasonable noise floor to be detected as signal. Thus, simply increasing the swath width by viewing at higher angles is not feasible for ocean sensing unless the orbital altitude is raised. On the positive side, however, viewing at angles beyond this narrow range improves the detection of ships and icebergs, because the ocean clutter becomes significantly lower than the target returns.  

• Introduction of multifrequency SAR instruments. On the airborne side multifrequency SAR instruments/observations were introduced with AIRSAR (C, L, and P-band) of JPL in 1987. AIRSAR was also the first SAR instrument that introduced the concept of quadrature polarization (or full polarization). The Russian IMARC SAR instrument used two frequencies (X and VHF-band) since 1990, three frequencies (X, VHF, and P-band) were available since 1993, and four frequencies (X, VHF, P, and L-band) since 1994. More information of other instruments is given in Table 17. - Spaceborne multifrequency SAR instruments (L, C, and X-band) were introduced with the two SIR-C/X-SAR Shuttle mission in April and October of 1994. The SIR-C/X-SAR missions featured in addition to multifrequency (3) the polarimetric observation capability (meaning the availability of full scattering matrix) to extend the data analysis into such fields as geology, hydrology, ecology, oceanography and other applications.

• ScanSAR refers to a radar imaging technique permitting extended observation coverage (e.g. wider swath). In ScanSAR mode, the scene size in range is extended by scanning the antenna in elevation and alternating illumination of several subswaths. Like in stripmap SAR, the scene extension in azimuth is principally only determined by the length of the observation period. The ScanSAR mode requires rapid electronic steering of the elevation beam pattern of the antenna (phased array antenna with analog beamforming). The principle of ScanSAR is to share radar operational time between two or more separate subswaths in such a way, as to obtain full image coverage of each. However, scanning in elevation implies that the synthetic aperture length is reduced to the burst length (the burst length or burst duration is defined as the time interval for each target illumination in a ScanSAR cross-track sequence). A consequence of the shorter burst length (as compared to stripmap SAR) is that each target has a different Doppler history (depending on its azimuth position) resulting in a reduced ScanSAR azimuth resolution. The basic differences between ScanSAR and stripmap SAR processing are: 

- The azimuth consists of several bursts, each of them corresponding to a fraction of the full synthetic aperture
- The azimuth resolution is limited by the burst duration and is no longer determined by the synthetic aperture length
- The Doppler history of each target within a burst has a different frequency offset depending on its azimuth location
- The azimuth multilook technique is constrained more by the scanning strategy than by the processing strategy

The radiometric correction due to the azimuth antenna pattern is much more critical than in stripmap SAR since each target is illuminated by different parts of the azimuth antenna diagram.

For SAR data processing, an additional mosaic operation is needed in azimuth and range directions to join the azimuth bursts and the range subswaths, respectively.

The ScanSAR technique was initially developed by JPL and first flown on two Shuttle missions with the SIR-C/X-SAR payload in 1994, SRL-1 (STS-59, April 9-20, 1994) and SRL-2 (STS-68, Sept. 30-Oct. 11, 1994). Further implementations of ScanSAR are on RADARSAT-1 (Canada, launch Nov. 4, 1995), SRTM/C-RADAR (NASA/JPL, launch Feb. 11-22, 2000), Envisat/ASAR (ESA, launch Mar. 1, 2002), and ALOS/PALSAR (Japan, launch Jan. 24, 2006). Until RADARSAT-1, the maximum swath width of any previously orbiting SAR instrument had been 100 km, a parameter tightly constrained by the need to: a) “fill the aperture” and b) receive all the returned energy between transmitter pulses. RADARSAT-1 achieved with ScanSAR swaths up to 510 km with 100 m resolution, from an 800 km orbit, through the use of multiple electronically steered antenna beams and carefully synchronized transmitter pulse timing.

The advantage of wider ScanSAR observation coverage is crucial in obtaining global repeat SAR imagery in several days, eventually on a daily basis (enhanced sampling capability) irrespective of cloud cover or sunlight conditions. The narrow-swath high-resolution (<10 m) SAR imagery yields exciting periodic snapshot views of the 2-D ocean surface to study a number of applications (interactions with the atmosphere, long waves, and current). The wide-swath ScanSAR capability of RADARSAT (up to 510 km), Envisat (up to 400 km) and ALOS (up to 350 km) permit for the first time the study of larger-scale phenomena (mesoscale wind fields and circulation features, atmospheric boundary-layer processes, study of storm dynamics, etc.), thus providing a better monitoring capability that may eventually lead to operational SAR missions. The potential of SAR imagery wind-field monitoring alone is much higher than is possible with spaceborne scatterometers. A future operational SAR mission service can of course also provide several other services for land surface monitoring besides ocean surface monitoring, such as monitoring of natural hazards in a wide variety of applications: flooding, earthquakes, wildfires, severe weather events, etc.

In SpotSAR mode (see O.8.3 for definition of SAR imaging modes), the antenna is steered in the azimuth direction (usually electronic beam-steering capability). During the formation of the synthetic aperture, the antenna is constantly looking into the scene center direction. The available synthetic aperture is in this case much longer than in stripmap mode and is denoted by spotlight aperture. The long spotlight aperture provides azimuth signals with a large Doppler bandwidth and therefore provides a high geometric resolution in azimuth.

Phased array microwave technology of SAR antennas (see also O.8.4). The observation requirements of wide swaths for global coverage led eventually to the introduction of a

new scanning concept referred to as ‘phased array technology,’ making use of electronic beam steering in the elevation domain (the use of electronic scanning allows flexibility in beam pointing and beam shape control for swath coverage). Naturally, the technology requires a lot of computer power to handle such complex radar functions as: beam switching, signal detection, frequency management, ranging, etc. The technique was first tested on active sensors (SARs) in the microwave region of the spectrum and later on laser radars. The SAR instrument of SEASAT (launch June 27, 1978) pioneered the phased array / beam-pointing method for spaceborne instruments (see chapter 1.2.3.3). Other instruments with phased array technology followed or are being planned, such as: PR on TRMM (launch Nov. 27, 1997), C-RADAR on SRTM (launch Feb. 11-22, 2000), ASAR on Envisat (launch Mar. 1, 2002), and PALSAR on ALOS (launch Jan. 24, 2006). The following instruments are operational on the airborne side: FOLPEN (SRI International), PHARUS (TNO), CRL-SAR (CRL), and Sandia SAR (SNL). In the 1990s the phased array has become a key component in the design of advanced antenna systems, taking advantage of the considerable advances in microelectronics, transmitter/receiver architectures, miniaturized device (module) integration methods, and signal processing techniques.

Phased arrays are random-access devices (active antennas) whose basic architecture consists of two building blocks, namely radiating elements and a beamforming network. They are employed for electronic beam-steering applications in the microwave and/or optical regions of the spectrum (see Glossary). The phased array antenna concept offers several striking performance advantages over other concepts (like conventional horn antennas).

- The most fundamental advantage of sampling the wavefront with nearly omnidirectional antenna elements is that it allows multi-beam operation at wide angle separation and with full sensitivity
- This opens up the possibility to run several independent observational programs simultaneously (multi-target tracking and imaging), each with full aperture sensitivity. The independent beam agility is important when the radar has multiple functions to be performed simultaneously.
- The benefits of random-access and rapid beam-pointing with no moving parts have made phased arrays the technology of choice. Sub-array units provide the capability of reconfiguration.
- Phased arrays can be used for spatial power combining techniques that are considered to be very effective for generating high power microwaves and millimeter-waves
- Phased antenna arrays find increasingly wider application in mobile communications; the concepts of spatial signal processing and of space-division multiple access (SDMA) based upon the utilization of antenna arrays are introduced and extensively used.

• Digital chirp generator. The radar chirp concept of pulse frequency modulation was developed at the Bell Telephone Laboratories (at Whippany and Murray Hill, NJ) by J. R. Klauder et al. in the 1950s and first reported in the literature in 1960 (declassification of work supported by the US military). Early experimental work on radar signal design used the chirp, a linearly frequency-modulated (FM) pulse with a frequency range set by the required angular resolution, and with a pulse duration set for the required range resolution performance. By transmitting a modulated pulse, it was possible to obtain range resolutions that were smaller than the transmitted pulse length by very large factors. The reported technique employed the so-called “pulse compression technique” (covering a frequency range many times the inherent bandwidth of the envelope), permitting radars to transmit a pulse with about 100 times the energy of a short pulse with equivalent range resolution and peak

208) Note: JHU/APL was instrumental in developing the phased array radar technology for the US Navy whose construction began in 1959. A first prototype was installed on a Navy ship in 1961. See: A. Kossiakoff, “APL - Expanding the Limits,” Johns Hopkins APL Technical Digest, Vol. 13, No. 1, 1992, pp. 8-27


210) The term “chirp” was coined at the Bell Telephone Laboratories in the 1950s to designate a new and more effective radar signal generation method.
power. The cost of the chirp radar technique is that the pulse compression processing in the receiver section is numerically intensive.

Modern spaceborne SAR instruments are equipped with a **digital chirp generator**; this technique allows to generate pulses with a programmable slope and bandwidth. The resulting flexibility in terms of pulse duration and frequency-tuning capability allows the operation of the SAR system in different modes like a high-resolution narrow-swath mode, and a wide-swath low-resolution mode. Also, within one mode of operation, it is useful to adjust the chirp bandwidth according to the incidence angle in order to maintain a more constant ground-range resolution and a more homogeneous signal-to-noise ratio over the access region (the number of independent looks within a cell can be increased by modulating the chirp over the bandwidth). 211) 212) This method is used for example in the ASAR instrument of Envisat for the global monitoring and the wide-swath mode with its 5 different swaths. The chirp waveform (linear FM) is also used for better onboard processing of the radar signals including compression schemes.

- **SAR instrument design constraints.** General well-known major design constraints of spaceborne SAR missions are the antenna size and the availability SAR instrument power. Both factors limit the swath/resolution ratio, a key performance criteria. The lack of continuous sufficient transmission power is usually handled with the introduction of a so-called duty cycle, representing the fraction of the orbital period (i.e. instrument observation time), in which a power-hungry instrument can be operated. Some examples: ESA introduced duty cycles for the AMI instrument of its ERS-1/2 missions (10%-12%) and for ASAR (30%) of the Envisat mission (launch Mar. 1, 2002). The SAR instrument of RADARSAT-1 (launch Nov. 4, 1995) of CSA has a duty cycle of up to 28%. The PALSAR instrument of JAXA's (Japan Aerospace Exploration Agency, formerly NASA) ALOS (launch Jan. 24, 2006) features a duty cycle of about 70%.

- **Some design considerations of conventional (planar array) SAR antennas.** SAR antennas, like those of RadarSat-1, and -2, of ASAR (on Envisat), or of PALSAR (on ALOS), are rather heavy and bulky elements of a SAR instrument, their mass is in the range of 500-800 kg (representing about 90% of the total instrument mass). A typical size for a spaceborne L-band SAR antenna is 10 m x 2 m. Hence, the antenna design will remain a key technological challenge in SAR systems. Naturally, the features of large mass and volume translate directly into launch costs; hence, they are important design drivers, restricting the available choices for the satellite and its launcher. 213) 214) 215) At the start of the 21st century, there are some emerging alternatives on the horizon offering large light-weight deployable antenna designs using membrane technology in combination with the inflatable structure technology. Both can serve as the basis for large antenna applications on spacecraft.

<table>
<thead>
<tr>
<th>SAR Mission (launch)</th>
<th>System description</th>
<th>Antenna mass (approx. value)</th>
<th>SAR instrument electronics mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEASAT (1978)</td>
<td>L-band</td>
<td>103 kg</td>
<td>120 kg</td>
</tr>
<tr>
<td>ERS-1 (1991)</td>
<td>C-band</td>
<td>85 kg</td>
<td>AMI shared with SCAT</td>
</tr>
<tr>
<td>JERS (1992)</td>
<td>L-band</td>
<td>130 kg</td>
<td>90 kg</td>
</tr>
<tr>
<td>SIR-C (1994)</td>
<td>L/C-band, distributed phased array X-band, using a conventional waveguide array antenna (12 m x 0.4 m)</td>
<td>450 kg 50 kg</td>
<td>450 kg (4 radar channels)</td>
</tr>
</tbody>
</table>


212) Note: “Chirping” a signal or a wave means stretching it in time. In chirped pulse amplification, the first step is to produce a short pulse and stretch it. The stretched pulse has low intensity, allowing it to be amplified again; thus, boosting the peak intensity. A “chirped pulse” is frequency modulated.


<table>
<thead>
<tr>
<th>SAR Mission (launch)</th>
<th>System description</th>
<th>Antenna mass (approx. value)</th>
<th>SAR instrument electronics mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envisat (2002)</td>
<td>C-band, electronic beam steering</td>
<td>832 kg (total ASAR mass)</td>
<td></td>
</tr>
<tr>
<td>ALOS (2006)</td>
<td>L-band, electronic beam steering</td>
<td>500 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td>TerraSAR-X (2007)</td>
<td>X-band, electronic beam steering</td>
<td>394 kg (total TSX-SAR instrument mass)</td>
<td></td>
</tr>
<tr>
<td>Radarsat-2 (2007)</td>
<td>C-band, electronic beam steering</td>
<td>850 kg (total SAR instrument mass)</td>
<td></td>
</tr>
<tr>
<td>TecSAR (2007)</td>
<td>X-band, electronic beam steering</td>
<td>100 kg (total SAR instrument mass)</td>
<td></td>
</tr>
<tr>
<td>TerraSAR-L (2008)</td>
<td>L-band, electronic beam steering</td>
<td>~920 kg (total L-SAR mass), very large antenna of 11 m x 2.9 m or 31.5 m²</td>
<td></td>
</tr>
</tbody>
</table>

Table 18: Overview of approximate masses of some spaceborne imaging radar systems

- **SAR data archive.** ESA operates and maintains a long-term and continuous archive of spaceborne SAR data from every continent (since 1991). It is probably the largest civilian SAR data archive in the world. This archive represents a unique source of reference imagery and can for instance be used to generate interferograms to identify and locate damage in the wake of a disaster.

- **Introduction of spaceborne SAR reflector antenna designs (curved apertures).** These antenna designs are relatively new in SAR observations compared to conventional flat panel antennas (also referred to as planar arrays) with electronic beam steering. Reflector antennas can provide observation support in the conventional support modes of: Stripmap, Spotlight and ScanSAR. Use of reflector antennas is seen in such applications as: surface mapping, rain radar, [soil moisture and ocean salinity radiometers], hazards monitoring, etc. Possible scanning technologies for such reflector designs are: a) spin-scanned reflector, b) spin-scanned feed, or c) pushbroom. The large reflector designs are generally of the deployable type; the conventional mechanical designs feature mostly a surface mesh (or dish) structure, while future inflatable structures may select the lighter membrane structure. The smoothness of the deployed reflector surface and its accuracy to required shape are of considerable importance in these antenna designs for high-quality observation performance.

Some SAR reflector antenna implementations are:

- **The Condor-E commercial SAR mission,** under construction at NPO Machinostroyenia (Reutov, Moscow region, with a planned launch in 2004), employs an antenna design concept using a large space-deployed **SAR reflector antenna** (parabolic configuration of 6 m diameter) with a cross-track pointing capability (see also chapter B.1 and Figure 113 for Condor-E).  

  The parabolic reflector antenna is mounted in the along-track direction of the S/C with an antenna look direction toward nadir. The reflector antenna configuration permits the SAR observing pattern to be dynamically redirected in the cross-track direction (the ground target observation capability is symmetrical to either side of the spacecraft). The concept employs a central electronically steerable phased array feed system at the focal point of the antenna (including a master oscillator and phase modulator linked to the S/C), using the antenna reflector to direct the outgoing radar signals and measuring the incoming echo (both signal streams, forward and return, are being reflected by the antenna; the antenna itself is only partially illuminated). Thus, a FOR (Field of Regard) within the incidence-angle range of 20-55º to either side of the spacecraft ground path may be observed. [Note: A sidelobe suppression problem might arise within this elegant SAR reflection configuration due to the curvature of the parabolic antenna].

- A similar large-diameter parabolic reflector (SAR antenna) design concept is also being employed on the US DoD Lacrosse/Onyx satellite series (X-band radar imaging reconnaissance program of NRO; manufacturer of spacecraft: Lockheed Martin). The prototype program and spacecraft of the series, referred to as Indigo, was launched in January 1982 (built by Martin Marietta Company). The first operational satellite, Lacrosse-1, was

216) Note: In 2003, the realization of project Condor-E became questionable.
launched Dec. 2, 1988 from Shuttle flight STS-27. Lacrosse-2 was launched from VAFB on March 8, 1991; the launch of Lacrosse-3 took place on Oct. 24, 1997, while Lacrosse-4 was launched on a Titan-4 vehicle from VAFB on Aug. 17, 2000 into a 680 km orbit at 68° inclination. Generally, two Lacrosse missions are kept operational for high-resolution SAR image recovery. The classified nature of the military program doesn’t permit any specifics.  

- The Cassini-Huygens deep space mission to Saturn and its moons, a joint venture of ESA, NASA/JPL, and ASI (Italian Space Agency), launch Oct. 15, 1997, employs a single high-gain 4 m diameter parabolic Cassegrain reflector. The radar instrument (five-beam Ku-band antenna feed assembly, 13.78 GHz) can operate in three ways: imaging, altimetry, and radiometry.  

- The USSR SAR missions Venera-15 (launch June 2, 1983) and Venera-16 (launch June 7, 1983) were flown to Venus with the objective to study the surface properties of the planet. Both S/C were identical, each carried an S-band SAR instrument with a parabolic dish antenna of 6 m diameter, permitting observations to either side of the ground track. In SAR mode, the antenna transmitted a code sequence of 127 pulses, each of duration 1.54 μs. After transmission, the antenna was switched to the receiver, which recorded the reflection of the radar pulses from the surface over a period of 3.9 ms.

- The satellite constellation, a German military mission with a spacecraft and SAR instrument design of OHB Bremen (launch of first S/C in constellation of 5 on Dec. 19, 2006), features also a parabolic SAR reflector antenna of 3 m diameter (see I.9). The fixed parabolic SAR antenna (used either for SAR observations or for RF communications of payload data) is integrated into the S/C design in such a fashion as to permit agile maneuvers of each satellite. This in turn implies a large FOR coverage capability into either the right or left cross-track direction for event observations (an important mission objective). Within this FOR, the spotlight (5 km x 5 km) or the stripmap (8 km x 60 km) observation modes can be conducted freely. In spotlight mode, the entire spacecraft (with a fixed antenna) is rotated to increase the integration time of the scene (increase of resolution in flight direction).

- At the start of the 21st century, the SAR technology can provide measurements that are key to the following applications:
  - Water cycle (e.g. soil moisture and water level)
  - Global ecosystem (biomasse estimation, land cover change)
  - Ocean circulation and ice motion
  - InSAR techniques can provide very accurate and systematic measurements of surface deformation and surface strain accumulation due to seismic and volcanic activity.

### 1.2.3.2 Radar (microwave) instrument classes in Earth observation

Radar systems for SAR applications may be classified by the signal measurement technique employed — there is the **pulse-modulated radar** class and the **FMCW** (Frequency Modulated Continuous Wave) radar class (the latter is also referred to as FM-CW). Each of these classes employs different principles with respect to the signal measurement technique. In a pulse-modulated radar system, the radar platform is considered to be stationary during the signal run time (transmission and reception of a pulse sequence). This stop-and-go approximation is valid because pulse-modulated radar systems employ very short pulses (the phase of the reflected signal changes). — On the other hand, FMCW radars transmit relatively
long sweeps (the frequency spread is typically made by means of a linear sweep of a signal having constant amplitude); the stop-and-go approximation may not be valid. Hence, the additional phase change due to the platform motion must be accounted for. Pulse-modulated radars measure range in the time domain; FMCW radars measure range in the frequency domain. For both measurement techniques (pulse-modulated and FMCW radar) the generation of SAR images requires the coherent combination of the echoes recorded. The orbital movement of the SAR platform with a certain constant speed introduces a Doppler effect, which is implicitly exploited in enhancing the image resolution in the direction of the movement.

The pulse-modulated radar is the most widely used type of monostatic radar systems. It is so called because the transmitter sends out pulses of microwave energy with relatively long intervals (listening periods) between pulses. The actual pulse duration (pulse width) in the energy transmission sequence is in the order of ns to ms. The receiver picks up the echoes of the returned signals; the elapsed time (or run time) is a measure of the distance travelled. Basic characteristics of pulse-modulated systems are:
- The peak power is generally many times greater than the average power
- The range resolution of a pulsed radar system is limited fundamentally by the bandwidth of the transmitted pulse (the wider the bandwidth, the better the range resolution).

The CW (Continuous Wave) radar system transmits continuous microwave energy at a known frequency. The return signals from the target area are shifted away from this base frequency via the Doppler effect. By measuring this change of the Doppler Shift, caused by motion of the transmitter, target or both, the speed of the object can be determined. However, this measurement configuration requires a separate receiving antenna in addition to the transmission antenna (i.e. bistatic), otherwise there is no basis for the measurement of the time delay (the resultant continuous echo cannot be associated with a specific part of the transmitted signal) in this arrangement. A disadvantage of conventional CW systems is that they cannot measure range (distance).

More recent and more sophisticated FMCW instrument designs, known as: 1) LFM (Linear Frequency-Modulated), and 2) FSK (Frequency Shift Keying) CW waveform radar, are also able to measure range (and of course the range rate). The range measurement is being done by tagging each part of the transmitted microwave signal (by continuously changing the frequency), rendering it recognizable upon reception. With the rate of frequency change known, the difference in frequency can be interpreted as a range measurement. Both configurations, CW and FMCW, are by nature bistatic systems, see chapter 1.2.3.6.

At the start of the 21st century, the capabilities of an emerging FMCW SAR imaging technology experience a new interest by the Earth observation community; the technique has the following advantages as compared to the classical pulse-modulated waveform procedure: 220)
- A considerably lower transmission power can be used due to the better efficiency of the continuous wave concept (the peak power is the same as the average power). The FMCW method can provide peak performance in both accuracy and sensitivity
- A higher bandwidth of the microwave signal can be used — resulting in a better reflection separation and a reduction of noise
- A smaller antenna size can be used for the same measuring range geometry
- The FMCW technology results in simpler and more compact (cost effective) instrument designs
- Lower data rates (resulting in smaller data volumes) are inherent with the use of the FMCW technique.

The state-of-the-art FMCW radar technology experiences already an introductory or operational status in such fields as ground-based industrial precision measurement applica-

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Earth Observation History on Technology Introduction

Electronic beam steering is a technique that applies the radar signal with a different phase shift to different parts (elements or panels) of the antenna. In this approach the SAR antenna design consists of several separate radiating parts. The method requires to apply the correct relative phase shift to each element and to maintain synchronization. This action causes the beam to point into the desired direction (the choice of the phase difference between two radiators defines the direction in which the phase front will propagate). Naturally, the antenna elements have to send a signal in that direction as well as to obtain the return information (echoes).

The conventional technique of electronic beam steering (or electronic scanning) with analog (i.e. RF) beamforming technology is based on the constructive/destructive interference concept (by stimulating individual elements or groups of elements within the array). The electromagnetic energy received at a point in space from two or more closely spaced radiating elements is a maximum when the energy from each radiating element arrives at a point in phase. Positioning the antenna beam to a specific angle off the antenna boresight axis is accomplished by applying a phase shift to the specific set of array elements which shift the angle of constructive interference.

The method of electronic beam steering of a phased array SAR antenna permits for some current operational systems the extension of the swath width with the use of the ScanSAR technique (instantaneous positioning of the radar beam), an important criteria in global coverage requirements. In particular, increased operational flexibility and functionality of the SAR instrument is provided in multi-mode operations support and in multi-target tracking capabilities.

Several techniques exist to apply the phase shift to the signal. 224)

1) **Time delay scanning.** By making the feed line to a certain antenna element longer or shorter, a time delay and thus a phase delay is introduced. This is mostly obtained by switching line sections in and out of the feed line, using diodes or using MEMS (Micro Electro Mechanical Switches).
   - Use of time delay to achieve the desired phase relationship
   - Time delay networks installed in front of each radiating element
   - Expensive, complex and heavy

2) **Frequency scanning.** By designing the feed lines to each of the radiating elements all with a different length, the phase shift to each element will change as the frequency of

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the signal that is sent is changed, for the line lengths are fixed but the wavelength changes.

- Simpler method
- The physical length of the wave guide is utilized to delay the frequency interval
- Vary the frequency about a base frequency. The receiver has to demodulate with the varying carrier frequency, that is the reason why the method is seldom used.

3) **Phase scanning.** By changing the properties of the medium in which the signal propagates, a phase shift can be obtained. This is mostly done by changing the permittivity ($\varepsilon$) or the permeability ($\mu$) of the medium. This changes the speed and the wavelength of the propagating wave in the medium and thus the phase at the end of the line.

- The radiating elements are fed by phase-shifting networks (phasers)
- The phasers are adjustable over a range of 0 to $2\pi$ radians
- More expensive than frequency scanning but cheaper than time delay
- The method is widely used.

Some spaceborne examples of system implementations with electronic beam steering are given. However, these systems provide **analog beamforming** (i.e. RF beam forming) which limits their beam steering capability to 1-D applications (see 1.2.3.8).

- Two Shuttle missions with the SIR-C/X-SAR payload in 1994, namely SRL-1 (STS-59, April 9 - 20, 1994) and SRL-2 (STS-68, Sept. 30 - Oct. 11, 1994), demonstrated phased arrays with electronic beam steering. The distributed C- and L-band SIR-C radars of JPL allowed electronic beam steering in range direction (elevation plane) permitting the acquisition of multi-incidence angle data.

- The SAR instrument of RADARSAT-1 of CSA (launch Nov 4, 1995) employs an electronically steerable active remote sensing radar antenna. A slotted waveguide array (and not a phased array) of 15 m x 1.5 m is used as the active microwave sensor. The azimuth beam pattern is fixed but the elevation angle of the main beam can be varied (the SAR instrument has seven beam modes to obtain different incidence angles from 10-60º) by the use of 32 variable phase shifters. Because the ferrite phase shifters are not reciprocal, they have to switch back and forth each time the antenna is switched between transmit and receive mode.

- ASAR (Advanced SAR) on Envisat of ESA (launch March 1, 2002) is an active phased array of size 1.3 m x 10 m with distributed T/R (transmit/receive) modules arranged across the antenna, such that by adjusting individual module phase and gain, the transmit and receive beams may be steered and configured (independent control of the phase and amplitude of the transmitted radiators from different regions of the antenna surface). The antenna array contains 20 tiles (each 1 m x 0.65 m in size) with 16 T/R modules each. Use of MMIC (Monolithic Microwave Integrated Circuit) technology, based on field effect transistors (FETs), for amplifiers, switches, attenuators, and phase shifters. ASAR also provides independent weighting of the received signal to each of these regions. Support of 37 different and mutually exclusive high-rate operating modes. In general, the use of digital technologies for signal generation and processing is implemented. These permit chirp versatility in terms of pulse duration and bandwidth required for the operational modes and various swaths of the instrument. Electronic beam steering is in elevation only, a phase-scanning implementation allowing observations at different incidence angles and alternating polarization modes providing simultaneous dual-polarized images.

- Background: Although the concept of spaceborne **phased array technology** was initially demonstrated on the SEASAT SAR instrument of NASA/JPL (launch June 27, 1978), it took a while before the concept of electronic beam steering found more applications in the 1990s. The early spaceborne SAR instruments such as SAR on SEASAT, or the AMI instruments on ESA's ERS-1/2 missions, employed a conventional passive phased array antenna.
On the other hand, an active phased array antenna design employs T/R modules to steer the beam in one direction (in elevation), thereby performing cross-track scanning. Active phased array technology is also being introduced in the communication satellite industry as well as in general communication downlinks from spacecraft. Examples: The Iridium constellation of nominally 66 satellites (Iridium Satellite LLC) was deployed (completed) in 1998. Each S/C carries three phased array panels. These allow each satellite to produce 48 fixed downlink beams. The EO-1 mission of NASA (launch Nov. 21, 2000) is flying XPAA (X-band Phased Array Antenna) as a communications experiment with the objective to demonstrate link-pointing capability with the use of a body-fixed low-mass and low-cost phased array antenna (see M.10).

The following advantages of electronic beam steering are expected, in particular for future spaceborne phased array systems, namely with the introduction of **digital beamforming (DBF) techniques** permitting instantaneous two-dimensional beam steering in elevation as well as in azimuth settings: 225)

- Electronic beam steering permits an antenna beam stabilization to compensate for roll and yaw angles of the platform. In addition, it enables true spotlight mode support to image a confined target area in high resolution, from varying aspect angles, and permits operation of different tasks in multiplex.
- Partitioning of the phased array antenna into multiple receiving subgroups in along-track substantially improves moving-target detection and estimation of motion and position parameters in the scene by exploiting the phase differences extracted from the different subgroups.
- Connecting the channels to antennas or subapertures in cross-track permits to extract height information of the imaged area using interferometric techniques. In contrast to conventional digital maps which show the height of the ground, this new method includes analysis of height information of vegetation canopy as well as of man-made structures/targets. In fact, the high-accuracy height measurement potential will eventually permit the detection of objects their mere elevation over ground level.
- Adaptive interference suppression. Steps against signal jamming can be taken by means of spatial jammer suppression. The distorted part of the SAR image is drastically reduced.
- For each pixel the polarimetric scattering matrix can be measured by assigning the channels to different transmit/receive polarizations. Hence, separation of target and clutter can be improved and target structures in SAR imaging can be supported.
- Real-time and near-real-time event recognition and subsequent event tracking in SAR scenes are rather desirable goals for spaceborne SAR systems, in parallel to conventional SAR imaging functions. These features are of importance in general surveying (monitoring of fires, volcanoes, floods, etc.) and in surveillance [MTI (Moving Target Indication)] applications. These operational support goals require in particular a high degree of onboard system processing capability and flexibility.

### 1.2.3.4 SAR interferometry (InSAR techniques in the microwave region)

Interferometric Synthetic Aperture Radar (IFSAR or InSAR) refers to active microwave fringe visibility phase measurements which are being used for moderate resolution imaging, polarimetry, and elevation mapping of planetary surfaces. Radar interferometers operate by independently detecting signals from two antennas (or from a single antenna in a repeat pass configuration) and combining them a posteriori for indirect fringe generation. This method involves heterodyne receivers which experience shot noise from their local oscillators - about 1 photon per Hz of bandwidth. However, this noise level is acceptable at microwave wavelengths.

225) [http://www.fhr.fgan.de/fhr/el/el_rsrch_sar00_e.html](http://www.fhr.fgan.de/fhr/el/el_rsrch_sar00_e.html)
SAR interferometry (see also O.9.1). Two interferometric observation concepts are in use: ‘single-pass’ and ‘two-pass’ (or multi-pass) interferometry. The InSAR principle relies on phase differences between repeat radar images and provides measurements of surface deformation in the satellite line-of-sight direction with sensitivities of a small fraction of the radar wavelength (sub cm level). The interferometric phase (or phase of the interferogram), i.e. the phase difference between the two images acquired with slightly different sensor positions, contains geometric information allowing the derivation of the 3-D position of the scattering element. The phase difference can be exploited to provide topographic height information, as well as changes on the Earth’s surface at cm scales. SAR interferometry techniques promise to produce global topography maps in a similar fashion as stereo photogrammetry. The InSAR technique is well suited to studying deformation associated with all phases of the seismic cycle, volcanic activity, and glacier flow.  

Simultaneous observation of the same footprint by two antennas in parallel (single-pass cross-track interferometry) separated at a distance (baseline) on the same spacecraft. Two separate images are received of the same ground track by two spatially-separated antenna systems (the interferometric baseline) to produce phase differences from slightly different viewing angles. DCS (Data Collection System of ERIM) is probably the first single-pass airborne InSAR instrument with first flights in 1987. TOPSAR (JPL) started its observations in 1991.

On the spaceborne side, the SRTM (Shuttle Radar Topography Mission, J.27) mission of NASA represents worldwide the first fixed baseline single-pass spaceborne InSAR (Interferometric SAR) system with simultaneous dual-polarization wide-swath scanning SAR and dual-frequency (C-band and X-band) coverage (Shuttle mission STS-99, Feb. 11-22, 2000). SRTM featured a fixed cross-track baseline which was achieved with separate receive antennas (X – and C – band) mounted on the tip of a 60 m long boom.  

The SRTM digital topographic map production objective (referred to as C-RADAR) calls for a spatial pixel (30 m x 30 m) posting with a 16 m absolute vertical linear accuracy and 20 m absolute horizontal radial accuracy at 90%. High-quality DEM mosaics of entire continents have been generated with the SRTM data from the JPL C-band radar and the DLR/ASI X-band radar, both systems operated in parallel.

Two-pass (multi-pass) measurements of a single-antenna SAR platform. The measurement of ground deformations from space (a historic perspective on two-pass SAR interferometry). Spaceborne SAR instruments can indeed detect barely perceptible movements of the Earth’s surface (after analysis and comparison of the data). In the 1990s, the value of SAR imagery experienced a considerable boost with the correct processing and interpretation of the phase and amplitude information in the SAR data. Superimposing SAR imagery obtained from different epochs (possibly from nearly identical observation positions of a single satellite) of the same surface area results in the ability to detect very small (centimeter-scale) movement of land surface features on the Earth (slipping faults, surging glaciers, bulging volcanos, etc.). In general, the single-antenna SAR repeat-pass technique is limited to observations to regions of low vegetation cover due to surface changes (such as vegetation growth) between passes. In addition, differences in atmospheric water vapor between passes may cause errors in the elevation models.

Some early examples of the technique of “repeat-pass interferometry” are:

229) http://www.jpl.nasa.gov/srtm/
- In 1974, L. C. Graham of Goodyear Aerospace first demonstrated that it was possible to take advantage of the phase measured by airborne radar (he took phase measurements and the conventional amplitude measurements of SAR images). He was the first to report experiments to determine terrain elevation of the Earth’s surface by repeat-pass interferometry.

- In the early 1980s, scientists at NASA/JPL showed that they could extract similar results from the phase measured by SEASAT, the first civilian radar satellite, which was launched in 1978 (but worked for only three months). They did so by comparing two radar images taken from roughly the same position but at different times. In a sense, that exercise was akin to taking two widely separated frames of time-lapse photography. Although the phase itself appeared random every time, the phase differences between corresponding pixels in the two radar images produced a relatively straightforward interference pattern.

- **Derivation of the first interferometric maps of the co-seismic displacement of the 1992 Landers earthquake.** Didier Massonnet of CNES and his colleagues produced a striking image of ground displacements caused by the magnitude 7.3 Landers earthquake, which struck south-eastern California (about 150 km east of Los Angeles) on 28 June 1992. For their demonstration, they assembled all the radar images of the area available from the ERS-1 satellite and formed several interferograms by combining one image taken before the earthquake with another one taken afterward from approximately the same position. Because the satellite tracks were never identical, the rugged relief in the region affected these interferograms markedly. Yet with the help of a digitized map of elevations, they were able to calculate the topographic contribution and remove it. Doing so unveiled a tantalizingly rich picture of interference fringes. But were these colored bands truly showing what the earthquake had done to the surface of California’s Mojave Desert? - Massonnet and his colleagues tested their representation of tiny ground movements by calculating an idealized interferogram based on measurements that geologists had made for the motion along the main fault. The model interferogram showed a striking resemblance to the radar pattern obtained by analysis. Geodesists around the world were struck by the remarkable detail visible in the image, which resembled the displacement pattern predicted by theoretical models of such an earthquake.

- Also in 1992, Richard M. Goldstein of the JPL and his co-workers used radar interferometry to track the movement of glacial ice in Antarctica. They took advantage of an exceptional opportunity presented by the ERS-1 satellite when it passed within a few meters of the path it had followed six days previously. Because the satellite had taken “before” and “after-the-event” radar images from virtually the same position, the topography of the glacier did not influence the pattern of fringes, and the resulting picture directly indicated the motion of the ice. That image displayed movement of an ice stream (where flow is relatively rapid) in superb detail.

- In 1993, Massonnet and his colleagues conducted a further demonstration of small deformation detection by radar interferometry. They experimented with a set of radar imagery of the Mount Etna volcano in Sicily. At the time, the volcano was nearing the end of an

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eruptive cycle during an 18-month period in 1992 and 1993 when the ERS-1 satellite passed over it 30 times. With those many radar images and an elevation map of the area, they were able to produce dozens of interferograms that were free from topographic effects. Some of the results were clearly degraded by changes in vegetation on the flanks of the volcano (certain pairs of images used in constructing these interferograms spanned many months; others encompassed more than a year). Nevertheless, they were able to follow the deflation of Mount Etna, as the last of the magma erupted and the pressure within the mountain declined. The radar images showed that Mount Etna subsided by 2 cm/month during the final seven months of eruption. This deformation extended for a large distance around the volcano, suggesting that the subterranean magma chamber was much deeper than geologists had previously thought. The great interest in SAR interferometry is due in large part to the quantity and quality of interferometric products made available from the ERS-1 mission.

- ESA’s ERS-1/2 tandem mission (start in Aug. 1995, end in May 1996) is considered the first SAR interferometry formation flight. The prime objectives were focused on the collection of SAR data pairs for exploitation in interferometry, together with the synergistic use of instruments on the two platforms. The configuration was that of two-pass measurements of a single-antenna SAR platform (the same SAR instrument on both satellites observing the same area on the ground), permitting the superposition technique of imagery (in data processing) of fairly close repeat tracks. The ERS-1/-2 tandem mission was flown with a one day delay of a coinciding ground track of the second S/C, providing good interferometric results. About 110,000 ERS SAR scene pairs have been acquired during the nine months period, covering nearly the total global land surface. The data of the tandem mission permitted the generation of DEMs (Digital Elevation Models), also over vegetated land surfaces. Over forests, however, many data sets had to be averaged to gain a DEM of acceptable quality. The SRL-1/2 missions of NASA in 1994 (April 9-20 for SRL-1, Sept. 30 - Oct. 11 for SRL-2) employed two-pass (and repeat pass) interferometry for topographic mapping (detection of topographic surface change in SRL-1 and SRL-2). The C-band SAR instruments of the ERS-1/2 and RADARSAT-1 (launch Nov 4, 1995) missions demonstrated the ability to detect cm-scale surface strain over large contiguous areas. The L-band SAR of JERS-1 (launch Feb. 11, 1992) demonstrated also two-pass SAR-interferometry for change detection.

- ERS-1/2 InSAR data were also used by USGS to study magma body systems by mapping the surface deformation and modeling the observed deformation (same technique as employed by Massonnet). InSAR measures the corresponding phase difference resulting from the difference in the round trip path length to the same ground point between two synthetic aperture radar (SAR) images. The phase difference is due mainly to five effects: 1) differences in the satellite orbits in the two passes, 2) topography, 3) ground deformation, 4) atmospheric propagation delays, and 5) systematic and environmental noise. Knowledge of the position and attitude of satellites is required to remove the effect caused by the differences in the satellite orbits of the two passes. The topographic effects in the interferogram can be removed by producing a synthetic interferogram based on an accurate DEM and subtracting it from the interferogram to be studied. This results in a deformation interferogram. The component of ground deformation along the satellite’s look direction can potentially be measured with a precision of from sub-centimeters to centimeters using the C-band

ERS-1/2 SARs. InSAR studies at six Alaska volcanoes were conducted, including New Trident, Okmok, Akutan, Kiska, Augustine, Westdahl, Peulik, Shishaldin, and Seguam.

The ERS-1/2 Tandem Mission\textsuperscript{240} was particularly interesting for POD (Precise Orbit Determination): a unique occasion of having two altimetric satellites flying the same orbit. With ERS-2 enjoying an abundance of tracking through SLR and PRARE (operational on ERS-2 only), these inputs were used to improve the ERS-1 orbits in simultaneous orbit determinations. Dual-satellite altimeter crossover height differences were used as a kind of satellite-to-satellite tracking data type, linking the two orbits. See also 1.8.3.8 for POD description.

- MAMM (Modified Antarctic Mapping Mission), a joint CSA/NASA interferometric mapping mission of Antarctica in the period Sept. 3 - Nov. 14, 2000, using RADARSAT. The overall objective of MAMM was to acquire repeat-pass interferometry to estimate ice surface velocity of the outer regions of the continent, north of 81º S. The science objectives called for SAR mapping of the Antarctic continent over three consecutive 24-day repeat cycles. See D.35.3

- AT-InSAR (Along-track Interferometric SAR) or ATI - motion sensing\textsuperscript{241}\textsuperscript{242}\textsuperscript{243} An along-track InSAR refers to a synthetic aperture radar instrumentation of two antennas, separated by a fixed distance, observing along-track, i.e. in the flight direction (a single-pass along-track interferometry configuration). Both antennas image the same footprint simultaneously, but with a short time lag in the acquisition of the two images, due to the baseline difference, results in a phase difference, which is proportional to the Doppler shift of the backscattered signal, and thus to the line-of-sight velocity of the scatterers. The phase difference image can thus be converted into a velocity map. Hence, the ATI technique offers beside other observations also direct velocity measurements [not available from the conventional cross-track InSAR (CT-InSAR) intensity image].\textsuperscript{244}\textsuperscript{245}\textsuperscript{246}\textsuperscript{247}\textsuperscript{248}\textsuperscript{249}\textsuperscript{250}

A number of experiments/campaigns, employing the AT-InSAR measurement technique, have shown a potential for oceanic and coastal applications, offering the promise of synoptic current measurements. AT-InSAR measurements have also been found to be useful for estimating bathymetry variations in shallow coastal waters, and for estimating surface wave spectra.

\textsuperscript{240} R. Scharroo, P. N. A. M. Visser, “ERS Tandem Mission orbits: is 5 cm still a challenge?” URL: http://www.deos.tudelft.nl/general/publicat/1997/Papers/florence/


\textsuperscript{246} J. Schulz-Stellenfleth, S. Lehner, R. Bamler, J. Horstmann, “A model for ocean wave imaging by a single pass cross track interferometric SAR (INSAR) - The SINEWAVE experiment,” IGARSS’98, Vol. II, 98CH36174, Seattle, WA, July. 6-10, 1998, pp. 962-964


\textsuperscript{249} Note: ATI is not based on a certain interferometric baseline but on the time lag between two moving SAR instruments separated in along-track direction and imaging the same terrain. A severe limitation of single-satellite ATI is caused by the physical dimensions of the spacecraft bus. The shorter the time lag, the coarser the resolution of velocity measurement.

The principle of AT-InSAR ocean current measurements was first demonstrated with the airborne AirSAR system of NASA/JPL in the late 1980s and early 1990s. However, the data processing and interpretation at the time was not properly understood. In the meantime, further AT-InSAR (as well as CT-InSAR) projects were conducted or are underway to test more performance aspects in the field. Examples are:

- Spaceborne ATI has successfully been demonstrated on the SRTM mission (STS-99 in 2000) of NASA/DLR/ASI. The along-track separation of the two SAR antennas of the SRTM was about 7 m (60 m in cross-track).

- The TerraSAR-X mission of DLR/EADS-Astrium (launch June 15, 2007). For ATI (Along Track Interferometry) support, the SAR antenna can be grouped into two segments, each of 2.4 m. The antenna transmits at full aperture and is capable to receive in two along-track half apertures. Ideal ATI time lags for oceanic current measurements at X-band should be on the order of a few milliseconds, i.e. about 20 times longer than this; thus, the sensitivity of TerraSAR-X to small ocean current variations will be quite low.

A completely different approach is proposed/planned in the spaceborne ICW (Interferometric Cartwheel) mission of CNES. The ICW concept employs a bistatic constellation of three passive microsatellites, each equipped with a receiver dish antenna (a slave receiver), to co-orbit with a conventional SAR mission (Envisat, RADARSAT-3) as “illuminator.” Such a co-planar constellation offers InSAR by definition (same footprint observation of all S/C), providing AT-InSAR as well as CT-InSAR measurements [see Ref. 307 and 308].

Complex data processing: The processing of ATI data requires accurate knowledge of the location of the phase centers of the antennas, motion compensation, correction for cross-track baseline components, etc. At the start of the 21st century, there is an improved understanding of the complex signature mechanisms/factors involved making interpretation of the data more reliable. According to model results, high radar frequencies, such as X-band, VV polarization, and incidence angles of \( \geq 45^\circ \) are preferable for ATI current measurements. The ATI time lag must be shorter than the coherence time of the backscattered signal, but long enough to obtain significant, detectable phase differences.

1.2.3.5 Scatterometry - the microwave measurement of wind fields

Surface wind fields (speed and direction) are an important observable in a wide variety of atmospheric and oceanic processes. They are required, for instance, to drive ocean models and to validate coupled ocean-atmosphere global models. Operational prediction of ocean circulation relies heavily on accurate knowledge of wind forcing. As the largest source of momentum for the ocean surface (input of momentum via surface stress), winds affect the full range of ocean movement - from individual surface waves to complete current systems. Winds over the ocean modulate air-sea exchanges of heat, moisture, gases, and particulates. This modulation regulates the interaction between the atmosphere and the ocean, which establishes and maintains both global and regional climates. One of the


important applications of surface wind observations is to increase the accuracy of weather analysis and forecasts and to improve NWP (Numerical Weather Prediction).

Conventional wind field measurements over the ocean are performed by a set of radar cross-section measurements at different azimuth view angles over the resolution cell, and by inverting the backscatter model, a so-called GMF (Geophysical Model Function), to extract the wind information, using the azimuth anisotropy of the radar backscatter of the sea-surface in the presence of wind.

Background: Scatterometry has its origin in early radar applications in World War II. These radar (microwave) measurements over oceans were corrupted by sea surface clutter (noise). It was not known at that time that the clutter was the radar response to the winds over the oceans. The radar response was first related to wind in the late 1960’s - by realizing that the sea surface roughened by the wind modifies the surface backscatter (reflected signal or echo) properties. Initial experiments of marine wind measurements began with a scatterometer [S-193, also referred to as RADSCAT (Radiometer/Scatterometer)] on Skylab of NASA in 1973 and in 1974. This was followed by SASS (SEASAT-A Satellite Scatterometer) on SEASAT (1978), the first S/C to measure sea surface wind vectors on two simultaneous swaths of 500 km (with a nadir gap of 350 km). SASS had two stick dual-polarization antennas on each side of the S/C. Typically, the SASS instrument achieved a wind speed accuracy of 1.6 m/s with respect to buoy measurements. Today’s scatterometers are flown on such missions as ERS-2, QuikSCAT and ADEOS-II, providing global wind fields.

Note: Communications with the ADEOS-II spacecraft stopped on Oct. 24, 2003, just after 7 months of Earth observation activities. A power failure is cited for the termination of the mission (due to very high solar flare activities). The satellite’s planned lifetime was three years. Japanese experts analyzed the possible causes of the failure. The most probable cause is that a short- or open-circuit failure occurred on the solar array paddle. Also, a space environment analysis demonstrated that the > 30 keV electron flux was two orders of magnitude higher than normal. In any case, the anomaly caused a permanent power outage when ADEOS-II was orbiting over the North Pole region – an end of the mission.259)

Scatterometers are active microwave instruments260) (radars that measure the target reflectivity or backscatter over a wide range of incidence angles; values are reported in terms of the normalized radar cross section, σº) offering a capability of wind speed and direction determination. Scatterometers operate by acquiring multiple spatially and temporally colocated measurements of backscattered power from different viewing geometries. The known relationship between cross-section, wind velocity, and viewing geometry is then used to estimate wind speed and direction.

Newer data analysis reveals that passive microwave instruments (i.e., radiometers) with V/H polarization capability, in operation or under development, like SMM/I and SSMIS (successor of SSM/I) on DMSP, Windsat on Coriolis and CMIS (Conical-scanning Microwave Imager/Sounder) on NPOESS, also have the ability to sense ocean surface wind speed and direction, among other parameters (like SST).261)262) The microwave radiation that is emitted by the wind-roughened ocean surface and measured by passive radiometer sensors shows a distinct signature with respect to the wind vector (the satellite brightness temperature measurements are space and time collocated with the wind vectors).

An overview of operational and emerging and complementary techniques for wind retrieval measurements are:

261) Note: Wind retrievals are also available from SSM/I, flown since 1987 on the DMSP series. However, the design of SSM/I, a microwave radiometer, only permits the retrieval of the speed component of the wind vector.
Earth Observation History on Technology Introduction

- Scatterometers (can be regarded as quasi-operational instruments at the start of the 21st century, their windfield measurements are used in global-scale meteorological models). The spatial resolution of today's scatterometer windfields turn out to be rather coarse, in the order of 15 to 25 km, quite suitable for open ocean observations, but not as suitable for coastal regions with more variability of wind patterns.

- Polarimetric radiometers (emerging wind retrieval applications)

- SAR instruments (SAR meteorology) is an emerging field with the potential of providing high-resolution wind fields. In addition, the SAR observation technique provides a means to image ocean waves. Unlike other techniques — wavebuoys, altimetry — SAR provides more complete information on the wave field, the spectrum, rather then some data at a view discrete points. Like polarizations (HH or VV) are needed to map and model ocean waves.

- Altimeter data. The altimeters of the missions: TOPEX/Poseidon, ERS-2 and GFO provide routinely along-track measurements of wind speed (no direction) and significant wave height (SWH) since 1992, 1995 and 1999, respectively.

- GPS reflection data from ocean surfaces (see chapter 1.5.6)

- The GIFTS (Geostationary Imaging Fourier Transform Spectrometer) wind system uses the retrieved moisture fields on constant altitude surfaces to identify gradients for motion vector calculation. This represents a novel approach to wind tracking, since it eliminates the vector height assignment issue (often the largest source of error). The ocean surface wind vector is a key parameter in understanding the weather due to its dominant role in the energy exchange at the air-sea interface. Winds over the ocean modulate air-sea exchanges in heat, moisture, and gases regulating much of the global weather.

The data analysis of the PR (Precipitation Radar) sensor on TRMM, designed for the measurement of the precipitation profile in the atmosphere, has shown that wind speed and direction can also be obtained from other instruments than scatterometers. The reason is that PR also measures the normalized radar cross section \(\sigma^0\) of the Earth’s surface. The small incidence angles of the PR beam and the single look capability of its cross-track scan geometry may act to limit its wind retrieval potential using traditional scatterometer techniques. Nonetheless, the small horizontal footprint and vertical range gate of the PR offer other advantages over the conventional scatterometer systems presently in use. More important, the potential addition of wind sensing capability to the TRMM PR complements in fact its rain profiling skills in providing coincident wind and rain observations at the same high spatial resolution, which represents a significant improvement in science value over the individually generated wind and rain measurements using separated sensors at different spatial resolutions.

Background: For a given wind speed and direction and radar geometry, the NRCS (Normalized Radar Cross-Section), an aspect of ocean surface reflectivity, also referred to as \(\sigma^0\) can be predicted using empirically-derived geophysical model functions. Unfortunately, the inverse is not true. A given NRCS does not correspond to a unique wind speed and direction pair. Many different wind speed and direction pairs could produce a particular NRCS. - Measuring the sea surface NRCS from a number of different aspect and incidence angles...
dent angles limits the number of potential solutions and alleviates this inversion difficulty. This multi-measurement approach to inversion is the basis of conventional spaceborne radar scatterometer measurements of the wind vector (Ref. 182). 268)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch Date</th>
<th>Spatial Resolution (km)</th>
<th>Swath Width (km)</th>
<th>Frequency GHz (Band)</th>
<th>Polarization</th>
<th>Data Rate (kb/s)</th>
<th>Altitude, Inclination (km/º)</th>
<th>Sensor, Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skylab</td>
<td>14.5.73</td>
<td>16</td>
<td>180</td>
<td>13.9 (K u)</td>
<td>VV,HH</td>
<td>5.33</td>
<td>435, 50º</td>
<td>S-193</td>
</tr>
<tr>
<td>SEASAT</td>
<td>27.6.78</td>
<td>50</td>
<td>500 x 2</td>
<td>14.6 (K u)</td>
<td></td>
<td>800/108º</td>
<td></td>
<td>SASS</td>
</tr>
<tr>
<td>Spacelab-1</td>
<td>28.11.83</td>
<td>50</td>
<td>500</td>
<td>5.3 (C)</td>
<td>LV</td>
<td>785, 98.5</td>
<td></td>
<td>M RSE, Shuttle</td>
</tr>
<tr>
<td>ERS-1 (Fanbeam)</td>
<td>17.7.91 to May 1996</td>
<td>50</td>
<td>500</td>
<td>5.3 (C)</td>
<td>LV</td>
<td>785/98.5</td>
<td></td>
<td>AMI in Scat. mode</td>
</tr>
<tr>
<td>ERS-2 (Fanbeam)</td>
<td>21.4.95</td>
<td>50</td>
<td>500</td>
<td>5.3 (C)</td>
<td>LV</td>
<td>785/98.5</td>
<td></td>
<td>AMI in Scat. mode</td>
</tr>
<tr>
<td>ADEOS</td>
<td>17.8.96</td>
<td>25,50</td>
<td>600 x 2</td>
<td>13.99 (K u)</td>
<td>VV,HH</td>
<td>2,9</td>
<td>797/98.6º</td>
<td>NSCAT</td>
</tr>
<tr>
<td>QuikSCAT</td>
<td>19.6.99</td>
<td>50</td>
<td>1800</td>
<td>13.4 (K u)</td>
<td></td>
<td>40</td>
<td>803/98.6º</td>
<td>SeaWinds</td>
</tr>
<tr>
<td>Envisat</td>
<td>1.3.2002</td>
<td>28 m x 30 m</td>
<td>5 km vignet, 7 subswath</td>
<td>5.33 (C)</td>
<td>VV or HH</td>
<td>900</td>
<td>800/98.6º</td>
<td>ASAR in wave mode</td>
</tr>
<tr>
<td>ADEOS-II</td>
<td>14.12.02</td>
<td>50</td>
<td>1800</td>
<td>13.4 (K u)</td>
<td></td>
<td>20</td>
<td>803, 98.6º</td>
<td>SeaWinds</td>
</tr>
<tr>
<td>Coriolis</td>
<td>6.1.2003</td>
<td>25</td>
<td>1400</td>
<td>6.8, 10.7, 18.7, 23.8, 37.0 GHz</td>
<td>Circular</td>
<td>5000</td>
<td>830, 98.7º</td>
<td>Windsat</td>
</tr>
<tr>
<td>MetOp-A</td>
<td>19.10.2006</td>
<td>50</td>
<td>2 x 550</td>
<td>5.255 (C)</td>
<td>VV</td>
<td>60</td>
<td>825, 98.7º</td>
<td>ASCAT (Fanbeam)</td>
</tr>
<tr>
<td>NPOESS</td>
<td>2011</td>
<td>15-50</td>
<td>1700</td>
<td>6-190 GHz (40 chan.)</td>
<td>V H, polariometric</td>
<td>280 kbit/s</td>
<td>833, 98.7º</td>
<td>CMIS</td>
</tr>
</tbody>
</table>

Table 19: Survey of spaceborne radar/microwave scatterometers (wind measurements)

Wind vector retrievals by today’s operational scatterometers (like AMI and SeaWinds) are based on indirect measurements, where the wind vector is inferred through a relationship between the backscattered power (NRCS), the small-scale ocean surface roughness, and the local wind vector at the ocean surface. This relationship is empirical, based primarily on matches between sensor measurements, buoy wind measurements and analysis from numerical weather prediction models. 269)

- The first spaceborne scatterometers were S-193 on Skylab (launch 1973) and SASS on SEASAT (launch June 28, 1978), followed by MRSE on Spacelab-1 and the AMI-SCAT (wind scatterometer mode) instrument on ERS-1 (launch July 17, 1991). 270) See Tables 19 and 20. The newer (since 1999) spaceborne wind vector measurement instruments can be put into three classes:
  - Broad-swath, dual-pencil beam active Ku-band scatterometers (e.g. SeaWinds)
  - Dual swath, 3-look active C-band scatterometers (e.g., ASCAT)
  - Dual- and single-look passive polarimetric radiometers (e.g., Windsat, CMIS)

With the launch of ADEOS-II (Dec. 14, 2002), there is the first opportunity since SEASAT to obtain collocated active microwave radar with SeaWinds-II and passive microwave radiometer data of AMSR (Advanced Microwave Scanning Radiometer) from the same platform. Note: Contact with ADEOS-II was lost on Oct. 25, 2003.

Traditional fanbeam scatterometer designs such as SASS, AMI-SCAT, and NSCAT require significant power and mass and have antenna systems which are difficult to accommodate.

aboard any spacecraft. The fanbeam systems employ multiple fixed antennas to cast broad fan-shaped beams on the Earth’s surface at multiple azimuth angles needed to measure wind. These designs have degraded wind performance limitations in particular in the near-nadir region of the measurement swath. The reason: the backscatter measurements in the region ±200 km to either side of the nadir track are at small incidence angles and are insensitive to wind direction, thus, creating a large “nadir gap” in their coverage.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sensor Provider</th>
<th>Frequency Band</th>
<th>Flown since</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta-K Spectrometer</td>
<td>IRI RAN, Moscow</td>
<td>X-band</td>
<td>1981</td>
</tr>
<tr>
<td>DUTSCAT</td>
<td>DUT/NLR, Holland</td>
<td>1.2-17.2 GHz (6 bands)</td>
<td>1983</td>
</tr>
<tr>
<td>ERASME</td>
<td>CNRS/CETP, France</td>
<td>C-band, X-band</td>
<td>1983</td>
</tr>
<tr>
<td>RACS</td>
<td>U. of Hamburg</td>
<td>C-band</td>
<td>1987</td>
</tr>
<tr>
<td>HUTSCAT</td>
<td>HUT, Helsinki</td>
<td>C-band, X-band</td>
<td>1988</td>
</tr>
<tr>
<td>MINISCAT</td>
<td>HUT, Helsinki</td>
<td>C-band</td>
<td>1990</td>
</tr>
<tr>
<td>C-SCAT</td>
<td>NASA/MIRSL</td>
<td>C-band</td>
<td>1990</td>
</tr>
<tr>
<td>RESSAC</td>
<td>CRPE, France</td>
<td>C-band</td>
<td>1990 (rebuilt ERASME)</td>
</tr>
<tr>
<td>NUSCAT</td>
<td>NASA/JPL</td>
<td>Ku-band</td>
<td>1991</td>
</tr>
<tr>
<td>RENE</td>
<td>CNRS/CETP, France</td>
<td>X-band</td>
<td>1992</td>
</tr>
</tbody>
</table>

Table 20: Overview of some airborne radar scatterometers

Figure 9: Rotating fanbeam scatterometer concept (RFSCAT)

Newer scatterometer designs employ the conical-beam scanning technique (with dual-beams). SeaWinds (of NASA/JPL on QuikSCAT, launch June, 19, 1999) introduced a scanning pencil-beam scatterometer with a dual-beam conical scan, provided by a 1 m diameter reflector (rotating dish) antenna. Although the pencil-beam approach adopted by SeaWinds significantly lessens the nadir gap problem by making measurements at suitably high
incidence angles, the problem is not completely eliminated. Measurements in the extreme inner and outer swath still suffer some degradation because the relative azimuth angles of backscatter measurements are too close together (approaching 0° for the outer swath), or are too far apart (approaching 180° for the inner swath) to determine the wind speed direction accurately. - A performance improvement is also introduced with the ASCAT instrument of ESA on MetOp-A of EUMETSAT, it employs a solid-state design and the use of a double-beam scanning technique. Scatterometer antenna and radar electronic concepts remain key technology issues in the design of efficient and low-cost instruments.

Beyond the original mission of spaceborne scatterometers to provide measurements of wind velocity over the ocean, a large number of applications of the radar data have emerged in such areas as: a) land applications, b) polar snow and ice, c) oceans and NWP (Numerical Weather Prediction), and d) polarimetric scatterometry. 271) 272) 273)

The capabilities of the next-generation polarimetric scatterometers are of particular interest (RFSCAT). They will be able to simultaneously measure the conventional co-polarized backscatter as well as the polarimetric correlation of the co- and cross-polarized radar returns from the ocean surface. 274) 275) 276) The technique promises potential performance gains by improving in particular the ambiguity resolution. Combined with the spacecraft motion of about 7 km/s of ground speed, large overlaps are produced by the successive sweeps. A pixel within the total swath, depending on its cross-track position, may be intercepted several times (up to 10 times) by the antenna footprint, first in the forward beam and later in the backward beam. The radar operates in a pulsed mode, so that each point of the echo profile can be attributed to a unique pixel position within the antenna footprint along the radial direction. The pixels in the radial direction are resolved by range-gating the radar echo. The following advantages of the fanbeam, multiple-beam concept and the conically scanning spot beam concept are provided:

- A large continuous swath can be achieved (order of >1500 km)
- A large number of azimuth views per pixel can be generated depending on the rotation speed and swath position
- The rotation speed of the antenna can be greatly reduced as compared to the conically scanning spot beam concept due to the large coverage of the fanbeam antenna
- A single, rotating fanbeam antenna is required (no switching is needed between different antennas
- Simple data processing is required (scan position and range dependent Doppler compensation, pulse compression, and look summations).

- **Estimation of the wind field from SAR NRCS (Normalized Radar Cross Section) imagery** poses a different challenge (Ref. 182). A SAR instrument measures NRCS at only one aspect angle and a unique wind vector solution is not possible. However, if the wind direction is known a priori, then wind speed can be determined. There are at least three ways to estimate wind direction: 1) determine wind direction from features in the SAR image, 2) use numerical weather forecast models, and 3) obtain wind direction from other space-

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borne instruments. What differentiates the various approaches are the NRCS model used and the manner to estimate wind direction. The ability to retrieve wind fields from SAR imagery, with the high resolution (< 1 km) and wide coverage (500 km), represents an important improvement for applications where knowledge of the wind field at fine spatial scales is crucial. SAR-derived wind fields can contribute to the usefulness of other SAR applications as well. For example, SAR winds can aid wave field retrieval by providing a first guess wind-wave spectrum. Algorithms for automated detection of oil spills and ships as well as ice identification can be improved with knowledge of the local wind field. 277) 278)

Examples of missions with wind retrieval from SAR data:

- For the ERS-1/2 SAR sensors (AMI in scatterometer mode) of ESA, which operate in VV polarization, the NRCS geophysical model function (GMF) comes from validated SCAT models.

- For the Canadian RADARSAT-1 SAR sensor, 279) 280) 281) 282) which operates in HH polarization, no such validated GMF models existed. A work-around for wind speed retrievals was found by compering SAR (RADARSAT-1) and SeaWinds scatterometer data (QuikSCAT). This involved comparison of SAR-derived wind speeds with SeaWinds wind speeds. When wind speed retrieval from SAR imagery is initialized with SeaWinds scatterometer wind directions, SAR wind speed retrievals are significantly improved.

- An investigation on the polarization effects on the SAR wind algorithms is being conducted with ASAR polarimetric data of Envisat (ESA, launch March 1, 2002). 283) SAR imagery permits also the study of mesoscale circulation systems such as polar low storms and hurricanes. In particular, SAR offers an effective way of centering the location of these systems at the ocean surface. SAR imaging of storm systems may also include patterns of convective cell activity, precipitation, cloud ice, and even storm-induced ocean swell. Other ocean features readily imaged by SAR and under active research include ocean fronts and mesoscale circulation, river plume outflow and coastal interaction, oceanic internal gravity waves, upwelling, biological activity, and near shore bathymetric features.

- Microwave rain measurement instruments. 284) First radiometer data evaluations with regard to rainfall started around 1975 using ESMR data of Nimbus-5 (launch Dec. 11, 1972) and later SMMR data of SEASAT (launch June 27, 1978). The SSM/I radiometer on the DMSP series is flown since 1987, rainfall is determined for sea surface regions. The airborne radiometer AMR (NASA, since 1995) is to confirm AMSR on ADEOS-II (launch Dec. 14, 2002). Active microwave instruments: CRL Radar/Radiometer (CRL Tokyo, since 1981), ARMAR (NASA/JPL, since 1992) is an airborne rain radar in support of the space-

277) Note: SAR imagery is not as extensive or complete as data from scatterometer or passive radiometric measurements, but offers the prospect of wind speed measurements in coastal areas where more conventional instruments fail.


284) L. J. Allison, et. al., “Tropical cyclone rainfall as measured by the Number 5 EMSR,” BAMS, Vol. 55, pp. 1074-1089, 1975
borne PR (Precipitation Radar) instrument on TRMM (launch Nov. 27, 1997). The TRMM mission represents the first concerted effort (NASA/NASDA) to tackle the complex nature of rainfall with a complement of passive and active sensors. - GPM (Global Precipitation Measurement), a follow-on mission to TRMM with a reference constellation of six to eight microsatellites and advanced rain-measuring instruments (passive microwave imaging radiometers), is in the design phase as of 2002/3 (NASA/JAXA). The goal of GPM is to provide precipitation rate on ground accurately and frequently from space with global coverage. - ESA also plans to join the project with EGPM (European GPM), the planned launch date is 2008/9. The EGPM instruments are: 1) a conical-scanning, multi-frequency microwave radiometer (18.7 - 157 GHz, a passive instrument), and 2) an optional 35 GHz nadir pointing rain radar. 

- Active microwave medium-penetrating instruments, in particular with regard to soil and foliage penetration (see also: ‘microwave signal penetration’ in Glossary), were first introduced with airborne instruments (Table 21). 285) Microwave observations of active and passive sensors in L-band, P-band, UHF, VHF and UWB (Ultra-Wide Bandwidth) are of great interest.
- The L-band is an attractive complement to the X-band in particular for biomass and land use applications. Fully polarimetric sensors provide valuable additional information for classification.
- The P-band (435 MHz) is attractive not only for biomass estimates, but also for sounding the thickness and internal layers of the Antarctic and Greenland ice sheets.

The dielectric properties of the underground are of fundamental importance for the system concept. The microwave permittivity of water is an order of magnitude higher than that of any natural dry material. 286) 287) Radar penetration and resolution tend to be reduced by the EM attenuation, with a range that goes from a few meters in conductive media, to 50 m at most for low-conductivity (below 1 ms/m) materials such as sand, gravel, rock and fresh water. High-power pulses are essential in order to increase the ratio between signal and clutter (or noise). For this reason, instead of using a pulsed radar, one may use swept-FM or step-frequency continuous wave transmitters (SFCW). The frequency synthesizer technique seems to overcome some of the limitations of pulse-modulated radars which makes them interesting for future developments.

<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPR (Ground Penetrating Radar)</td>
<td>First airborne tests/studies (ice penetration) were conducted in 1974, GPR first flown in 1993</td>
</tr>
<tr>
<td>SRI, P94.1</td>
<td></td>
</tr>
<tr>
<td>FOLPEN, SRI, since 1990, P94</td>
<td>FOLPEN-I and-II are VHF impulse SAR systems with foliage penetration capability</td>
</tr>
<tr>
<td>CARABAS, FOA, Sweden, P49</td>
<td>Penetration of vegetation/foliage and to some extent of the ground surface, since 1992</td>
</tr>
<tr>
<td>TOPSAR, JPL (upgrade 1994), P13.1</td>
<td>Calculation of the differential penetration characteristics of the dual-frequency radar waves for different Earth terrain types</td>
</tr>
<tr>
<td>P3/SAR, ERIM/Navy (upgrade 1994), P82.3</td>
<td>Support of foliage and ground penetration experiments/applications</td>
</tr>
</tbody>
</table>

286) Note: In ground penetrating applications the frequency range is determined by ground losses which in general are increasing with the frequency range selected.
287) Note: In general, the medium-penetrating SAR instruments are also referred to as GPR (Ground Penetrating Radar). The GPR technology is one of the most promising concepts for land mine detection.
### Table 21: Overview of medium-penetrating airborne microwave instruments

<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LARSEN, CCRS, since 1985, P.111</td>
<td>A lidar for the measurement of shallow water depths</td>
</tr>
<tr>
<td>LFS, University of Oldenburg, P.116</td>
<td>Lidar for the analysis of the upper sea surface layers, since ’93</td>
</tr>
<tr>
<td>SHOALS, USACE, 1994, P.186</td>
<td>A lidar for the measurement of shallow water depths</td>
</tr>
<tr>
<td>SASAR, U. of Cape Town, since 1996, P.183</td>
<td>The VHF-band of SASAR offers a surface/foliage penetrating capability</td>
</tr>
<tr>
<td>Passive Instruments</td>
<td></td>
</tr>
<tr>
<td>PBMR, GSFC/WFF, since 1983, P.162</td>
<td>L-band radiometer for the measurement of soil moisture, etc.</td>
</tr>
<tr>
<td>RADIUS, NPO Vega, since 1986, P.173</td>
<td>Microwave radiometer for the measurement of soil moisture, etc.</td>
</tr>
<tr>
<td>ESTAR, MIRSL/GSFC, 1988, P.87</td>
<td>L-band radiometer for the measurement of soil moisture and ocean salinity</td>
</tr>
<tr>
<td>AIMR, AES, Canada, since 1989, P.8</td>
<td>Microwave radiometer for the measurement of soil moisture and snow depth</td>
</tr>
<tr>
<td>PORTOS, CNES, since 1992, P.169</td>
<td>Microwave radiometer for the measurement of soil moisture</td>
</tr>
<tr>
<td>MIRAS, ESA, since 1996, P.133</td>
<td>L-band radiometer (2-D aperture synthesis) for the measurement of soil moisture and ocean salinity</td>
</tr>
<tr>
<td>STAR-Light (U. of Michigan), since 2002</td>
<td>L-band radiometer (10 element 1.4 GHz 2-D aperture synthesis using 3-bit correlation), measurement of soil moisture</td>
</tr>
</tbody>
</table>

Spaceborne L-band SAR instruments were flown on SIR-A (NASA/JPL, Shuttle, Nov. 12, 1981), SIR-B (Shuttle, Oct. 5, 1984), and SIR-C/X-SAR (Shuttle, SRL-1 April 1994, SRL-2 Sept. 1994), and on JERS (NASA/MITI, launch Feb. 11, 1992).

In the late 1990s, the applications of medium-penetrating radars (a non-destructive monitoring technique), are becoming rather divers. The technique is employed in civil engineering for void detection, prediction of concrete deterioration from variations of its permittivity by the presence of moisture and chloride, pavement profiling for programmed road and bridge deck maintenance, reinforcing bar location, subgrade deterioration in railroad and airport runways. Object detection and classification by extent and permittivity contrast with the overburden, it is crucial in environmental engineering. Furthermore, the technique is useful for mapping hazardous wastes and buried contaminant containers, imaging and monitoring subsurface contaminants (e.g., gasoline and other hydrocarbon fuels). Stratigraphic and bedrock mapping are essential in geotectonic, archaeologic, and hydrogeologic applications, in site characterization, in mining planning (e.g., borehole profiling), in tunnel excavations, ice thickness profiling, permafrost mapping, etc. 288)

1.2.3.6 Bistatic and Multistatic Systems in Remote Sensing

The bistatic remote-sensing concept 289) refers to a measurement geometry in which the transmitter and receiver of an active system [Doppler radar, SAR, lidar (altimeter), radio-navigation systems (GPS, GLONASS, Galileo), all broadcasting systems, etc.] are separate units (i.e. physically different antennas), either collocated on the same platform but separated by some distance, or they (transmitter and receiver) are positioned on different platforms. 290) 291) 292)

**Bistatic**, or for that matter “multistatic” observation concepts that may be divided into fully active and semi-active configurations.

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In a fully active configuration, each radar has both transmit and receive capabilities where all radars look into a common footprint (different views of the observed target area). The TechSat-21 constellation design of three satellites in formation flight (the project was cancelled in 2003 due to the technical challenges involved) is an example of a fully active system; so is the RADARSAT-2/3 tandem mission configuration.

Semi-active systems combine an active illuminator (one transmitting system) with one or more passive receivers. All systems look into a common footprint (multiangle observations as in the fully active configuration). An example design is the ICW (Interferometric Carthwheel) configuration. The passive members in such a system require obviously reduced power budgets; when in addition deployable antennas (receivers) are used, the payload may be accommodated on microsatellites. The use of a single illuminator in a semi-active configuration represents a significant reduction in constellation investment cost.

Both of these distributed arrangements, can improve system flexibility and reliability, offering some advantages such as stereoscopic views, different target signatures, and in particular shorter revisit times. - In fact, the flexibility of the multistatic observation concept is such as to permit the positioning of the transmitter and receiver satellites into different orbits; configurations of LEO - MEO and/or LEO - GEO constellations are possible. The ultimate goal is a highly reconfigurable and scalable satellite constellation for a broad spectrum of remote sensing applications. - Bistatic/multistatic SAR observations may require accurate time synchronization; antenna pointing between transmitter and receiver may also be involved.

The distributed nature and functionality in bistatic and multistatic SAR systems allows for a natural separation of the radar payloads, providing the potential to support the use of small, low-cost satellites in the future. A constellation of multiple radar satellites, recording the signals from a common illuminated footprint, is regarded as a large aperture system with sparsely distributed subaperture elements. [Within this context, a multichannel instrument (i.e. a distributed system configuration) can be obtained of a single SAR antenna by splitting the active phased array antenna electrically into multiple subapertures for multiple beam support]. This fact opens a number of new potential applications:

- The linear combination of multiple receiver signals can be treated in the framework of array processing.
- Sparse aperture systems enable highly accurate velocity measurements of moving objects on the ground and may also overcome the problem of blindness against certain directions of target motion.
- Precise target location capability.
- A coherent combination of multiple SAR images acquired from slightly different view angles can also improve the geometric resolution (super-resolution technique).
- A further promising application is SAR tomography which enables e.g. a real 3D imaging of the vegetation structure for biomass estimation on a global scale.
- Another very promising application for future bistatic and multistatic SAR systems is digital beamforming on receive. Multiple independent beams in elevation allow for the simultaneous and unambiguous mapping of several distinct subswarths with full azimuth resolution and high antenna gain. Multiple subswarths can then be combined to form a wide image swath.

In contrast, a monostatic system refers to a measurement arrangement, in which both transmitter and receiver functions are collocated on the same platform, the same antenna unit is being used for both functions (transmitter and receiver have also the same viewing geometries). The reasons for the selection of a monostatic system are mostly mission simplicity and autonomy. The monostatic geometry is understood, specifically with regard to the imaging mechanisms and to the data precessing. The great majority of all radars (SAR instruments, Doppler radars, lidars, etc.) in use today (and flown on spaceborne missions) are of the monostatic type, providing their own illumination and measuring the echo at the
same location. The dual monostatic or repeat-pass approach (for interferometric opera-
tion) has been demonstrated by the ERS-1/2 tandem mission (Aug. 1995 to May 1996) of
ESA. In a tandem mission in monostatic mode, the two spacecraft have equal status, there is
no direct link between them. In the bistatic semi-active concept, one satellite (the master or
illuminator) generates the radar pulses, and the reception of the echoes by both master and
slave must be synchronized.

Background. It is interesting to note here that all early radar experiments, conducted by ex-
perimenters in various countries like in France, Germany, Italy, Japan, Russia, UK, and
USA (from about 1904 on until after World War II), were of the bistatic type. In the USA,
for instance, an observation of the radar effect was made in 1922 at the U.S. Naval Research
Laboratory (NRL) in Washington, D.C. NRL researchers conducted an experiment by
positioning a radio transmitter on one shore of the Potomac River and a receiver on the oth-
er. A ship sailing on the river caused fluctuations in the intensity of the received signals
when it passed between the transmitter and receiver. Today, such a configuration is called a
bistatic radar system. In spite of the promising results of this experiment, U.S. Navy officials
were unwilling to support further work at the time. Practically all early military radar sys-
tems until the end of World War II were of the bistatic type. - In the space age era, bistatic
radar systems employing an orbiting transmitter and an Earth-based receiver have been
used for lunar and planetary exploration.

Bistatic or multistatic radar systems offer some advantages: 293)
- A significant cost reduction can be achieved in the design and operation of a bistatic
  system (passive radiometers are significantly less expensive than active SAR instruments).
  Microsatellites may be used to accommodate the passive receiver antennas.
- The physical separation of the transmitter and receiver function permits for instance
designs, in which the number of participating receivers can be any number in an observation
system; thus, the receiver function is of a parasitic or opportunistic nature, simply passively
participating in an observation environment/arrangement, it is in a sense “independent” of
the transmitter function (not in the time domain for SAR applications). Systems with two or
more receiving sites are also referred to as multistatic systems. They employ overlapping
coverage of the illumination footprint and combine target data coherently and nonco-
herently at a central location.
- Bistatic systems offer the potential of upgrading existing monostatic missions. For
  instance, an existing SAR mission may be complemented with a constellation of passive re-
ciever spacecraft in its neighborhood. This improvement results in added value to the mas-
ter mission offering bistatic SAR data. Interferometric processing of the bistatic data may
be unrealistic, due to rather large antenna separations; however, cross-track and along-
track interferometry may be achieved. See also the Cartwheel mission below.

There may be also some disadvantages in upgrading an existing monostatic system: a) the
transmitting antenna and satellite are non-cooperative; i.e., they are unaware of the new
satellite with its receiver; in this case, time-synchronization of the receiving-only antenna
may pose added complexities on the data processing side. Hence, long-term plans are need-
ed for upgrading options.

Since the 1990s, bistatic systems are also finding ever increasing applications in the wide
field of Earth observation. A typical example is atmospheric research where ground-based
bistatic multiple-Doppler radar networks have significant scientific and economic advan-
tages accruing from the use of only single sources of illumination. The NEXRAD (Next-
Generation Weather Radar), a bistatic ground-based Doppler radar network of NMS/
NOAA (distributed over the entire USA) with the name of WSR-88D (Weather Surveil-
lance Radar-1988 Doppler), is an example. Individual spatial volumes are viewed simulta-
neously from multiple look angles, minimizing storm evolution induced errors. The passive
receivers in a bistatic network do not require expensive transmitters, moving antenna hard-
ware, or operators. Thus they require only a small percentage of the investment needed to field traditional transmitting radars.

Some examples of bistatic system designs are:

- **PoldiRad (Polarimetric Doppler Radar)** is a C-band bistatic Doppler ground-based radar system installed in 1988 at DLR in Oberpfaffenhofen, Germany. This system is a bistatic installation for a C-band weather radar system using a magnetron transmitter. The remote receiver is located at the DLR Weilheim tracking site at a distance of 27 km from the radar. The bistatic hub of the system receives the Doppler velocity and reflectivity from both receivers. The data from each ray are merged into a common data file and the horizontal wind vectors are estimated in real time. - Two more bistatic receivers were installed in 1999 into the PoldiRad network. 294)

![Figure 10: Schematic illustration of a ground-based bistatic multiple Doppler network](image)

- In 1993, NCAR (National Center of Atmospheric Research) developed a ground-based dual-Doppler weather radar network at its facilities in Boulder, CO, referred to as BINET (Bistatic Radar Network). The network provides three-dimensional fields of full vector winds, including directly measured vertical precipitation particle velocities for numerous applications in meteorological research, aviation, forecasting, media, and education. 295) 296) 297) 298)

- The GPS and GLONASS spaceborne navigation constellations are also examples of multistatic systems. By its very nature, each navigation constellation provides the transmitter function while the “signal user community” at its numerous instant locations plays the role of the receiver function. The direct reception of GNSS signals can be used a) as navigation function, b) as timing reference, and/or c) as remote sensing function (for refractive...


295) [http://www.atd.ucar.edu/homes/mitch/binet2.html](http://www.atd.ucar.edu/homes/mitch/binet2.html)


sounding, etc.). Manuel Martin-Neira of ESA/ESTEC was one of the earliest advocates of bistatic/multistatic altimetry using GPS signals. See also chapter 1.5.6 (GPS Signal Applications - Bistatic Reflection Measurements).

- Lately, indirect or reflected GNSS signals are also being used as information of opportunity (bistatic or multi-static scattering is at the heart of this phenomenon). In radar remote-sensing nomenclature, GPS reflection data (of the ocean surface or of any ground surface) can be characterized as a “bistatic radar scatterometer.” Upon impinging on the ocean surface, the GPS signal is reflected primarily in the specular (forward) direction, in an amount dependent on surface roughness and angle of incidence. An airborne or spaceborne GPS receiver, connected to a down-looking antenna, is able to collect such scattered signals. By analogy to traditional altimetry, the bistatic GPS reflected signals are analyzed to derive the important descriptors of the ocean surface: i.e., sea surface height and sea surface wind vector (an augmentation to existing spaceborne altimetry; the GPS coverage is dense and rapid; sea surface heights are obtained not only along the altimetry tracks but at many points in between). An entire new spectrum of remote sensing applications is beginning to unfold with the measurement of this new source of reflection data. Initial experiments with airborne GPS receivers were conducted in the early 1990s (see also “ocean reflection measurements of GNSS signals” in 1.5.6).

- Reflected ocean wave spectra, caused by Bragg scattering, were already performed with LORAN-A (Long-Range Navigation) radionavigation systems in the 1960s. The LORAN-A bistatic experiments demonstrated that the Doppler shift of the radar echo is exactly equal to the wave frequency; it is also related to the bistatic angle. See LORAN background in chapter 1.12.1.

- The D2P (Delay-Doppler Phase-monopulse Radar) payload is an airborne bistatic Ku-band radar altimeter system of JHU/APL, sponsored by NASA. D2P is a proof-of-concept instrument featuring the new altimetric concepts of: a) pulse-to-pulse coherence and full Doppler processing to allow for the measurement of the along-track position of the range measurement, and b) use of two antennas and two receiver channels that allow for measurement of the across-track angle of the range measurement (bistatic configuration). Measurement campaigns were conducted in April 2000 and May 2002 (see P.62).

- **Bistatic SAR systems.** SRTM (Shuttle Radar Topography Mission), a cooperative project of NASA, DLR and ASI on STS-99 (Feb. 11-22, 2000, see J.27), was the first spaceborne bistatic SAR mission (single-pass InSAR) where both SAR systems operated with the main antenna of each instrument located in the open cargo bay of the Shuttle, and a second receive antenna mounted on a deployable outboard mast, respectively (a single-pass interferometer on a 60 m baseline in cross-track and 7 m along-track).

- The SIRAL (SAR Interferometer Radar Altimeter) instrument of ESA's CryoSat mission (launch on Oct. 8, 2005 — but launch failure) is a bistatic radar Ku-band altimeter using two Cassgrain antennas, mounted side-by-side and forming the interferometric cross-track. Both antennas are identical; one is used to transmit and receive, whereas the other antenna is used to receive echoes (bistatic configuration, see E.2). Note: The SIRAL instrument has two major heritage lines. 1) The hardware is essentially that of Poseidon. Alcatel's nickname for SIRAL is Poseidon 3 (Alcatel is the manufacturer of SIRAL). 2) The SIRAL

design concept is essentially that of the D2P radar, with delay-Doppler as the driving theme along-track, and the cross-track interferometer proven by D2P campaigns.

Bistatic interferometric systems such as the SRTM, D2P and SIRAL are referred to as short-baseline systems. Examples of long-baseline systems are: the Cartwheel constellation of CNES, the BINET approach of NCAR, and the TechSat-21 constellation of AFRL. The short-baseline interferometers are “bistatic” only in a narrow sense; they do not enjoy the major advantages of long-baseline systems.

Interferometric capabilities are becoming a key requirement at the start of the 21st century to obtain topographic performance. A number of projects under development are planning to test the bistatic concepts in the spaceborne arena of close formation-flying satellite missions. A viable option in such a distributed concept is for example a master-slave implementation. A single so-called master spacecraft is equipped with an active radar (i.e., a transmitter and receiver function), while the rest of the constellation (slave spacecraft) is outfitted with just a radiometer (receiver). All observation instruments of the constellation are directed to look into the same footprint. Thus, all passive instruments in the constellation are also able to detect coherently the bistatic responses from the single active radar of the master spacecraft as well. The multi-location (or nodal) spacecraft data collected in this fashion provides automatically interferometric imagery after ground processing. The distributed apertures improve also the performance of the system with regard to detection and resolution capabilities. A wealth of independently sampled angle-of-arrival data can be collected, the constellation forms a large but sparse coherent array. By virtue of its sparseness, the independent apertures look through different parts of the ionosphere, thus temporal and spatial variations on the scale of their separation could adversely affect their operation. This innovative bistatic observation concept has the potential to reduce the mass, power and cost of the constellation as a whole.

Examples of the first collaborating constellations demonstrating the new bistatic and multistatic SAR observation technologies (for along-track and cross-track interferometry) are under intensive study at the start of the 21st century.

- In Europe, CNES (in cooperation with ESA and DLR) is proposing/planning a so-called Interferometric Cartwheel (ICW) mission constellation of three passive microsatellites, each equipped with a receiver dish antenna (a slave receiver), to co-orbit with a soon-to-come conventional SAR mission (as host or “illuminator” or master satellite). The candidate conventional SAR missions considered for Cartwheel are: Envisat, RadarSat-2, TerraSAR-X and -L, and ALOS (in fact, any radar satellite mission provides a suitable context for a cartwheel mission). An “interferometric cartwheel orbit” of the passive constellation is employed. In such a cartwheel concept, the locations of the passive satellites are planned to be ahead or behind of the transmitter satellite at a fairly constant angle. Their orbits are the same as the transmitter spacecraft orbit, but with an eccentricity slightly different from that of the transmitter spacecraft orbit (the three passive satellites are moving relatively to a common reference point, in motion and coplanar with

303) Note: Coherent detection requires synchronization between master and slaves. The synchronization may either be achieved using a crosslink from master to slaves, or by accurate synchronization of all involved to the same source.


306) The term “cartwheel orbit” was initially coined by D. Massonnet of CNES in 1997.


the transmitter S/C; the common reference is either lagging or preceding the transmitter S/C orbit at a constant angle). The new orbital concept is considered to offer a good geometric stability of the baselines, both vertically and horizontally, essential for interferometric processing (see O.10.8 for a definition of the Cartwheel orbit). The Cartwheel configuration is a single-pass InSAR implementation (a multi-static configuration); it offers increased geometric resolution of SAR images by: \(^{310}\)

- The along-track displacement of the receiving (parasitic) satellites
- Different Doppler centroids
- Super-resolution in azimuth by coherent combination of shifted Doppler spectra
- Cross-track displacement of the receiving satellites
- Different incidence angles
- Super-resolution in range by coherent combination of images with different range spectra
- A potential for moving analysis in the SAR imagery.

A SAR campaign, BASE (Bistatic Airborne SAR Experiment), took place Feb. 11-14, 2003 as an ICW (Interferometric Cartwheel) preparatory project in the vicinity of Nimes, France. The campaign was conducted with an X-band SAR instrument on each aircraft, namely E-SAR of DLR on the Do-228 (Germany), and RAMSES of ONERA on a Transall (France) aircraft. One of the two systems served as transmitter and receiver while the other was operated in a passive receive-only mode. The main objective was to simulate the following footprint geometries: \(^{311}\)

- Along-track configuration. This geometry is very suitable in support of bistatic interferometric data acquisition; also, the synchronization strategies were tested.
- Cross-track configuration. This geometry is suitable for improved scene and target classification support by evaluating bistatic scattering coefficients.

- The TanDEM–X mission concept of DLR (launch 2009) is based on an extension the TerraSAR–X mission (launch June 15, 2007) by a second TerraSAR–X–like satellite, namely TanDEM–X. A close orbit formation flight is planned for both satellites — thereby providing a flexible single–pass SAR interferometer configuration, where the baseline can be selected according to the specific needs of the application. In the TanDEM–X and TerraSAR–X spacecraft mission design, the SAR (Synthetic Aperture Radar) instruments of each spacecraft are fully compatible, both offer transmit and receive capabilities along with polarimetry. Availability of the following support modes: a) monostatic, b) bistatic, and c) alternating bistatic mode. \(^{312}\)

1.2.3.7 SAR imaging and detection of moving targets (motion sensing)

The conventional cross-track SAR imaging technology is based on the assumption that an imaged target (i.e., a scene) is motionless, thus allowing the computation of the variation of the range during the observation (integration time) required for the in-phase (coherent) synchronization of the successive pulse returns. If an object is moving through the scene during its illumination by the radar, the range, and hence the relative phase of successive echoes, varies significantly (different rates), causing localization errors and out-of-focus blur. The latter may even lead to the invisibility for a vehicle of large radar cross section on the synthesized images.

Motion sensing and subsequent event recognition, however, is a very desirable goal in SAR imagery for many applications in the civil as well as in the military domains. Since the mo-


tion of moving objects interacts with the conventional image forming process in the SAR scene, resulting in both location errors and blurring, other concepts with considerably more functional capability had to be devised to solve the problem.

Today’s motion sensing synthetic aperture radar concept, referred to as SAR/MTI (Synthetic Aperture Radar/Moving Target Indication), uses two or more physical antenna phase centers aligned with the platform flight vector (i.e. in the along-track direction) in order to provide a means of detecting and/or measuring the radial component of object velocities within the observed scene (cross-track direction). This scheme permits time and azimuth position to be partly decoupled, which allows radial velocity of a scatterer to be distinguished from an offset in azimuth position of that scatterer. 313)

In general, the measurement of object motion using SAR requires two operations. Firstly, detection of motion in the SAR scene, and secondly, parameter estimation such as location, speed and trajectory. Target detection and estimation can either be performed incoherently with a single SAR sensor, or coherently, with much higher fidelity, using two or more apertures. 314) 315)

Background: The pulsed Doppler radar technology was developed during World War II to better detect aircraft and other moving objects in the presence of echoes from sea and land that are illuminated by microwave emissions through sidelobes of the antenna’s radiation pattern. Although pulsed Doppler radar was developed in the early 1940s, Doppler effects were observed in radio receivers when echoes from moving objects were received simultaneously with direct radiation from the transmitter or scattered from fixed objects. The earliest pulsed Doppler radars were called MTI (Moving Target Indication) radars in which a coherent CW (Continuous-Wave) oscillator, phase-locked to the random phase of the sinusoid in each transmitted pulse, is mixed (i.e., beat) with the echoes associated with that pulse. The mixing of the two signals produces a beat or fluctuation of the echo intensity at a frequency equal to the Doppler shift. 316)

The first application of pulsed Doppler radar principles to meteorological measurements was made by Ian C. Browne and Peter Barratt of the Cavendish Laboratories at Cambridge University in England in the spring of 1953. Barratt and Brown showed that the shape of the Doppler spectrum agreed with the spectrum expected from raindrops of different sizes falling with different speeds.

The MTI technology has also its roots in post World War II political developments in the 1950s with regard to North American air defense/surveillance requirements [a) threat of manned bombers carrying nuclear weapons across the arctic region was of paramount concern in continental defense, b) some time later the threat of intercontinental ballistic missiles]. For the first threat, MIT/LL (Massachusetts Institute of Technology/Lincoln Laboratory) developed the so-called DPCA (Displaced Phase Center Antenna) technique which was used to improve the detection performance of airborne MTI radars that are subject to clutter. 317) 318) In the second case, MIT/LL formulated a concept of what became later known as BMEWS (Ballistic Missile Early Warning System), this ground radar warning system was eventually built and installed by industry in Greenland, the UK, and in Alaska. In the 1970s several innovative waveform and signal processing techniques were synergistically combined to significantly improve the detection of moving targets in the presence of large clutter echoes. An early advanced MTI system of MIT/LL is referred to as MTD (Moving

313) http://www.ewh.ieee.org/soc/grss/if/ Saper5.html
316) http://windfall.evs.cynthia.edu/~class/Jeremy/drhist.htm
Target Detection), a concept that is currently being used extensively in airport-surveillance radars.

Pulsed Doppler radars (or simply “pulse Doppler radar”) are very useful radar systems as they combine their ability to determine target velocity with the other functionality of a standard pulse-modulated radar. A pulsed Doppler radar can, therefore, determine range, angle and velocity of a target. This makes the pulsed Doppler radar extremely valuable in situations involving many small moving targets hidden by heavily cluttered environments.

- Today’s MTI (Moving Target Indication) measurement concept utilizes the pulsed Doppler radar technique, mostly in combination with a high-resolution SAR imaging capability (due to its all-weather and day/night observation capability) to detect and locate the motion of moving targets (cars, trucks, etc.) in the ground segment, as well as airborne or spaceborne vehicles within the SAR image. In general, MTI systems have the capability to provide location and tracks of moving space/air/ground vehicles, but not to identify them. Of course, the SAR/MTI concept may also be complemented with other imaging sensors (IR, VIS, etc.) for possible identification enhancement. Potential future motion sensing capabilities may also be provided by polarimetric SAR systems and along-track interferometric SAR systems (used for single-pass extraction of topographical information). Some SAR/MTI basics are:

  - MTI discriminates moving targets from background by the Doppler frequency shift induced by radial motion
  - MTI employs a narrow beam which a large antenna
  - The S/C motion complicates MTI: fast-moving platforms require additional clutter suppression using multiple antennas or an antenna divided into subapertures.
  - MTI target tracking can be accomplished by repeated beam scans
  - Advanced MTI systems employ STAP (Space-Time Adaptive Processing) techniques to cancel the background clutter (conventional STAP implementations require a very high computational load, see also Glossary on STAP). STAP offers a means of detecting targets that compete with clutter located within the skirts of the mainlobe. The introduction of STAP allows antenna apertures to be reduced by perhaps as much as 50 to 75 percent.
  - A promising solution to detect moving targets with a SAR/MTI system is the use of a multi-channel system with phase centers separated in along-track direction and the exploitation of the data via algorithms like along-track interferometry or STAP.

A SAR image is formed by processing many radar pulse echoes from a target. Each pulse provides information as to the range to the target, and the pulse-to-pulse variations at a given range provides the necessary information to extract the azimuth target position. A moving target may pass through many range resolution cells during this data collection process (which may be in the order of many seconds) producing a blurred image using conventional ground focused SAR image formation techniques.

Obviously, the MTI technology is of great interest in reconnaissance/surveillance applications, in the military as well as in the civil communities. Potential MTI applications include: environmental monitoring, change detection, oceanography, analysis of meteorological features, marine traffic monitoring, monitoring of vehicles on land, air traffic monitoring, treaty verification, etc.). At the start of the 21st century, most existing MTI systems were developed for military peace-keeping reconnaissance applications and are flown on aircraft or on UAVs (Unmanned Aerial Vehicles). Some AGS (Airborne Ground Surveillance) implementations are:

- JSTARS (Joint Surveillance and Target Attack Radar System) is a joint development of the US Air Force and Army. Since 1996, the system has been installed in 13 aircraft (Boeing 707-300 aircraft series E-8C - the aircraft employs a canoe-shaped radome of 12 m in

length). JSTARS was first deployed in Operation Desert Storm in 1991 when still in development (2 aircraft were used in Desert Storm with a JSTARS demonstrator). JSTARS was designed and built at Northrop Grumman Norden Systems in Norwalk, CT (delivery of the 13th aircraft in April 2002). - The new next-generation JSTARS will be an electronically scanned 2-D X-band active aperture radar which features a helicopter detection mode with an ISAR (Inverse Synthetic Aperture Radar) imaging capability, as well as an MTI mode, allowing realtime imaging of moving objects. 320) 321)

- TESAR (Tactical Endurance Synthetic Aperture Radar) of Northrop Grumman, operational since 1996. The radar payload operates in both synthetic aperture radar (SAR) and moving target indication (MTI) modes. In SAR mode, continuous, fully focused, high-resolution (0.3 m), near real-time stripmap imagery is formed on either side of the aircraft. The radar provides two SAR stripmap modes and a spot map mode. In MTI mode, the radar provides target reports overlayed on a digital map. 322)

- The EL/M-2055 is a high performance SAR and MTI tactical airborne reconnaissance system, developed by ELTA Electronics Industries Ltd., a subsidiary of Israel Aircraft Industries Ltd. The system is available as of 1999. It provides real-time SAR image generation offering strip mode, spot mode and MTI mode operations support. 323)

- HISAR (Hughes Integrated Synthetic Aperture Radar) is an airborne reconnaissance/surveillance system (of Raytheon) designed to provide high-resolution SAR imagery in real-time displayed on a workstation onboard an aircraft (support of military and civil applications). 324) Baseline HISAR modes include wide-area search to provide a rapid overview of a large area. An operator can map land areas as large as 110 km x 70 km in seconds with resolutions of 15-50 m depending on range to the target. Baseline HISAR modes also include stripmap for border or coastline surveillance or environmental monitoring. In this mode, HISAR maps a continuous swath at an aircraft’s speed up to 37 km wide and 110 km away from the ground track. The resolution of the pixels is 6 m x 6 m. MTI is also available in this mode. HISAR is available as of 2000.

- AER-II (Airborne Experimental Radar-II) designed and developed by FGAN (German Defense Research Facility for Applied Science), Wachtberg near Bonn, Germany. 325) 326) This X-band SAR system (10 GHz) possesses a fully polarimetric phased array with variable subaperture partitioning. A vertical displaced auxiliary antenna of identical geometry allows the use of the interferometric mode. Four receive channels may be used simultaneously with four subapertures for an improved moving target indication (MTI), in addition four polarimetric channels are provided in parallel. By exploiting the electronic steering in azimuthal direction, operational modes are possible which cannot be employed with conventional SAR systems with fixed look directions. AER-II comes with four parallel receive channels in the analog and digital domain. Thus, it is possible to create four complex coherent SAR images of the same scene within one acquisition. AER-II is operational since 1998 installed on a Transall C-160 aircraft (it was preceded by AER since 1996). The AER-II instrument provided the first spotlight demonstration in Europe with its electronic beamsteering capability.

A further FGAN instrument with improved capabilities is PAMIR (Phased Array Multi-functional Imaging Radar). Since 2003, a new SCAN/MTI mode has been implemented

320) http://www.airforce-technology.com/projects/jstars/

321) Note: ISAR is a well-established technique to identify the reflectivity centers of the target with high spatial resolution. A fine 2-D reflectivity map of the target is generated by using large bandwidth transmitted signal, to have high range resolution, and by coherently processing the echoes received from different aspect angles of the target, to achieve fine cross-range resolution. An ISAR image is a 2-D representation of the target, with the resolution in the horizontal dimension determined by the short pulse characteristic of the radar and the vertical dimension by the Doppler of the radar returns. The result is a recognizable image at long range under all weather conditions.


323) http://www.elta-iai.com/site/catalog/radar_families/elm2055.asp


326) http://www.fhr.fgan.de/fhr/el/el_facil_aer00_e.html
and experimentally tested. This mode provides a significant improvement to the usual MTI mode with fixed beam, since the antenna is regularly steered to different azimuth angles, allowing to scan much larger scenes (see P.161). 327)

- **MiniSAR** (Miniature, Lightweight, Scalable SAR System) is being developed by TNO-FEL (Netherlands Organization for Applied Scientific Research - Physics and Electronics Laboratory), The Hague, The Netherlands (and a consortium of industrial partners). 328)

  The demonstrator system will be integrated in a two-seater motor glider platform. MiniSAR operates in X-band with a center frequency of about 9.75 GHz. The design aims at achieving a bandwidth of 500 MHz for the first demonstrator system. The system covers a swath of at least 1 km in high resolution mode and a swath of about 4 km in stripmap mode. MiniSAR features also an MTI mode capable of operating simultaneously with the typical SAR modes.

- **ASTOR** (Airborne Stand Off Radar) is a joint program of the British Army and Royal Air Force (RAF). ASTOR is a similar in concept to JSTARS, its objective is to develop a surveillance capability (SAR/MTI on aircraft). Raytheon Systems Ltd. UK was awarded the prime contract in 1999 to build the system (five ASTOR systems along with with two portable ground sites and six tactical ground stations), funded by MoD (Ministry of Defence), London, UK. The ASTOR system features a low-resolution wide-swath mode, and a spot mode for high resolution imaging of specific targets. Initial flights are expected in 2004 on a “Global Express” business jet of Bombardier. 329)

- **SOSTAR** (Stand-Off Surveillance and Target Acquisition Radar) is a European SAR/MTI system under development for airborne ground surveillance support functions in the context of NATO. SOSTAR is to provide detection and tracking of slow-moving targets, high-resolution imaging and target classification. A group of five companies from Germany, France, Italy, Spain and The Netherlands have developed a plan, in close cooperation with their governments and Ministries of Defence, for the realization of a ground surveillance system, SOSTAR. In Feb. 2001, a new joint venture company was established called SOSTAR GmbH, Friedrichshafen, Germany. The consortium consists of the following companies: EADS/Dornier (Germany), Thales Airborne Systems (Elancourt, France), FIAR (Milan, Italy), INDRA (Madrid, Spain), and Fokker Space (Leiden, The Netherlands). The SOSTAR contract was awarded by BWB (Bundesamt für Wehrtechnik und Beschaffung - German Federal Office of Defence Technology and Procurement, Koblenz), acting on behalf of all governments. Initial activities of the program started in 1999. 330) The first demonstrator system, SOSTAR-X, is expected to be available in 2005. The demonstrator will perform all the required functions of the full scale model, including the simultaneous interleaved operation of SAR and MTI, but has a smaller antenna size (than the final version) to reduce costs. SOSTAR-X will be installed on a Fokker-100 aircraft for evaluation and demonstration purposes. 331)

  - At the start of the 21st century, there is an increasing interest in spaceborne MTI applications such as LEO satellite constellations for global coverage. 332) These SAR/MTI systems could of course provide an unobstructed view of any area of interest along with real-time information availability. However, there are considerable technical challenges for a spaceborne SAR/MTI system implementation. Very large antenna sizes would be needed for a single spacecraft for an acceptable performance of MTI as well as for azimuth estima-

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328) http://www.tno.nl/instit/fel/os/resources/minisar.pdf

329) http://www.airforce-technology.com/projects/astor/


tion in an X-band SAR system. A multi-satellite system (in formation flight) with a sparsely distributed antenna array would be able to measure up to such a task.

- A spaceborne MTI project under development was the DoD Discoverer-II space-based radar technology demonstration program of DARPA, USAF and NRO which started in 1998, the design featured also a SAR/MTI capability. However, the US Congress cancelled the two-spacecraft program in 2000 due to fear of large cost overruns.

- TechSat-21 (Technology Satellite of the 21st Century) was a DoD initiative under AFRL management with the objective to exploit new paradigms (formation flight of a three microsatellite constellation) and enabling technologies such as SAR/MTI. Demonstration of sparse-aperture sensing to combine InSAR and GMTI (Ground Moving Target Indication) using innovative waveforms and signal-processing technologies. A launch was projected for 2006; however, the TechSat-21 program was cancelled in early 2003 due to cost overruns and the technical challenges involved.

1.2.3.8 Digital Beam Forming (DBF)

Digital beamforming (DBF) is an enabling technology for modern SAR system functions such as MTI (Moving Target Indication) and many other applications. Beam steering in DBF systems can be achieved using signal processing techniques in the digital domain. The DBF scheme represents an advanced technology in avoiding tolerance problems and temperature effects — thus reducing significantly the time-consuming procedures in very complex RF calibration tests still needed today (2006) for phased array sub-units such as T/R modules, radiators, etc.

SAR beamforming techniques: Todays conventional multiple-mode SAR systems, like ScanSAR, employ an electronically steered phased array antenna using T/R (transmit/receive) modules and enabling analog beamforming (ABF) with the T/R modules. The analog techniques previously developed for the electronic steering of phased arrays relied on components such as line stretchers, phase shifters, time delay lines, and attenuators. Such a system design offers the advantage of distributed power radiation and hardware redundancy. However, the overall efficiency of the system is still low and the complexity is rather high. A major disadvantage of the analog beamforming system is the inherent loss of information during the beamforming process. 333) 334) 335)

The general tendency is to move the digital interface further towards the antenna (very early in the receive chain, at the array element level), replacing, whenever possible, analog RF hardware. Instead of analog beam forming future SAR instruments will utilize DBF on the receive data. 336) In this concept, one transmit antenna is fed through a high power amplifier. On receive, the signals from each of the sub-arrays are amplified, down-converted and digitized for processing. The footprint of all receive sub-arrays is identical (coverage of the entire transmit target area); hence, each antenna covers the same spatial target area both in azimuth and elevation.

The introduction of DBF (Digital Beamforming) technology offers reconfiguration and improved performance of the SAR system with 2-D beam steering capabilities. This 2-D beam steering technology is also referred to as AESA (Active Electronically Scanned Array) permitting very flexible support modes. AESA principle: By controlling the relative phase of the transmitted/received signals, the beam direction can be changed without any moving parts. An AESA radar consists of an array of T/R modules linked by high-speed processors

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(space-time processing). The various T/R modules in the array can be configured and assigned to different tasks (ranging, mapping, multi-target tracking, etc.) with more modules allocated to tasks that require greater power or sensitivity. The concept permits also the simultaneous support for several tasks. - The availability of today's high-speed digital processing acts as an enabler for digital beamforming, enhancing radar functionality and instantaneous coverage in bistatic applications. A DBF radar or SAR (i.e. an AESA) uses multiple receive channels simultaneously, each corresponding to an elemental radar whose data are digitized and processed to be digitally combined for final output. This is why DBF radars are so flexible. The number of beams is virtually unlimited and their characteristics can be optimized for each mission, type of target and environment.

The major difference of DBF to conventional T/R module systems is that the beamforming is performed during the digital processing. The DBF configuration is a bistatic configuration since separate antennas are used for transmit and receive functions. The two antennas can be mounted on one carrier or placed on two platforms. A further advantage is the possibility of separate optimization of transmitter and receiver subsystems. For example a high-efficiency high-power amplifier can be used on the transmit side, whereas low noise amplifiers can be integrated into the receive sub-arrays. The DBF concept includes the advantages of T/R module based systems while increasing the coverage. It is adaptable to various requirement sets and the system can be reconfigured by software. Digital beamforming provides superior performance over traditional analog sub-array beamforming. It allows the radar to maintain its performance in the presence of a strong clutter environment (as well as in severe electronic countermeasures). The digital beamforming technique offers the potential of virtually an infinite number of independent beams, all with different shapes.

DBF concepts provide several advantages like fast beamscanning, adaptive beamforming, and multiple beam generation on a software basis. At the start of the 21st century, the design of a DBF phased array system poses great challenges with respect to antenna array design, the electronic circuitry, the general modular construction architecture, and the processing hardware and software for the DBF part. This is due to the complex nature of the integration and packaging tasks involved; each antenna element in a DBF array must be equipped with dedicated transmitter/receiver circuitry, great demands are put on the selection of materials, components and technologies that allow a cost-efficient implementation. In particular, high frequency implementations (Ka-band) require a high degree of packaging densities involving component miniaturization (i.e. MEMS technology). In spite of all complexities involved, DBF demonstrator systems are of great interest in many spaceborne applications, in remote sensing, in surveillance, as well as in communications. 337) 338) 339)

- An early implementation of the DBF concept, using the AESA technology of Northrop Grumman, is the USAF F-35 aircraft, under development by Lockheed Martin (the F-35 is expected to enter service in 2008). 340)

1.2.3.9 SAR technology roadmap

The history of SAR technology, also projected into the future, shows an implementation scenario based on the various orbital observation levels: each level with increasing system complexity, new technology introduction (also new measurement methods), more ad-


340) http://www.faqs.org/docs/air/avf35.html
advanced and enabling capabilities and potentials, and also with a considerably greater harvest of information and derived knowledge. 341)

1) **Demonstration of new SAR technology in ground-based and airborne systems** (an ongoing activity that started in the 1950s)

2) **LEO SAR satellite systems.** The considerably higher altitudes of spaceborne SAR mission orbits provided the capability of much wider swaths (coverage).

- Starting in 1978 with the launch of the NASA demonstration mission SEASAT. Later (1990s) long-term SAR observations evolved into a well-established technology and service infrastructure due in particular to the ERS-1/2 missions of ESA, the JERS mission of NASA, and the RADARSAT-1 mission of Canada.

- The SIR-A (Shuttle Imaging Radar) mission of NASA/JPL (STS-2, Nov. 12, 1981, 3—day mission) was the first SAR mission with a side-looking SAR antenna (fixed angle look angle configuration).

  - The SIR-B mission of NASA/JPL (STS-41-G, Oct. 5, 1984, 1 week mission) provided for the first time the ability to mechanically tilt the SAR antenna over a range of 15 - 55º so that radar imagery from multiple angles of incidence could be obtained.

  - Introduction of a distributed analog T/R (Transmit/Receive) module phased array antenna architecture on the SIR-C/X-SAR on flight STS-59, Apr. 9-20, 1994). In the multiple T/R module approach, the total peak transmit power is shared among all the modules, and each one only needs to transmit at a relatively low peak power. – Note: The first long-term mission using T/R technology in an active phased array configuration is Envisat of ESA (launch March 1, 2002).

  - The distributed C- and L-band SIR-C radars allowed electronic beam steering in the range direction (123º) from a fixed antenna position of 38º (look angle), thus making it possible to acquire multi-incidence angle data without tilting the entire antenna. First demonstration of ScanSAR operating mode for wide swath data acquisition.

  - The SIR-C/X-SAR mission represents also the first spaceborne multi-frequency and multipolarization SAR observations from the same platform.

    - Introduction of configurations with interferometric capabilities [ERS-1/2 with repeat pass interferometry, SRTM with single-pass short-baseline interferometry (on Shuttle flight STS-99, Feb. 11-22, 2000)]. Interferometric SAR (InSAR) advanced SAR data processing techniques through analysis of phase differences between SAR images of the same scene - thus, obtaining terrain elevations [generation of DEMs (Digital Elevation Models)].

- Introduction of ScanSAR technology in long-term missions like RADARSAT-1 of Canada (launch Nov. 4, 1995). ScanSAR provided a much greater flexibility in observation support (subswaths) and swath widths of up to 500 km.

- The T/R module is a key component of SAR phased array antenna modularity and performance. 342) Its efficiency has direct implications on the power dissipation and power generation requirements of the system.

  - In 2001/2, NASA started an ACT (Advanced Component Technology) program to improve the overall performance and architecture of L-band T/R modules. The goals are: integration of power amplifiers into T/R modules, reduction of power consumption (30 W of peak transmit power), miniaturization of T/R modules (<100 g of mass, size of 10 cm x 2 cm x 0.1 cm), large bandwidth (80 MHz), and overall module efficiency of 70% or better.

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- EADS Astrium GmbH in Ulm, Germany, started the SMTR (Standardized Modular Transmit/Receive) module development, along with the FEU (Frontend Electronics Unit) and CE (Control Electronics) subassemblies, all assembled into a common housing, and firstly installed in the TSX—SAR antenna of the TerraSAR spacecraft (launch 2007, see Figure 11). The development work was funded by DLR and Astrium. The most important requirements for SMTR were:

  - High precision of amplitude and phase adjustment over the temperature range $-20^\circ\text{C}$ to $+60^\circ\text{C}$.
  - Full polarimetry of operation (HH, VV, HV, VH) and switching capability of polarization from pulse to pulse
  - High overall efficiency
  - High reliability of the mission lifetime
  - Low mass
  - Affordable cost
  - Uniform T/R module performance.

The key features of this new T/R development are polarization agility with excellent channel isolation, high gain and phase accuracy, low noise amplification during receive operation and internal temperature drift compensation over a wide temperature range.

Figure 11: T/R module RF architecture for the TerraSAR antenna (image credit: EADS)

- Introduction of UWB (Ultra-Wideband) SAR imaging technology. The UWB SAR technology has the potential to make high-resolution but low-frequency band (say, P-band, VHF, UHF) SAR imaging applications feasible. Conventional SAR instruments use a frequency band (say, C-band, X-band, Ku-band) with a signal bandwidth generally $<10\%$ of the center frequency (also referred to as narrowband SAR signal). An UWB SAR system (a UWB system uses RF signals with a bandwidth $>25\%$ of the center frequen-

345) Note: Bandwidth refers to the difference between the highest and lowest frequencies of interest, containing about 95% of the signal power.
cy) could be the answer in terms of resolution requirements and other features such as range measurement accuracy, ground penetration capability, etc. The UWB technology permits topographic as well as tomographic imaging applications.

An introduction of UWB technology in SAR systems (with very short duration pulses resulting in a high RF bandwidth) has only been done in airborne SAR instruments so far. The introduction of UWB technology on spaceborne SAR instruments has to overcome the following obstacles: 1) the power requirements are very large for spaceborne UWB instruments, and 2) regulatory issues of the ITU might refuse licensing of a UWB spectrum allocation for spaceborne applications.

Examples of early airborne UWB SAR instruments are:

- CARABAS (Coherent All Radio Band Sensing). CARABAS (see P.49) is a Swedish airborne experimental SAR instrument designed and built at FOA (National Defense Research Establishment, Linköping, Sweden), which operates in the lower part of the VHF-band. The objective is good penetration of vegetation/foliage and to some extent of the ground surface. The frequency band was chosen: 1) to reduce the image speckle level without sacrificing resolution, and 2) to obtain a system with diffraction-limited resolution (i.e. a system with a dimension of the resolution cell comparable to those of the wavelengths employed, to minimize the influence of speckle). CARABAS-I was first flown in a SAR campaign in Oct. 1992. An upgraded CARABAS-II version is flown since 1996. CARABAS-II operates in the frequency range of 22-80 MHz (HF/VHF-band) with a center frequency of 51.25 MHz and a bandwidth of 58 MHz. The bandwidth is provided by stepped frequency generation.

- P-3/SAR (ERIM/Navy Sensor) is operational since 1988. The P-3/SAR system (see P.82.3) is jointly owned and operated by ERIM and NAWC/AD, and is installed on a US Navy P-3A Orion aircraft. The sensor is a multimode SAR operating at X-, C-, and L-band. A polarimetric UWB mode (200-900 MHz) was added in 1994 (foliage and ground penetration experiments).

- SAR Earth surface imagery with resolutions < 1 m can only be provided with X-band (or higher frequency, i.e. Ku-band) instruments. The L-band is an attractive complement to X-band in particular for such applications as: biomass and land use as well as for ocean salinity mappings. Fully polarimetric SAR instruments provide valuable additional information for such applications as classification, geological investigations, and in particular for lithological mapping. The PALSAR instrument of JAXA’s ALOS mission (launch Jan. 24, 2006) provides L-band polarimetric imagery in a support mode with duty cycle.

- The RADARSAT-2 mission of CSA/MDA, Canada (launch 2007) features a C-band dual-receive phased array antenna capability (two subapertures in along-track may be used independently with two separate receivers) in combination with a DPCA (Displaced Phase Center Antenna) scheme [two channels, where the second channel views the same scene as the first, but one pulse repetition interval (PRI) later]. The AT-interferometric technique is being used for very high resolution imagery as well as for SAR-GMTI (Ground Moving Target Indication) demonstrations. In addition, RADARSAT-2 is the first mission offering the choice of right- or left-looking observations from the subsatellite track on an operational basis (see D.35.4). This left- or right-looking direction capability of the SAR antenna doubles the instrument FOR (Field of Regard) coverage for event monitoring and

other tasks. The provision of multi-polarization as well as polarimetric imagery is another enabling feature of RADARSAT-2.

- The TerraSAR-X (TSX-1) mission of DLR/EADS Astrium GmbH (launch June 15, 2007) introduces also the concept of split along-track antenna design providing full-transmit and dual-channel receive apertures for AT-interferometry applications (increased resolution and demonstration of ocean current motion sensing). The DPC (Displaced Phase Center) antenna technique is used on a single platform. In receive, time-frequency variant digital beam forming is applied to focus the receive gain on the transmitted pulse as it observes on the Earth’s surface. - While nominal observations of TSX-1 are taken on the right of the subsatellite track, there is also a capability for left-side observations for limited periods only. This support mode limitation is due to the fact that power generation is interrupted (the S/C performs a roll maneuver turning the solar array away from the sun).

- The TerraSAR-L mission of ESA (launch in 2009) offers also the capability of dual-sided observations (typically about 20 minutes per orbit).

- Bistatic configurations (see 1.2.3.6) offer the potential of upgrading existing monostatic missions (Interferometric Cartwheel proposed mission of CNES). In this concept, a single SAR instrument on a spacecraft in LEO serves as illuminator - with receiving-only instruments on other nearby spacecraft, participating in the signal recovery from the illuminator (providing in parallel an interferometric configuration). The Cartwheel configuration employs a number of comparatively inexpensive receive antennas mounted on simple platforms arranged such that they can make parasitic (bistatic) use of the signals from a classical SAR instrument (a transmitter) flying in the same orbit and maintaining an optimal interferometric baseline.

- Most spaceborne LEO SAR observations so far (civil missions) were from orbital altitudes between 500 and about 800 km on free-flying spacecraft. Exceptions to this rule were: 1) Almaz-1 with an S-band SAR of the Soviet Union operated at altitudes of 270-380 km (launch March 31, 1991, end of mission Oct. 17, 1992); and 2) The Shuttle missions operated SAR instruments at altitudes between 225 - 300 km.

- Introduction of long-term multiband (multifrequency and multipolarization) SAR systems on a single platform. An instrument with L-band, C-band, and X-band capabilities could greatly enhance the observation return.

- Introduction of the AESA (Active Electronically Scanned Array) 2-D digital beam steering capability, an enabling technology into next-generation civil spaceborne projects (beyond 2010). The AESA technology is providing a spectrum of new applications, including MTI (Moving Target Indication) observations (into otherwise static conventional SAR imagery). – The functional potential of a phased array antenna with 2-D digital beam steering is greatly increased offering such features as: a) introduction of a multichannel system by splitting the beamforming network of the radar antenna and the addition of simultaneous receiving channels, b) simultaneous beam steering in elevation and azimuth (the steering capability in elevation allows the acquisition of images in each point of the access region; the steering capability in azimuth allows the implementation of spotlight-SAR modes that yield high resolution imagery), c) the presence of an active antenna, together with control in both amplitude and phase of each individual T/R module independently in transmission and reception mode, allows optimization of the antenna beam for each individual operational mode.

- The introduction of an onboard information extraction capability (in particular for event monitoring) will be a logical consequence of the image processing capability as the


information is the final objective of SAR observations. Naturally, this real-time function requires considerable onboard processing capabilities. The onboard SAR processing capability reduces also considerably the downlink data transmission needs in support of high-resolution imagery.

3) LEO SAR satellite constellations and formations

At the start of the 21st century, the technology frontier (and the challenges) in high-resolution Earth observation involves LEO constellations/formations as well as eventually observations from MEO and/or GEO.

- The space segment of the COSMO/SkyMed program of ASI, Italy (the launch of the first satellite took place on June 8, 2007) represents the first constellation of SAR satellites (4 S/C in total, each equipped with an X-band SAR instrument), all S/C are phased in the same orbital plane (see B.3). Nominal observations are taken on the right of the subsatellite track; however, there is also a capability for left-side observations for limited periods only. Provision of commercial SAR imagery for civil and military use. Frequent global coverage capability.

- SAR-Lupe, a German military mission, consists of a constellation of 5 S/C in three orbital planes (launch of first S/C in constellation of 5 on Dec. 19, 2006, the SAR-Lupe-2 launch took place on July 2, 2007). Orbital plane 1 contains 2 S/C; orbital plane 2 contains 1 S/C, orbital plane 3 contains 2 S/C. The angle between orbital plane 1/2 is 64º; the angle between orbital planes 2/3 is 65.6º. The phase angles of the S/C are: Orbital plane 1 = 0º + 69º; orbital plane 2 = 34.5º; orbital plane 3 = 0º + 69º. The five spacecraft constellation offers very short response times and a high system redundancy.

- Introduction of bistatic and multistatic SAR system configurations (starting with the TechSat-21 mission, a three spacecraft SAR formation of DoD/AFRL. Note: The TechSat-21 program was cancelled in early 2003.

- Starting in early 2009 with the launch of the Tandem-X spacecraft, a close−orbit X-band SAR constellation will be formed with the TerraSAR−X spacecraft (launch June 15, 2007). Both spacecraft, owned and operated by DLR, will provide high−resolution interferometric observations in monostatic, bistatic, and alternating bistatic modes.

4) GEO SAR/Radar satellites — in study phase as of 2002/5. 353) 354) 355) The GEO location provides a continuous observation capability (and much larger target areas, i.e. footprints, to be observed than from LEO); for instance, large weather systems can be sampled in intervals of minutes to an hour or so (depending on the application — rather than days as is normally provided by LEO spacecraft — this is because SAR interferograms may only be formed from identical viewing geometries, so the temporal sampling of an InSAR system is determined by the time required for the spacecraft to repeat its flight track).

Generally, SAR observations from geostationary orbit require larger apertures (GEO S/C are 45 higher in orbit than LEO S/C) and additional power to achieve sufficient SNR as compared to LEO missions; also a relative motion to the target area is needed to form a synthetic aperture. An inclined GSO (Geosynchronous Orbit) provides a relative motion to the target area. The advantages of GSO apply, i.e. the observation coverage time of a region of interest is greatly increased, the overall FOR (Field of Regard) is dramatically increased at this altitude. With a ±8º beam-steering capability in cross-track as well as in along-track,

it is possible to cover out to 6800 km on either side of the nadir point and the beam can be squinted forward and backward as desired. A key characteristic of a geosynchronous SAR is that it is very flexible in terms of operational modes (stripmap, ScanSAR, spotlight).

- RELOSS (Regional Earth-Locked Observation SAR System) is an ESA study (completed in 2003) for a possible future mission, to assess the feasibility of a SAR observation concept from a GSO platform.

- NIS (NEXRAD-In-Space), is a challenging mm-wave technology development concept in NASA's ESE (Earth Science Enterprise) program. The objective is to fly a Doppler radar instrument on a GEO spacecraft, permitting detailed tracking and monitoring of the life cycle of severe storm systems like hurricanes and cyclones. A Doppler radar has the ability to penetrate precipitating and non-precipitating clouds to support the study of: a) the dynamics of mesoscale structures, b) vertical profiling of precipitation and c) input data for NWP models. The requirements call for the use of a Ka-band (35 GHz) Doppler radar for high spatial resolution and the use of a very large scanning reflector antenna (30 m diameter, deployable system). The instrument is designed to measure rainfall rate at 13 km horizontal resolution and 300 m vertical resolution, and the line-of-sight Doppler velocity at 0.3 m/s precision, of the 3-D hurricane structure once per hour throughout its life cycle. A spirally scanning radar with a maximum off-nadir look angle of 4º results in a 28º incidence angle from GEO providing a coverage of 5,300 km diameter on Earth's surface. 356 357

- SAR observations from GEO require the introduction of new technologies to make the concept affordable. In particular, lightweight, large-aperture, and electronically-steerable phased array antennas are required to address the measurement needs. 358 Current LEO systems are designed using modular architectures where electronic components are individually packaged and integrated onto rigid manifolds or panels (the phased array structure of the SRTM mission had an aerial density of 20 kg/m²). One method to dramatically reduce the weight, volume and associated cost of space-based SAR is to replace the conventional rigid manifold antenna architecture with a flexible thin-film membrane. NASA/JPL designed a new membrane antenna with an aerial density of < 2 kg/m² providing an antenna bandwidth of 80 MHz at L-band. This concept requires nothing less than the development of "T/R membrane," analogous to the T/R module system of LEO missions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEO</th>
<th>Low MEO</th>
<th>High MEO</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>800 km</td>
<td>3000 km</td>
<td>14,000 km</td>
<td>35,800 km</td>
</tr>
<tr>
<td>Capability enabled</td>
<td>- Improved modeling of fault dynamics</td>
<td>- Local earthquake forecasting - Limited disaster response</td>
<td>- Earthquake forecasting - Disaster response</td>
<td>- Earthquake forecasting - Disaster response</td>
</tr>
<tr>
<td>Usable swath</td>
<td>350 km</td>
<td>3900 km</td>
<td>6200 km</td>
<td>7000 km</td>
</tr>
<tr>
<td>Repeat time</td>
<td>8 day</td>
<td>2 day</td>
<td>1 day</td>
<td>1 day</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>30 m</td>
<td>30 m</td>
<td>30 m</td>
<td>30 m</td>
</tr>
<tr>
<td>3-D displacement acc</td>
<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Radiation environment</td>
<td>Moderate</td>
<td>High</td>
<td>Severe</td>
<td>High to severe</td>
</tr>
<tr>
<td>Antenna area</td>
<td>50 m²</td>
<td>400 m²</td>
<td>500 m²</td>
<td>700 m²</td>
</tr>
<tr>
<td>Transmit power</td>
<td>5 kW</td>
<td>30 kW</td>
<td>45 kW</td>
<td>60 kW</td>
</tr>
<tr>
<td>Beam scan</td>
<td>±30º (elevation)</td>
<td>±15º (az/ele)</td>
<td>±8º (az/ele)</td>
<td>±6º (az/ele)</td>
</tr>
<tr>
<td>No of T/R modules</td>
<td>400</td>
<td>14,000</td>
<td>17,000</td>
<td>24,000</td>
</tr>
</tbody>
</table>

357) http://esto.nasa.gov/conferences/estc2003/Presentations/B3/B3P2(Im).pdf
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEO</th>
<th>Low MEO</th>
<th>High MEO</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/R module efficiency</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td>DC power</td>
<td>1667 W</td>
<td>7500 W</td>
<td>9000 W</td>
<td>10,000 W</td>
</tr>
</tbody>
</table>

Table 22: Summary of InSAR L-band characteristics for LEO, MEO, and GEO observations \(^{359}\)

5) **GEO or GEO/LEO SAR satellite constellations.** This field of multistatic SAR applications (see chapter 1.2.3.6) is in the study phase by several institutions. Such concepts may of course drastically increase the capabilities of future SAR remote sensing applications.

- Geostationary illuminator - LEO echo data reception, i.e., the transmitter and receiver are in different orbits (concept feasibility study phase of DLR as of 2002/3). Such a multistatic SAR imaging concept consists of an illuminator S/C in GEO, using a high-power FMCW (Frequency Modulated Continuous Wave) transmitter and a steerable antenna that can be pointed to an observation region of interest (CW operation implies higher average power or lower peak power of the transmitter). \(^{360}\) In parallel, a cluster of microsatellites is flown in LEO, with a receive antenna on each S/C. Such a configuration may be optimized for a broad range of applications like frequent monitoring, wide swath imaging, single-pass cross-track interferometry, along-track interferometry, resolution enhancement or radar tomography (the SAR tomographic information is obtained from a wideband pulse that provides multiple illuminating wavelengths). - This concept offers a number of implementation solutions to suit project constraints/requirements. An example is the installation of the transmitter payload on a commercial communications satellite in GEO (a low-cost flight of opportunity), this would save the cost of a separate GEO spacecraft for the illumination function. \(^{361}\)

The coverage region of a SAR instrument in GEO is restricted to approximately ±55° latitude due to the shallow incident angle with respect to the illuminator. This restriction may be avoided by use of illuminators in GEO or in MEO.

A SAR constellation in GEO (illuminator) and in LEO (multiple receiver platforms) offers an interesting feature by the fact that the transmit path exceeds by far the distance from the target to the receiver (the ratio is about 45:1). As a result of the long transmit path, the antenna footprint of the geostationary illuminator will have an extension of more than 100 km in both azimuth and range. \(^{362}\) This is in fundamental contrast to the small footprints of the LEO receivers for which we will have a typical diameter in the order of 6 km, assuming a downward-looking parabolic antenna with a radius of 1.25 m. Thus, the simultaneously accessible region with a fixed aperture receiver is very limited from LEO. Such a limitation may be avoided by DBF (Digital Beamforming) on receive, where the receiver antenna is split into multiple subapertures and each subaperture signal is separately amplified, down-converted, and digitized. The digital signals can then be combined in a dedicated signal processor to form multiple antenna beams with arbitrary shapes. This makes effective use of the total signal energy within the large illuminated footprint and will introduce a high flexibility in operating the bistatic SAR constellation (see Ref. 289).

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\(^{360}\) Note: Pulse radar systems measure range in the time domain, whereas FMCW radars measure range in the frequency domain. An advantage of the FMCW technology may lead to smaller instruments.


- **DBF in elevation:** The formation of multiple independent beams in elevation allows for the simultaneous mapping of several distinct subswaths with full azimuth resolution and high antenna gain. By combining multiple subswaths, it is also possible to map a wide image swath (>100 km). Furthermore, the use of a frequency modulated continuous wave (FMCW) illumination source with low chirp rate will allow for a sub-sampling of the recorded signals, thereby reducing the data rate substantially. This is due to the fact, that at any instant of time the bandwidth within a sufficiently narrow elevation beam will only be a small fraction of the total bandwidth of the transmitted chirp. The digital beamforming corresponds therefore to a bandpass filter bank which divides the recorded range spectrum in multiple sub-spectra.

- **DBF in azimuth:** The formation of multiple beams in azimuth will allow for the division of a broad Doppler spectrum into multiple sub-spectra with different Doppler centroids. The bandwidth in each subchannel corresponds to the total length of the receiver antenna, which determines the minimum allowable PRF. A coherent combination of the sub-spectra will then yield a broad Doppler bandwidth for high azimuth resolution. This technique is especially attractive for high resolution imaging with SAR systems that require long antenna structures for the unambiguous imaging of a wide swath.

- **GLORIA (Geostationary/Low-Earth Orbiting Radar Image Acquisition System),** a study proposal by the University of Michigan. The proposal is based on a constellation of few (4) geostationary, radar transmitter satellites in L-band (as illuminators), and a constellation of LEO receiver satellites in various orbits. Tandem LEO satellites with sufficient spatial separation, are envisioned to form a high-resolution single-pass bistatic interferometric SAR. 364)

6) **Planetary ground-penetrating radar:** MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) is a low-frequency nadir-looking pulse-limited radar sounder and altimeter on ESA’s Mars Express mission (launch June 2, 2003) designed to search beneath Mars’s surface for liquid water, ice, or permafrost layers. MARSIS employs

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363) The image was kindly provided by Gerhard Krieger of DLR, Oberpfaffenhofen, Germany
SAR techniques and a secondary receiving antenna (monopole) to isolate subsurface reflections. The primary goal is to map the composition of the top 5 km of the planet’s crust; secondary goals are surface characterization and ionospheric sounding. The instrument broadcasts very long wavelength radio waves (in the VF and VLF range) and observes the time of the reflections, an observation technique called ground-penetrating radar. RF waves in the range 1.3 - 5.5 MHz (corresponding to a wavelength range of 230 m to 55 m) are being transmitted from a 40 m long deployed antenna (high-efficiency dipole antenna). A significant portion of the VF/VLF waves are capable of penetrating the planet’s surface to depths of 2 to 5 km, thereby encountering various layers of different material. For boundaries between materials of different types — like ice and rock, or sand dunes and bedrock — there should be a detectable radar echo. The time delay between the surface reflection and any subsurface reflections permits to determine the depth to the boundary. The time differences involved are tiny, measured in nanoseconds. The multi frequency observation allows the estimation of the material attenuation in the crust, providing significant indications on the dielectric properties of the detected interfaces. The best ground penetrating studies are being made during night when the Martian ionosphere is least active and when the spacecraft is less than 800 km from the Martian surface, a condition that occurs for 26 minutes during each 6.75 hour orbit of Mars Express.  

In its standard operating mode, the instrument is capable of making parallel measurements in 4 bands centered at 1.8, 3.0, 4.0 and 5.0 MHz. MARSIS functions by transmitting a linear frequency modulated chirp using a nadir-looking dipole antenna. The return signal is received on both the dipole antenna and a secondary monopole antenna oriented along the nadir axis. The secondary antenna has a null in the nadir direction and receives primarily the off-nadir surface reflections. The main transmit and receive antenna is a deployable dipole with two 20 meter elements, arranged so that its peak gain is in the spacecraft nadir direction. The entire instrument, including antenna and data processing unit, weighs about 12 kg. The PI of MARSIS is Giovanni Picardi, “La Sapienza” University of Rome, Rome, Italy.

<table>
<thead>
<tr>
<th>Center frequency (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Radiated power (W)</th>
<th>Transmit pulse width (μs)</th>
<th>PRF (Pulse Repetition Rate) (Hz)</th>
<th>Science data rate, max (min) (kbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>1.0</td>
<td>1.5</td>
<td>250 or 30</td>
<td>130</td>
<td>75 (18)</td>
</tr>
<tr>
<td>3.0</td>
<td>1.0</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>1.0</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>1.0</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 23: Characteristics of the MARSIS instrument

The typical spatial resolution of the MARSIS data is 5 km x 10 km in the along track and cross track directions, respectively. The ground resolution requirements for the subsurface and surface sounding experiments indicate the maximum footprint dimensions at the surface. The along-track requirement of 10 km width and spacing means that the system is required to obtain data uniquely associated with a 10 km wide along-track footprint, every 10 km. The cross-track footprint shall be no larger than 32 km in a pulse-limited sense; for most smooth regions, the surface area responsible for echoes in cross-track dimension is expected to be much smaller. The range resolution requirement of 150 m in free space is intended to result in a subsurface depth resolution better than 100 m.  

The MARSIS instrument was developed within the framework of a Memorandum of Understanding between the Italian Space Agency (ASI) and NASA. It was developed by Ale-
nia Spazio under ASI management and the scientific supervision of the University of Rome, La Sapienza, in partnership with the Jet Propulsion Laboratory (JPL) in Pasadena, California, and the University of Iowa. JPL provided the antenna manufactured by Astro Aerospace. It is the first instrument designed to actually look below the surface of Mars.

Note: MARSIS started its science operations on July 4, 2005, after the first phase of its commissioning was concluded. 369)

369) http://www.esa.int/esaCP/SEMQAN808BE_index_0.html
1.2.4 Microwave Region, Passive Observations

Radiometry is the science of radiation measurement in any portion of the electromagnetic spectrum, i.e. the study of creation, transport, and absorption of electromagnetic energy, and the wavelength-dependent properties of these processes (see O.7). The term radiometry is also often used to include the detection of the quantity, quality, and effects of such radiation. Microwave radiometry is the measurement microwave radiation, generally considered to be in the wavelength region from about 1 mm to 1 m. A passive system is restricted to measuring the incoming radiation intensity of a wave spectrum in question. – The term photometry describes these phenomena for the optical region of the spectrum, generally considered to be in the wavelength region from about 0.1 μm to 1000 μm (the latter value corresponds to 1 mm).

Some background in radiative history: It was Johann H. Lambert (1728-1777) who noted that the amount of radiated energy in a solid angle is proportional to the cosine of the angle between the emitter and the receiver. Gustav Kirchhoff (1824-1887) discovered that the emissivity of a radiating surface is equal to its absorptivity and that the total of reflection, absorption and transmission of a material was always equal to 1. The Austrian physicist Josef Stefan (1835-1893) determined the total radiant emittance from a source for all spectral wavelengths to be equal to the emissivity multiplied by a constant (the Stefan-Boltzmann constant) times its temperature raised to the fourth power. In 1866, Samuel P. Langley (1834-1906) used a crude bolometer to study the radiation of carbon at different temperatures. The main architect of modern radiometry was Max Planck (1858-1947, Humboldt University, Berlin). In 1900, Max Planck presented his blackbody radiation law, representing a great achievement in all of physics (in 1918, Max Planck received the Nobel prize in physics for his work).370)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant energy</td>
<td>Joule (J)</td>
<td>Energy leaving or reaching a surface or a point</td>
</tr>
<tr>
<td>Radiant flux</td>
<td>Watt (W)</td>
<td>Energy per unit of time (also referred to as “power”)</td>
</tr>
<tr>
<td>Radiant emittance</td>
<td>Watt/meter² (W/m²)</td>
<td>Radiative energy leaving a point on a surface as measured on the hemisphere centered on that point</td>
</tr>
<tr>
<td>Irradiance</td>
<td>Watt/meter² (W/m²)</td>
<td>Radiative flux incident on a surface</td>
</tr>
<tr>
<td>Radiant intensity</td>
<td>Watt/steradian (W/sr)</td>
<td>Radiative energy per unit time measured per unit solid angle</td>
</tr>
<tr>
<td>Radiance</td>
<td>Watt/meter²/steradian (W/m²/sr)</td>
<td>Radiative flux emitted from a single point per unit solid angle</td>
</tr>
</tbody>
</table>

Table 24: Radiometric terms and abbreviations (quick reference)

Passive microwave radiometry is of fundamental importance in Earth observation yielding a wealth of information, in particular in such applications as meteorology, climate, and hydrology (water cycle).371) A microwave radiometer is a highly sensitive receiver system capable of detecting and measuring the rather low energy levels of microwave radiation whose nature is generally incoherent (i.e. noise-like source). Note: If there is mentioning of “coherent” microwave radiation in the literature, it usually refers to the “sampling method at Nyquist frequency or better.” - When a scene is observed by a microwave radiometer, the radiation received by the antenna is partly due to the self-emission by the scene and partly due to the reflective radiation originating from the surroundings. For sounding applications (i.e. measuring the atmosphere), microwave radiometers are relatively unaffected by cloud cover, this is considered a great advantage when compared to observations in the infrared region, making the microwave region particularly suitable for future NWP (Numerical Weather Prediction) applications.


1.2.4.1 Microwave radiometers

The spectral range of remotely-sensed data was considerably enlarged by the use of radiometers in the microwave region [the overall microwave region is considered for wavelengths from about 1 mm (300 GHz) to 1 m (300 MHz); remote sensing is being conducted in the MMW (millimeter-wave) region (i.e., 1-10 mm or 300 GHz to 30 GHz); the frequency range from 1-20 GHz is mostly used for surface radiometry due to atmospheric attenuation].\textsuperscript{372}

Passive microwave (MW and MMW) Earth observation radiometry introduced such applications as temperature sounding for meteorological and climate applications, sea-ice mapping for navigation in polar regions, measurements of ocean surface temperature and ocean surface wind speeds. Eventually the applications of radiometers included also observations of land surface features and the measurement of atmospheric constituents (trace gases for atmospheric chemistry applications). – Imaging in the MMW region is known to provide reasonable penetration of poor weather and dielectrics. This attribute has always been of interest to the civil and military communities with such applications as surveillance mapping.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Ocean Surface</th>
<th>Land Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, moisture soundings</td>
<td>Sea Surface Temperature (SST)</td>
<td>Vegetation condition monitoring</td>
</tr>
<tr>
<td>Winds, Clouds, Aerosols</td>
<td>Surface winds</td>
<td>Soil moisture, Snow cover</td>
</tr>
<tr>
<td>Precipitation monitoring</td>
<td>Ocean color</td>
<td>Albedo, Insolation</td>
</tr>
<tr>
<td>Earth radiation budget</td>
<td>Ice cover</td>
<td>Fire location, plume smokes</td>
</tr>
<tr>
<td>Trace gases (ozone, CO\textsubscript{2}, etc.)</td>
<td>Sea level</td>
<td>Land Surface Temperature (LST)</td>
</tr>
</tbody>
</table>

Table 25: Typical application spectrum of radiometric instruments

Two generic types of radiometers have evolved, **profiling instruments** (or sounders, also referred to as broadband radiometers), and **surface imaging instruments** (multichannel radiometers). The respective measurement techniques employed by these radiometer types involve in general multi-channel observations:

1) Measurement of microwave emissions (brightness temperatures) near known molecular “absorption/emission lines” are used for profile retrievals.\textsuperscript{373} The retrieval water vapor profiles (and inferred temperate) involve measurements of brightness temperatures near known absorption lines of oxygen and water vapor molecules (oxygen lines near 50-57 GHz and near 118 GHz; water vapor absorption lines are for instance near 22.3 GHz, 183 GHz, 383 GHz, 425 GHz, 625 GHz). Note: Other atmospheric trace gases exhibit absorption lines different from those of oxygen or water vapor. See also chapter 1.2.6.

2) Atmospheric “window frequencies” refer to those wavelength regions of the spectrum, where absorption for the whole atmosphere is very low; hence, these “transparent” frequencies are mostly used to study surface phenomena (ocean, ice, land, etc.). The most common window frequencies from LEO are near: 6 GHz, 10 GHz, 19 GHz, 23 GHz, 37 GHz, 90 GHz, and 150 GHz. Typical “sounding channels” are at: 23 (water vapor), 50-60 (oxygen), 118, 166-183 (water vapor), 380, 425 GHz, etc. - the concept exploits more the absorption bands. Hence, the profiles observed at the different frequencies exhibit also different sensitivities to the various items being observed.

3) Dual polarization for roughness effects (over the sea) and scattering from ice (over land).

- Spaceborne microwave observations started September 23, 1968 with the launch of Cosmos 243 satellite (in sun-synchronous LEO) which carried a non-scanning, nadir-view-

\textsuperscript{372} L. Phalippou, E. Gerard, “Study report to the European Space Agency on the use of precise microwave imagery in numerical weather prediction,” ECMWF, 1996.

\textsuperscript{373} Note: The absorption/emission principle is based on energy exchanges between the gas molecules and the electromagnetic field occurring at characteristic frequencies.
ing 4-channel radiometer [wavelengths: 8.5 cm (3.5 GHz), 3.4 cm (8.8 GHz), 1.35 cm (22.2 GHz), and 0.8 cm (37.5 GHz)] with the objective to estimate atmospheric water vapor, liquid water, ice cover, and sea temperature. The same radiometer was also flown on Cosmos 384 with a launch in 1970. Nimbus-5 (launch Dec. 11, 1972) of NASA carried a radiometer with the name of NEMS (Nimbus-E Microwave Spectrometer). This represented the first step in the application of the microwave spectrum to global sensing of the atmospheric temperature structure. Another radiometer on Nimbus-5 was ESMR (Electrically Scanning Microwave Radiometer). The Skylab (launch of Skylab-1 May 14, 1973) space station flew two radiometers, S-193 and S-194. The NEMS instrument on Nimbus-5 was followed by SCAMS (Scanning Microwave Spectrometer), flown on Nimbus-6 (launch June 12, 1975), which led to the first MSU (Microwave Sounding Unit), flown on TIROS-N (launch Oct. 13, 1978). The SMMR sensor was flown on SEASAT (launch June 27, 1978) and on Nimbus-7 (launch Oct. 24, 1978). See also chapter O.7 and Table 793. 374) 375)

- Passive spaceborne radiometers have been primarily frequency-tuned to vertically sound and map specific constituents (gases and dust in atmospheres, and bulk properties on planetary surfaces). The first systems implemented were sounders (profiling systems). These were followed by the new type of surface imaging radiometers with the availability of focal plane antennas and better processing capabilities. The 1980s and 1990s mark a shift away from Dicke-switched superheterodyne radiometers to total-power systems, facilitating radiometer configuration simplification and sensitivity improvements (example: the SSM/I instrument, flown on the DMSP series since 1987, is the first mission which employs a total-power radiometer configuration). In the 1990s, superheterodyne receivers with mixers directly coupled to feedhorns and feeding low-noise IF amplifiers continue to dominate MMW radiometry. The mixers in superheterodyne radiometers remain the critical element for sensitivity. Mixers with whiskerless diodes yield significant improvements in reliability relative to mixers with whisker-contacted diodes.

- Future radiometer instruments are expected to include more receiver channels in a wider spectral range (MW, MMW, and sub-MMW), offering the ability for interpretation of a wider range of geophysical parameters. To reduce mass and volume, multichannel sounding instruments generally employ a single reflector antenna, along with FSS (Frequency Selective Surface) technology in the quasi-optical feed train to provide spatial demultiplexing. Improvements are likely to come from solid-state technologies based on MMIC (Microwave Monolithic Integrated Circuit) receiver chip development, providing direct amplification and detection in combination with FPA (Focal Plane Array) imaging. In addition, the aperture synthesis method seems to be a promising development, providing a capability of 2-D radiometer imagery generation. Some required technologies in radiometry are:

  - Improvements to the front-end quasi-optical components, particularly the beam splitters, are required to satisfy the demanding radiometric performance which has been specified for future mm-wave instruments. 376)
  
  - The MMIC technology is gradually replacing the older MIC (Microwave Integrated Circuit) and TWTA (Traveling Wave Tube Amplifier) technology in RF electronics. MMIC-based receivers are capable of observing the stronger atmospheric signals
  
  - SIS (Superconductor-Insulator-Superconductor). SIS-based receivers provide the lowest noise level environment in the frequency range of 200-300 GHz
  
  - The HEB (Hot Electron Bolometer) technology provides best noise performance in the frequency range >1000 GHz

  - An effective low-power cooling system is essential for all microwave measurements.


Submillimeter-wave radiometers [300 GHz (1 mm) < frequency range > 3000 GHz (0.1 mm)]. At the end of the 1990s, new generations of microwave limb sounders (profilers) and imaging radiometers (or spectroradiometers) are emerging with advances in microwave detector technology, extending their measuring capability into the sub-mm wavelength region. The technology for these high-frequency ranges requires radiometers with superconducting heterodyne receivers or with FTS-based systems (the FTS technique provides a means to measure atmospheric radiance). The cooling to superconducting temperatures of the detection system represents always a major investment in instrument design. The problem of past LTS (Low-Temperature Superconductivity) cooling seems to be gradually replaced by HTS (High-Temperature Superconductivity) cooling systems.

The interest in the short wavelengths is due to the fact that many molecules of importance in photochemistry exhibit emission lines in these wavelengths (e.g. HCl, OH). Submillimeter remote sensing has in addition advantages that complement visible and infrared techniques. Since the wavelength of submillimeter radiation is comparable to the size of ice particles in cirrus clouds, observed brightness temperature changes from cirrus are correlated to ice mass. Some early airborne instruments in this class are: MIR (Millimeter-wave Imaging Radiometer) of NASA/GSFC flown on ER-2 which was upgraded in 1994 with three 325 GHz channels, THOMAS (THz OH Measurement Airborne Sounder, since 1994) of DLR, and ASUR (Airborne Submillimeter SIS Radiometer, since 1994) a cooperative sensor of SRON (Groningen, Netherlands) and the Institute of Environmental Physics at the University of Bremen. The NASA-sponsored FIRSC (Far Infrared Sensor for Cirrus) FTS instrument is flown on a T-39 (Sabreliner) aircraft since April 1998.

The first spaceborne sub-mmw instruments for the measurement of trace gases are: SMR (Submillimeterwave Radiometer) flown on the Swedish satellite ODIN (launch Feb. 20, 2001). There are sub-mm channels and one lower frequency channel on SMR. SMILES (Superconducting Submillimeter-wave Limb Emission Sounder) of JAXA (Japan Aerospace Exploration Agency), formerly NASA, is planned to fly on ISS/JEM in 2008. ESA/ESTEC has the following limb-sounding sensors (in the sub-mm region) under development: MASTER (Millimeter-wave Acquisition for Stratosphere Troposphere Exchange Research), SOPRANO (Sub-millimeter Observation of Processes in the Absorption noteworthy for Ozone) and PIRAMHYD (Passive InfraRed Atmospheric Measurements of HYDroxy). NASA developed MLS (Microwave Limb Sounder), with three channels in the mm-range and two double sideband sub-mm channels, flying on Aura (former EOSCHEM) in 2004 (launch July 15, 2004). MLS is a high background microwave sounder with room temperature detection capability. The new MLS instrument (frequencies of > 600 GHz) is a further development of MLS flown on UARS [Note: MLS on UARS has observed atmospheric thermal emissions from chlorine monoxide (ClO), ozone (O3), water vapor (H2O), sulfur dioxide (SO2), and molecular oxygen (O2), at frequencies of 63, 183 and 205 GHz].

Radiometric imaging and the introduction of sea ice observation. The NOAA-2 S/C (launch Oct. 15, 1972) was the first operational weather satellite to rely solely upon radiometric imaging to obtain cloudcover data and some sea ice information using VHRR. Prior to the launch of NOAA-2, the U.S. Navy's F-106D satellite included an imaging radiometer for observing cloud cover. The NOAA-2 satellite carried the first operational weather satellite that employed radiometric imaging to observe cloud cover. The VHRR (Visible and Infrared Radiation Satellite System) instrument onboard NOAA-2 was able to detect cloud cover over the ocean and land surfaces, providing valuable information for weather forecasting and marine navigation. The VHRR instrument aboard NOAA-2 operated in the visible and infrared spectral regions, allowing it to observe a wide range of atmospheric conditions. The data from the VHRR instrument helped improve the accuracy of weather forecasts, particularly in remote areas where ground-based observations were limited. The VHRR instrument onboard NOAA-2 was a significant advancement in satellite remote sensing, marking the beginning of a new era in operational meteorology.
to 1972, sea ice observations were generally obtained from coastal stations, transiting ships, and aircraft patrol. Nimbus-5 of NASA followed shortly thereafter (launch Dec. 11, 1972) with a payload of 4 radiometers, in particular EMSR (Electrically Scanning Microwave Radiometer). Nimbus-5 made it possible for the first time to routinely observe sea ice covered regions of the globe from space. The sea ice observing capability was greatly enhanced in 1978 with SEASAT (launch June 28, 1978), TIROS-N (launch Oct. 13, 1978) the first AVHRR sensor is flown, and Nimbus-7 (launch Oct. 24, 1978). SEASAT and Nimbus-7 were flying SMMR (Scanning Multichannel Microwave Radiometer), permitting sea ice observations among other geophysical parameters. The DMSP series of DoD is providing sea ice observation data with OLS (since 1979) and in particular since the launch of the first SSM/I in 1987. 382)

The polar orbiting weather satellites of today continue to provide information on sea ice (surveillance function). The extent of sea ice is of importance to the all seafaring nations (forecasts for operation of commercial marine, navy, etc.). In addition, the extent and topography of sea ice is an important variable in connection with both ocean heat budget and Earth's radiation balance [in the context of climate research (global change, cryosphere and its effect on sea level, etc.)], using such radiometers as MODIS, MERIS, ASTER, AMSR, AMSR-E and WindSat (Wind Microwave Radiometer).

- Conventional radiometers offer bandwidths in the order of about 20 MHz at a particular center frequency (say, at L-band of 1.4 GHz). For increased sensitivity in radiometry, bandwidths in the order of 100 MHz are desirable. 383) However, RFI (Radio Frequency Interference) impairs considerably the operation of microwave radiometry, in particular at L-band, to improve sensitivity in applications such as soil moisture and ocean salinity sensing. Much of the RFI in this band originates from radars with pulse lengths of microseconds. Conventional total-power radiometers, which integrate over intervals in milliseconds or greater, are affected by the interference; hence, they are poorly suited to this task. A mitigation technique, using FPGAs, has been demonstrated in a number of field tests and flights (in 2002) conducted by the Electro Science Laboratory at OSU (Ohio State University) with NASA and NSF funding. The results indicate that appropriate choices of the parameters of the RFI mitigation algorithms can significantly reduce the impact of the interference on the microwave brightness measurements. Obviously, these findings are of considerable value in future radiometer designs. 384)

As of 2003/4, NASA/GSFC is developing CoSSIR (Conical Scanning Submillimeter-wave Imaging Radiometer), an airborne total-power broadband microwave radiometer that is designed to measure cirrus cloud parameters: IWP (Ice Water Path), Dme (Median Mass Diameter of Ice Crystals), and WV (Water Vapor) profiles (between 0-12 km altitudes). The instrument has fifteen channels; nine of them at the frequencies of 183.3 ± 1, 183.3 ± 3, 183.3 ± 6.6, 220, 380±0.8, 380±1.8, 380±3.3, 380±6.2, and 640 GHz are horizontally polarized, and the remaining six are dual-polarized at three frequencies of 487±0.7, 487±1.2, and 487±3.3 GHz. The goal of this radiometer development is a receiver centered at 874 GHz with a 75 GHz LO input, an RF horn antenna and an output connector for the IF amplifier. The system will be useful for a broad frequency range without tuning, and the resulting receiver will also be readily scaled to other frequencies in THz band. 385)

1.2.4.2 Soil moisture in passive microwave radiometry

The microwave portion of the electromagnetic spectrum offers a large contrast between water and dry soil sensing, offering the greatest potential for monitoring soil moisture. Soil moisture is a fundamental parameter of the terrestrial environment. Its spatial distribution and temporal variation are crucial ingredients of hydrologic, ecologic, and climatic models, on regional and global scales. \(^{386}\) These measurements are based on relatively low frequency thermal microwave emission [at L-band (1.4 GHz) for soil moisture and SSS (Sea Surface Salinity), 10 GHz and up for precipitation monitoring, and 19 and 37 GHz for snow]. Passive microwave sensing of soil moisture [< 6 GHz (i.e., C-band, L-band, UHF, VHF)] in particular offers a very large contrast between dry and wet soils, little absorption by the atmosphere, and low scattering by vegetation canopy, resulting in analysis over large areas with little or no contamination of the signal. - However, the long wavelengths at these frequencies (microwave range), coupled with the high spatial and radiometric resolutions required by the various global hydrology communities, necessitate the use of very large apertures (e.g., > 20 m at 1.4 GHz) and highly integrated stable RF electronics on orbit. - At the start of the 21st century, technology developments point into the direction of distributed instrument architectures using microwave interferometric techniques such as "synthetic thinned array radiometry" to reduce the mass of large area antenna structures.

<table>
<thead>
<tr>
<th>Satellite; Instrument</th>
<th>Coverage</th>
<th>Frequency (GHz)</th>
<th>Polarization</th>
<th>Ground resolution</th>
<th>Repeat period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Microwave Instruments (radiometers)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nimbus-7, SMMR SEASAT, SMMR</td>
<td>1978-1988 1978-1978</td>
<td>6.6, 10.69, 18, 21, 37 6.6, 10.69, 18, 21, 37</td>
<td>H, V H, V</td>
<td>0.25° 0.25°</td>
<td></td>
</tr>
<tr>
<td>DMS; SMM/I</td>
<td>since 1987</td>
<td>19.4, 22.2, 37.0, 85.5</td>
<td>H, V</td>
<td>70 km x 5 km</td>
<td>1-2 days</td>
</tr>
<tr>
<td>TRMM; TMI</td>
<td>since 1997</td>
<td>10.7, 19.4, 21.3, 37.0, 85.5</td>
<td>H, V</td>
<td>60 km x 6 km</td>
<td>1 day</td>
</tr>
<tr>
<td>IRS-P4; MSMR</td>
<td>since 1999</td>
<td>6.6, 10.65, 18, 21</td>
<td>V&amp;H, V&amp;H, VH, VH</td>
<td>50 km x 36 km</td>
<td>2 days</td>
</tr>
<tr>
<td>Aqua, AMSR-E</td>
<td>since 2002</td>
<td>6.9, 10.7, 18.7, 23.8, 36.5, 89.0</td>
<td>H, V</td>
<td>75 km x 7 km</td>
<td>2-3 days</td>
</tr>
<tr>
<td>ADEOS-II, AMSR</td>
<td>since 2002</td>
<td>6.9, 10.7, 18.7, 23.8, 36.5, 89.0</td>
<td>H, V</td>
<td>70 km x 6 km</td>
<td>2-3 days</td>
</tr>
<tr>
<td>Coriolis, WindSat</td>
<td>since 2003</td>
<td>6.8, 10.7, 18.7, 23.8, 37</td>
<td>H, V</td>
<td>50 km x 10 km</td>
<td>2-3 days</td>
</tr>
<tr>
<td>DMS; SSMIS</td>
<td>since 2003</td>
<td>24 channels: 19.35-183.31</td>
<td>H, V, and H + V</td>
<td>70 km x 42 km 14 km x 13 km</td>
<td>1-2 days</td>
</tr>
<tr>
<td>SMOS; MIRAS</td>
<td>2007</td>
<td>1.4 (L-band)</td>
<td>H, V</td>
<td>&lt; 50 km</td>
<td>3 days</td>
</tr>
<tr>
<td>NPOESS, CMIS + VIIRS</td>
<td>2009</td>
<td>24 channels: 6 - 183.31 3 channels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Microwave Instruments (SARs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERS-1/2, AMI</td>
<td>since 1991</td>
<td>5.3 (C-band)</td>
<td>VV</td>
<td>30 m</td>
<td>35 days</td>
</tr>
<tr>
<td>Radarsat-1, SAR</td>
<td>since 1995</td>
<td>5.3 (C-band)</td>
<td>HH</td>
<td>7-100 m</td>
<td>24 days</td>
</tr>
<tr>
<td>Envisat, ASAR</td>
<td>since 2002</td>
<td>5.3 (C-band)</td>
<td>VV or HH, VV/ HH or VV/VH</td>
<td>30-1000 m</td>
<td>35 days</td>
</tr>
<tr>
<td>ALOS, PALSAR</td>
<td>since 2006</td>
<td>5.3 (C-band)</td>
<td>HH/HV or VV/ VH; HH or VV</td>
<td>10-100 m</td>
<td>46 days</td>
</tr>
<tr>
<td>Radarsat-2, SAR</td>
<td>2007</td>
<td>5.3 (C-band)</td>
<td>HH, VV, HV and VH</td>
<td>3-100 m</td>
<td>24 days</td>
</tr>
</tbody>
</table>

Table 26: Overview of LEO instruments for passive and active soil moisture retrieval

Background on synthetic aperture radiometry. Aperture synthesis is a relatively new technique for microwave remote sensing of the environment (monitoring of “microwave brightness temperature” which is analogous to brightness temperature monitoring in the optical range of the spectrum). The technique (pioneered in radio astronomy) generates high spatial resolution images by dividing the collection area of a telescope (or antenna) into smaller

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apertures spread out in a pattern covering several baselines. In microwave radiometry the concept employs an interferometric technique, in which the product from antenna pairs is sampled as a function of pair spacing. Substantial reductions in the antenna aperture needed for a given spatial resolution can be achieved with this technique. However, the advantages gained from aperture synthesis comes at the expense of reduced sensitivity resulting from the corresponding reduction in physical aperture. Detection sensitivity is an especially critical issue for measurements in LEO orbits (with orbital speeds of about 7 km/s) because of very limited instrument integration time availability per scene. 387)

ESTAR [of NASA/GSFC and MIRSL (Univ. of MA, Amherst), P.87, first flown in 1988], a hybrid real-and-synthetic aperture combination, was the first radiometer built to test the concept of aperture synthesis. The experiences with the airborne ESTAR and MIRAS (ESA, P.133) instruments have demonstrated in particular the potential of aperture synthesis for remote sensing of soil moisture. While ESTAR is based on a 1-D (across-track) interferometer approach, MIRAS employed the 2-D synthetic aperture alternative. The new technology may eventually lead to a new generation of spaceborne passive microwave sensors by helping to overcome limitations set by antenna aperture size. The advantage of aperture synthesis is that it can achieve spatial resolutions equivalent to a total power radiometer with a large effective collecting area using relatively small antennas. The reduction in sensitivity that this entails can be restored because the synthetic aperture system does not need to scan and collect energy from many independent antenna pairs simultaneously.

[Note: Spaceborne soil-moisture sensing may already get a start with two active instruments, namely ASAR (Advanced SAR) on Envisat (launch Mar. 1, 2002), and with PALSAR (Phased Array L-band Synthetic Aperture Radar) on ALOS (launch Jan. 24, 2006). Each of these SAR instruments is dual-polarized, permitting the retrieval of soil moisture for bare soil surfaces and for surfaces with short vegetation cover.]

Examples of passive microwave radiometry (sounding instruments) from LEO satellites for soil moisture retrieval (among other parameters) are:

- ESMR (Electrically Scanning Microwave Radiometer) of the Nimbus-5 mission (launch Dec. 11, 1972) and Nimbus-6 (launch June, 12, 1975) provided first tests of soil moisture retrieval.
- SMMR (Scanning Multichannel Microwave Radiometer) on Nimbus-7 (launch Oct. 28, 1978) and on SEASAT (launch June 28, 1978) provided data for soil moisture retrieval. The instrument provided data until July 1988. 388)
- SSM/I (Special Sensor Microwave Imager) of DMSP series. Soil moisture retrieval is provided with spatial resolutions of 50 km on a 1400 km swath. SSM/I is flown since 1987. SSMIS (Special Sensor Microwave Imager Sounder) is the SSM/I successor instrument on DMSP with soil moisture retrieval capabilities. The first mission of SSMIS is flown on F-16 (launch Oct. 18, 2003). See G.1.1. 389)
- MSMR (Multifrequency Scanning Microwave Radiometer) of ISRO’s IRS-P4 mission (launch May 26, 1999) demonstrates soil moisture retrievals. MSMR is a dual-polarized four-frequency radiometer (see D.22.7).

- AMSR-E (Advanced Microwave Scanning Radiometer-EOS) of AMSR heritage on NASA's Aqua S/C (launch May 4, 2002) retrieves land surface wetness.\(^{390}\)

- AMSR (Advanced Microwave Scanning Radiometer) of JAXA's ADEOS-II mission (launch Dec. 14, 2002) retrieves soil water content.

- WindSat (NRL/IPO) is flown on the Coriolis mission (launch Jan. 6, 2003). The WindSat instrument is considered a technology validation of CMIS (Conical-scanning Microwave Imager/Sounder) a prime instrument on the NPOESS series.

- VIIRS (Visible/Infrared Imager and Radiometer Suite) of the US NPOESS series (first launch in 2009) provides for soil moisture retrieval in 3 channels.\(^{391}\) In addition, CMIS, also flown on NPOESS, providing estimates soil moisture at coarse spatial resolution. A data fusion solution of coarse CMIS and fine VIIRS imagery will provide excellent soil moisture retrievals.

- A first spaceborne demonstration project, employing “synthetic thinned aperture radiometry” (i.e. passive microwave remote sensing) with a sparsely filled 2-D antenna design, is MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) of ESA's SMOS (Soil Moisture and Ocean Salinity) mission, an approved science-driven demonstration mission in the ESA Explorer program - the objective is to obtain multi-incidence observations with sufficient spatial resolution and revisit time. A launch of SMOS with a microwave imaging radiometer (the interferometric design employs aperture synthesis) is confirmed for late 2007 (D.44). In this concept, the required spatial resolution of <50 km for global microwave brightness temperature retrieval (3 day revisit time) in (L-band, 1.4 GHz), demands in turn a large number of aperture synthesis radiometer elements - each having an independent receiver. Measuring the microwave brightness temperature over the oceans enables a determination of sea surface salinity (SSS). At best (open ocean with high salinity) the brightness sensitivity to salinity is \(\Delta T_B / \Delta S = 1 \text{K}/\text{psu} \) (practical salinity unit), and salinity determination to a 0.1 psu level thus requires radiometric measurements to better than 0.1 K. - The swath width of the radiometer is 934 km at an orbital altitude of 755 km, sufficient for a 3-day equatorial revisit time. The microwave brightness temperature is observed in H and V polarization (standard operating mode) with the option to acquire full polarimetric data. The quest for still higher resolutions (in the order of 10 km x 10 km) of future missions will certainly increase the number of receivers in their designs. - On the applications side such data is very much needed for the implementation of hydrologic models of large basins.\(^{392}\)\(^{393}\)

A key issue in comparing passive and active microwave spaceborne methods is the tradeoff between the high spatial resolution of SAR (Synthetic Aperture Radar) methods and the robust retrieval and frequent temporal coverage provided by passive methods (Table 26).\(^{394}\)

- Aquarius/SAC-D is a cooperative mission of NASA and CONAE (Argentina, provider of S/C in definition phase as of 2002/4. The goal is to observe SSS (Sea Surface Salinity) and its variations to climate changes, to study the hydroospheric cycle and variations in the general ocean circulation. The L-band pushbroom radiometer employs a fixed offset system with three beams to scan the ocean surface. It employs a parabolic reflector (3 m diameter push-


broom antenna) illuminated by three feedhorns. On each of the feedhorns is an L-band radiometer (1.413 GHz) to measure ocean microwave emissions. An L-band (1.26 GHz) real-aperture scatterometer (correction for ocean surface roughness) shares the antenna with the radiometer system. The radiometer is of polarimetric design with four separate channels and four noise diode calibration sources. A launch of Aquarius is planned for 2008 (SSO at 600 km altitude with a revisit time of 8 days). The resolution (footprint size) of the data varies between 62 and 100 km. Monthly 100 km resolution maps of SSS will be provided for a mission life of 3 years. 395) 396)

- The NASA technology development program STAR (Synthetic Thinned Aperture Radiometry) is focused on achieving a 10 km spatial resolution global soil moisture mission towards the end of the decade (study phase as of 2002/4) from LEO. 397) 398) The L-band STAR microwave sounding technology promises higher spatial resolutions comparably sized mechanical scanners as well as antenna software-based antenna beam-forming to match the geometry and size of other sensors’ footprints (use of low-power digital correlators and ADC ASICs). Digital correlators are a key hardware component of the new STAR radiometer designs. Combinations of antenna signals are correlated and the resulting spatial coefficients are processed by image reconstruction algorithms. Also development of CULPRiT (CMOS Ultra-Low Power Radiation Tolerant) IC chip design. - This involves a 2-D L-band radiometer with light-weight components, namely LRR (Lightweight Rainfall Radiometer). - The STAR technology concept is also a prime candidate in the GPM (Global Precipitation Measurement) mission of NASA and JAXA (launch 2009) at a center frequency of 10.7 GHz (X-band) to permit high-frequency sampling of rainfall. The technology provides wide swath pushbroom imaging with no moving parts, which significantly reduces spacecraft accommodation requirements. The LRR-X prototype aircraft radiometer is functionally equivalent to the candidate spaceborne sensor design. 399) 400) 401)

1.2.4.3 Conically-scanning microwave radiometers in LEO missions

- Introduction of conical-scanning multi-frequency microwave sounding/imaging radiometers. The general design of such a radiometer features a mechanical scanning mechanism in which a parabolic antenna reflector is physically rotated around an axis. For Earth surface sensing this is normally a vertical axis, and a conical scan with constant incidence angle on the ground results. The antenna reflector can provide a range of frequencies, and the result is often a compact and efficient system. The technology provides a common FOV (Field of View) combining imaging and sounding channels in a wide-swath observation geometry. For each frequency channel, a constant-size resolution cell pattern is maintained along the continuous rotating observation scene using a constant incident angle observation scheme. Ground resolution sizes may range from about 5 km to about 80 km, the higher the frequency channel the finer the resolution. The passive microwave technology has the advantage of cloud penetration observations, it also has the potential to provide such ob-

395) http://aquarius.gsfc.nasa.gov/
servations as rain rate, wind speed and direction over oceans, as well as the conventional temperature and humidity profiles. However, the conical-scanning concept has severe constraints coming from the fact that all data at a given frequency normally is time multiplexed through one single receiver. This means that if a small footprint on the ground is required, the scan speed is large, the dwell time per footprint is small, hence the radiometer integration time is short and the potential radiometric sensitivity is possibly not satisfactory. The large scan speed in itself is also a challenge (for the satellite manufactures). 402)

The following list provides an overview of conical-scanning microwave radiometers:

- **SMMR (Scanning Multichannel Microwave Radiometer)**, a conical-scanning dual-polarization Dicke type instrument (6.6 - 37 GHz) flown on SEASAT (launch June 27, 1978) and on Nimbus-7 (launch Oct. 28, 1978) of NASA. Measurement of SST and wind speed in a 600 km swath.

- **SSM/I (Special Sensor Microwave Imager)**, a conical scanning microwave radiometer with 7 channels, 4 vertical and 3 horizontal. SSM/I of DoD is flown since 1987 on the DMSP series. However, the design of SSM/I, a microwave radiometer, only permits the retrieval of the speed component of the wind vector. The follow-up of SSM/I is SSMIS (Special Sensor Microwave Imager Sounder), first flown on DMSP-F-16 (launch Oct. 18, 2003). SSMIS, a 24-channel instrument, provides a conical scan with a swath width of 1700 km. It is also capable of retrieving soil moisture.

- **MSR (Microwave Scanning Radiometer)**, a conical-scanning instrument flown on the MOS-1 (Marine Observation Satellite-1; launch Feb. 19, 1987) and MOS-1B (launch Feb. 7, 1990) of NASDA, Japan. MSR is composed of two Dicke-type radiometers at 23.8 and at 31.4 GHz.

- **ATSR (Along-Track Scanning Radiometer and Microwave Sounder)**, a conical scanning infrared radiometer (IRR) flown on ERS-1 (launch July 17, 1991), ERS-2 (Apr. 21, 1995), and as AATSR on Envisat (launch March 1, 2002).

- **TMI (TRMM Microwave Imager)** is a dual-polarization conical-scanning radiometer (10-85 GHz) on the TRMM mission of NASA (launch Nov. 27, 1997). The 9 channels on

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TMI allow for simultaneous retrieval of SST, wind speed, columnar water vapor, cloud liquid water, and rain rate. Accurate through-cloud SST retrievals were first provided by TMI at a resolution of 10 km.

- IKAR-P is a 3-channel conical-scanning microwave radiometer that was flown on the Priroda module (launch Apr. 23, 1996) of the MIR station. Measurement of SST.

- MSMR (Multifrequency Scanning Microwave Radiometer) is a dual-polarized four-frequency conical-scanning radiometer flown on IRS-P4 (OceanSat-1) of ISRO (launch May 26, 1999). The eight-channel MSMR employs six independent receivers at 6.6, 10.6, 18, 21 GHz. MSMR provides SST, sea surface wind speed, atmospheric water vapor and cloud liquid content in a swath of 1360 km.

- MTVZA (Microwave Imaging/Sounding Radiometer) flown on Meteor-3M-1 spacecraft of Russia (launch Dec. 10, 2001); a 26-channel instrument with a swath of 2200 km. A follow-up instrument, MTVZA-OK (Combined Microwave-Optical Imaging/Sounding Radiometer), a 22-channel instrument, is flown on (launch Dec. 24, 2004) of Ukraine (NSAU) and Russia (Rosaviakosmos). Swath of 2000 km. Monitoring of SST, sea surface wind speed, precipitation, ocean color, and atmospheric temperature and humidity profiles.

- AMSR-E (Advanced Microwave Scanning Radiometer-EOS) is a JAXA instrument flown on NASA’s Aqua mission (launch May 4, 2002). The AMSR-E instrument is a conically scanning total power passive microwave radiometer sensing microwave radiation (brightness temperatures, 40 rpm, 1.6 m parabolic reflector) in 12 channels and 6 frequencies ranging from 6.9 to 89.0 GHz. Horizontally and vertically polarized radiation are measured separately at each frequency. At an altitude of 705 km, it measures the upwelling scene brightness temperatures over an angular sector of ± 61º about the subsatellite track, resulting in a swath width of 1445 km. AMSR-E is of AMSR heritage.

- AMSR (Advanced Microwave Scanning Radiometer) is flown on ADEOS-II (launch Dec. 4, 2002) of JAXA. AMSR is an eight-frequency, total-power microwave radiometer with dual polarization (2 m aperture). Conical scanning at 40 rpm is employed to observe the Earth’s surface with a constant incidence angle of approximately 55º. A swath of 1600 km is provided for the measurement of SST, soil moisture, sea wind speed, water equivalent of snow cover, precipitation intensity, sea ice distribution, precipitable water, etc.

- The WindSat (Wind Microwave Radiometer) instrument on the Coriolis mission (launch Jan. 6, 2003) of NRL uses a conically scanned 1.83 m parabolic offset reflector with multiple feeds.

- The MADRAS (Microwave Analysis and Detection of Rain and Atmosphere Systems) radiometer of ISRO is planned to be flown on the cooperative mission of ISRO and CNES, called Megha-Tropiques (planned launch 2009). MADRAS is a five-frequency (9 channel) mechanical conical-scanning passive microwave radiometer providing brightness temperature measurements (18.7 to 157 GHz). The LEO S/C orbit will only cover the equatorial regions (inclination of 20º), see A.22.

- The AMSR-2 (Advanced Microwave Scanning Radiometer-2) of AMSR heritage is planned to be flown on the GCOM-B1 (Global Change Observation Mission) mission of JAXA (successor to ADEOS, ADEOS-II in the timeframe 2007).

- The CMIS (Conical-scanning Microwave Imager/Sounder) instrument of the IPO NPOESS program (first launch in 2009) employs dual-rotating reflectors with apertures of 2.2 m and 0.7 m in diameter to make “all-weather” measurements across a large frequency range of 6-190 GHz and use of an an FFT implementation. Polarizations for selected imaging channels are being used to derive ocean surface wind vectors similar to what has previously been achieved with active scatterometers. Measurement of soil moisture, cloud base
height, etc. CMIS is considered to be the next-generation conical-scanning microwave radiometer (with regard to capabilities); it is the largest and also the most complex payload of the NPOESS satellites.

- As of 2003/4, NASA is defining HYDROS (Hydrosphere State Mission) within ESSP. The objective is to provide a global view of the Earth’s changing soil moisture and land surface freeze/thaw state. The HYDROS measurement approach employs a combined passive/active low-frequency (L-band) microwave instrument to measure the land hydrosphere state globally from space. The scatterometer (1.26 GHz) and radiometer (1.41 GHz) share a common 6 m diameter antenna pointing at 39.3º (incidence angle) with respect to nadir. The antenna is rotated at 14.6 rpm to provide a scanned swath of 1000 km (conical scan). Polarization of the scatterometer in VV, HH, and HV with a resolution of 3 km. The radiometer is polarized in H, V, and U with resolutions of 40 km. An expected launch of HYDROS is in 2009/10 (SSO of 670 km altitude). The revisit time is 3 days. 403) 404)

1.2.4.4 Pushbroom versus synthetic aperture concept in radiometry

The provision of adequate spatial data resolution on the ground (i.e., to obtain a small footprint size for brightness temperature observations) has been an inherent requirement (and problem area) for all LEO spaceborne missions carrying a radiometer payload, in particular of the type L-band microwave radiometer (spectral window of 1.4 GHz, wavelength of about 22.5 cm), needed for the derivation of such geophysical parameters as soil moisture and ocean salinity.

A conventional microwave radiometer (such as a conically scanning instrument) creates imagery by mechanically scanning the antenna in such a way that the footprint covers a certain swath consecutively. Apart from mechanical complications, this observing method (of a single radiometer) leads to relatively short dwell times for each footprint, resulting in a short integration time and in poor instrument sensitivity.

In most microwave radiometer implementations, the antenna is generally the dominant instrument subsystem that determines the ultimate measurement performance and governs the spacecraft accommodation (dictated by resolution requirements). Of course, higher spatial resolutions of radiometers can be achieved by providing larger real-aperture antennas (and using the pushbroom imaging concept) or by the application of synthetic aperture (i.e., thinned array) techniques. So far, antennas of substantial size (10 m aperture or more) have not been employed in spaceborne microwave applications because of the substantial penalty in associated physical weight and launch packaging volume required.

The two configuration concepts for parallel (simultaneous) radiometric observations may be characterized by: 405)

- Thinned arrays remove much of the bulk of the antenna by using elements at carefully selected positions (related to a wavelength) and “filling in the antenna pattern” with computer processing techniques. They are attractive for single frequency remote-sensing applications, such as soil moisture, but increase in complexity with added frequencies and polarizations.
- In the pushbroom concept, a special antenna having many simultaneous beams each associated with its individual feed and receiver, is employed (analogy to a pushbroom CCD line array). When the satellite moves forwards the beams sweep the Earth’s surface like a broom and make an image without scanning. The many receivers ensure the

404) http://hydros.gsfc.nasa.gov/mis.html
ultimate in radiometric sensitivity. The price to pay is: many receivers as well as a complicated and large antenna. However, at the start of the 21st century, receivers made as MMICs (Microwave Monolithic Integrated Circuit) are small and low power units, and a foldable reflector structure, that works well at L-band, is possible using proven technology.

The radiometer technology that is employed in real-aperture pushbroom radiometer systems utilizes significantly less complex electronic circuitry as compared with the electronic subsystems required for synthetic aperture radiometers. The traditional real-aperture system design utilizes a more mature technology. \(^{406}\) \(^{407}\)

The synthetic aperture radiometer works as a radio camera and acquires a two-dimensional image of the ground by interferometric means. As the satellite moves forwards a swath is imaged. Again, many receivers (and antenna elements) are needed. The big advantage is that a relatively slim structure — the antennas can for example be positioned along 3 arms arranged in a Y shape — can be used, and the structure is easily foldable. A drawback is substantial data processing requirements and less straightforward calibration issues.

The main virtues of the pushbroom radiometer system are that it gives superior radiometric resolution and very likely also superior accuracy and stability.

The main virtues of the synthetic aperture system is that it measures the brightness temperature as a function of incidence angle, and that it is relatively straightforward to fold the Y-shape structure for launch.

The advantages of a pushbroom system might point towards use in cases with extreme requirements to radiometric resolution and accuracy, like in the case of ocean salinity. The advantages of the synthetic aperture system, on the other hand, point towards use in cases with complicated targets like vegetation covered soil, where it is possible to retrieve soil moisture, cleaned for the vegetation influence, due to the multi-incidence angle imaging.

Spaceborne missions under development with implementations of the two techniques:

- **The SMOS (Soil Moisture and Ocean Salinity) mission in LEO (Low Earth Orbit) of ESA (launch in 2007) employs the synthetic aperture radiometer concept** with MIRAS (Microwave Imaging Radiometer using Aperture Synthesis). MIRAS is a 1.415 GHz system with 69 antenna elements and radiometers mounted on three 4.3 m long arms as well as on a central hub, that also holds the many correlators — one for each possible pair of antennas (Y shape, providing a 2-D interferometric radiometer configuration). The corresponding interferometer measurements, also called complex visibilities, are obtained by cross-correlating the signals collected by every pair of antennae; a regularized reconstruction process provides a band-limited brightness temperature map in the reference frame of the instrument. The spatial resolution of the data is \(< 50\) km on a swath of 934 km at an orbital altitude of 754 km. SMOS, although a dual-purpose mission, has its largest focus on soil moisture.

- **The Aquarius/SAC-D spaceborne mission, a cooperative project of NASA and CONAE under development** (launch planned for 2008), employs the pushbroom radiometer concept. The objective of the radiometer is to demonstrate the measurement of microwave brightness temperatures of the ocean surface with sufficient accuracy and resolution, which are sensitive to salinity and surface roughness. In parallel, the scatterometer measures the surface roughness for correcting the radiometric brightness temperature. The radiometer implementation provides only a small and simple pushbroom demonstration system with 3 beams. The footprint sizes of the beams are: \(62 \text{ km} \times 68 \text{ km}\).


\(^{407}\) http://www.cesbio.ups—tlse.fr/data_all/SMOS_WS/smm3.htm
km, 68 km x 82 km, and 75 km x 100 km, respectively.

The Aquarius/SAC-D mission concept builds on experiences gathered by the airborne instrument PALS (Passive-Active L- and S-band Radar and Radiometer), a pushbroom radiometer of NASA/JPL. The PALS instrument was installed on the NCAR C-130 aircraft and first soil moisture measurements were made in support of the SGP'99 (Southern Great Plains) campaign in Oklahoma from July 8-14, 1999. Other campaigns with PALS participation were SMEX02 (Soil Moisture Experiment) in Iowa in 2002, and SMEX03 conducted in Oklahoma, Georgia, and Alabama (USA) during the summer of 2003 and in Brazil during December 2003.

Background: The idea of a pushbroom radiometer was initially proposed in the late 1970s to improve the spatial resolution of radiometers. This concept places many identical microwave receivers (a line array) in the focal plane of the reflector antenna, such that each receiver observes at a specific pixel cross-track to the orbital motion of the large reflector antenna. An image is thus developed through the forward motion of the spacecraft. The swath width can be increased by adding identical receivers. This can add up to 50 or more for a modest footprint size across a wide swath.

The pushbroom microwave radiometer concept was initially demonstrated with airborne instruments, developed in parallel by NASA/LaRC and the Technical University of Denmark. Initial flights of TUDRAD (Technical University of Denmark Radiometer), a 3 receiver 21 channel frequency-scanned pushbroom system, were conducted in Nov. 1990 using a C-130 aircraft of the Royal Danish Air Force. A parabolic antenna of 1 m aperture was used scanning vertically. TUDRAD was designed to give a contiguous coverage over a swath of 2000 m at a flying altitude of 2000 m. This resulted in a minimum dwell time per footprint of 34 ms (at 15.4 GHz). However, the difficulty with the pushbroom concept at the time was the continued growth in antenna size that was required in order to accommodate a large number of receivers. A 10 km ground resolution with a 1000 km swath would have required an antenna aperture with dimensions of 25 m x 50 m.

1.2.4.5 Microwave sounding from GEO (Geostationary Earth Orbit) satellites

The idea of microwave sounding from GEO is of great interest because such a concept offers some unique observation capabilities of great value for the meteorological community (temperature and humidity sounding as well as the precipitation rate). The attraction of GEO observations is based on the capability to continuously view the same portion of the Earth (an area of interest which can be of considerable size, a continent), during day and night and at all weather conditions. Hence, observations from GEO provide very high temporal resolutions suitable not only for NWP (Numerical Weather Prediction), but in particular for nowcasting and very short range weather forecasts. The full viewable Earth disk from GEO subtends an angle of 17.4º, representing 42% of the Earth’s surface area. However, with the GEO radial distance 45 times larger than the average LEO distance of 800 km, the GEO concept requires a considerably larger aperture (antenna structure) to achieve a sufficiently high spatial resolution for applications in the microwave region. The large aperture requirement is the only reason why microwave sounders and radiometers haven’t been flown in GEO so far. Another disadvantage of GEO observations is the limited coverage of the high latitudes. An alternative to GEO are MEO (Medium Earth Orbit) observations. The MEO might offer a compromise on antenna size and as well as a less dramatic degradation of the spatial resolution at the swath edges. The concept has even the potential of covering the poles.

Microwave soundings from GEO or MEO are highly desirable for short-interval observation of rapidly evolving meteorological phenomena such as convective systems, precipitation and cloud patterns, providing the required high temporal resolution from a geostationary or medium Earth orbit. Some potential observation parameters to be obtained are: 1) the precipitation rate from convective clouds; 2) the cloud liquid and ice water column content; 3) atmospheric temperature and humidity profiles; and 4) atmospheric motion vectors (winds). At the start of the 21st century, the technology is available to extend radiometry to the submillimeter-wavelength range, which enables corresponding reductions in antenna size or, alternatively, improvements in resolution for a given antenna size.

The principle of precipitation measurement from geostationary orbit is based on the use of absorption bands of O$_2$ for atmospheric temperature profiling and H$_2$O for water vapor profiling. Profiles retrieved by bands at different frequencies are differently affected by liquid water, ice water, drop size and shape, and hence precipitation.

Background: So far, infrared/microwave (IR/MW) sounder instrument combinations, [like the TOVS (TIROS Operational Vertical Sounder) instrument series with HIRS, SSU and MSU flown since TIROS-N (launch 1978), and the ATOVS (Advanced TOVS) HIRS/AMSU-A and AMSU-B (Advanced Microwave Sounding Unit) combination, first flown on NOAA-15 (launch May 13, 1998)], have only been flown on operational weather satellites in polar orbits [i.e., LEO (Low Earth Orbit)]. The Aqua LEO mission of NASA (launch May 4, 2002) flies two microwave sounders (AMSU, HSB) in combination with AIRS (Atmospheric Infrared Sounder). Together, the three sensors constitute the advanced operational sounding system. These combined IR/MW observations have the advantage to provide more nearly all-weather soundings (recovery of vertical distribution of temperature and humidity soundings). Such S/C observations have had a significant impact on weather forecasting accuracy, especially in regions where in-situ observations are sparse. Infrared sounders alone do not have adequate cloud-penetration ability to satisfy most forecast requirements, while microwave sounders alone do not satisfy observations in the infrared region.

The following initial concept studies on the topic of GEO MW (Microwave) sounding give an overview of converging activities in the field, leading eventually to a solid mission with international cooperation.

- Two early US studies on GEO MW sounding were conducted for NASA in 1978. The essential conclusions of both studies were that placing a large aperture antenna to realize reasonable spatial resolution and developing reliable low-noise receivers sensitive enough for GEO sounding measurements were of greatest challenge.

In Europe, GEOMW sounding was placed in 1984 as a requirement for the MSG (Meteosat Second Generation) mission of ESA/EUMETSAT. However, the technology prerequisites were not available at this time. The current post-MSG activities involve studies for future MW sounders in GEO or MEO. Main drivers for the GEO concepts are

the large main reflector of about 3.5 m diameter, the scan mechanism and the combination of radiometric accuracy, geographical coverage and repeat cycle. 417)

- In the USA, a “Geosynchronous Microwave Sounder Working Group” 418) reported to the NOAA/NESDIS GOES Program Office in 1997 (first time). This led in 1998 to the GMS (Geostationary Microwave Sounder) proposal [also referred to as GEM (GEostationary Microwave Sounder/Imager)]. The intent is to demonstrate the GMS observation concept on future NOAA GOES platforms starting with GOES-R, the next-generation satellite (launch 2014). 419) The GMS instrument is considered along with the HES (Hyper-spectral Environmental Suite) infrared sounder (see also 1.5.3).

- NASA/HQ released in Sept. 1998 a research announcement for new measurement concepts of the planned EO-3 (Earth Observing-3) mission. 420) 421) Four concepts were selected in March 1999, these were: a) active large aperture optical systems to provide high resolution thermal imaging from GEO (referred to as HORIZON), b) GEO/SAMS (Geostationary Synthetic Aperture Microwave Sounder), c) GIFTS (Geostationary Imaging Fourier Transform Spectrometer), and d) GEO-TRACE (Geostationary Tropospheric Trace-gas imager). Regarding GEO/SAMS, the proposed concept employs the synthetic aperture radiometer technique (a sparsely populated antenna array is substituted for a filled array). However, in 2000 the GEO/SAMS proposal was not accepted.

- As of Jan. 2003, a new proposal was selected/awarded (within IIP) to NASA/JPL, namely GeoSTAR (Geostationary Synthetic Thinned Aperture Radiometer), an interferometric system for geostationary microwave sounding applications using aperture synthesis. The development effort under way at JPL, with important contributions from the Goddard Space Flight Center and the University of Michigan, is intended to demonstrate the measurement concept and retire much of the technology risk. 422) 423) 424) 425) 426) 427)

GeoSTAR is an atmospheric sounder with rain mapping capabilities. It operates primarily in two millimeter-wave bands. For tropospheric temperature sounding it will have a small number of channels positioned near 50 GHz. For water vapor sounding it will use a set of channels positioned near 183 GHz, which are also used for rain mapping. In addition, there is also an intermediate “window” channel near 90 GHz (same approach as implemented

419) Note: Accommodation issues on the spacecraft are most severe for microwave sounding instruments due to large antenna size requirements
with AMSU-A/B on the current POES series). GeoSTAR will also use the 183 GHz water vapor sounding channels for precipitation measurements. The GeoSTAR approach is primarily based on measuring the scattering effects associated with precipitation. The GeoSTAR scattering approach derives from observations made in recent years with 183 GHz radiometers operated on high altitude aircraft. When passing over rain cells, a pronounced apparent cooling due to scattering is observed. This cooling can exceed 100 K over intense convective cells, a very large signal that can be used to detect and track hurricanes and other severe storms without the need for high radiometric sensitivity (i.e. dwell time).

The goals are to complement LEO microwave soundings of the POES series from GEO (on future GOES satellites, considered for GOES-R and thereafter) and to provide full hemispheric observations at resolutions of ≤50/25 km (temperature/moisture) every 1/2 to 1 hour on a continuous basis. The GeoSTAR project foresees a first step in ground testing to demonstrate the feasibility of the synthetic aperture approach — in the form of a small ground-based prototype. The GeoSTAR design concept employs a 2-D spatial interferometric system (synthetic aperture imaging approach) of horn antennas and receivers, which measures the complex cross-correlations between the output signals of all receiver pairs that can be formed from a large number of millimeter wave radiometers arrayed in a “Y-shaped” configuration.

For GEO where the required field of regard is about 17.5° — the size of the Earth disk as seen from GEO, the receiver spacing is therefore approximately 3.5 wavelengths (about 2 cm at 50 GHz and about 6 mm at 183 GHz). The longest baseline determines the smallest spatial scale that can be resolved. To achieve a 50 km spatial resolution at 50 GHz, an aperture diameter in excess of 4 meters is required. That corresponds to approximately 100 receiving elements per array arm, or a total of about 300 elements. This in turn results in 45,000 unique baselines and 90,000 uv sampling points.

Within NASA’s IIP (Instrument Incubator Program), BATC (Ball Aerospace and Technologies Corporation) was awarded the SIRAS-G (Spaceborne Infrared Atmospheric Sounder for Geostationary Orbit) technology study in Jan. 2003. SIRAS-G is an instrument concept for infrared sounding at a moderate spectral resolution $\lambda/\Delta\lambda$ of 1400, using 2048 channels in the spectral range 3.4 - 15.4 $\mu$m. The concept (laboratory demonstration instrument) utilizes the grating spectrometer technology of AIRS (Atmospheric Infrared Sounder) heritage flown on NASA’s Aqua mission. SIRAS-G employs a WFOV hyperspectral infrared optical system that splits the incoming radiation into four separate grating spectrometer channels. This allows for slow scanning of the scene, increased dwell time, and improved radiometric sensitivity. The ability of SIRAS-G to provide simultaneous observations of the Earth’s atmospheric temperature, ocean surface temperature, and land surface temperature, as well as humidity, clouds, and the distribution of atmospheric trace gases enables SIRAS-G to provide a single data set that can be used to understand the horizontal and temporal changes in column abundances of important minor atmospheric gases such as CO$_2$, CO, CH$_4$, and N$_2$O. 428) 429) 430) 431)

Background: The SIRAS-G program builds on an earlier IIP effort (referred to as SIRAS-1999) in which one of the SIRAS spectrometers was demonstrated. Initially, the SIRAS grating spectrometer instrument architecture was primarily seen as a potential option

for the next-generation IR sounder (like AIRS—Light). \(^{432}\) \(^{433}\) AIRS on Aqua has a mass of 150 kg, an average power consumption of about 250 W, and a volume of about 0.8 m\(^3\). Both SIRAS and AIRS—Light enable large reductions in mass (> 2x), power (> 2x), and size (> 5x) through 2 different strategies of technology introduction. SIRAS uses a strategy of combing wide—field refractive optics with high dispersion gratings to miniaturize the instrument. AIRS—Light introduced a newly—developed photovoltaic detector, namely an HgCdTe long—wave infrared FPA for the 14.5—15.5 µm band and a pulse—tube cryocooler technology. \(^{434}\)

Subsequently, it has been shown that this instrument architecture is also well suited to a large variety of Earth science missions including geosynchronous deployment. SIRAS-G will provide measurements similar to those currently being made by AIRS (AIRS is in LEO on Aqua), but from GEO. Again, SIRAS-G is primarily a laboratory instrument; the objective of the program is to develop innovative conceptual designs and to test these for future missions. SIRAS-G potentially serves as a technology pathfinder for the Hyperspectral Environmental Suite (HES), planned to be flown on the GOES-R (NOAA 3rd generation geostationary satellite, launch 2014) mission.

- In Europe, \(^{435}\) \(^{436}\) a new analysis was prepared for EUMETSAT in 2000. \(^{437}\) And in January 2002, a proposal by the name of GOMAS (Geostationary Observatory for Microwave Atmospheric Sounding) was submitted to ESA in the framework of the Earth Explorer Opportunity Missions. GOMAS includes all GMS (GEM) heritage.

- The GMS (USA) / GOMAS (Europe) observation principle is based on the use of absorption bands of oxygen (54, 118 and 425 GHz) and of water vapor (183, 380 and 424 GHz). The design considers narrow-bandwidth channels (for a total of about 40 in the six bands) so as to observe the full profiles of temperature and water vapor. \(^{438}\) \(^{439}\) \(^{440}\) The GMS (Geostationary Microwave Sounder) concept employs a scanning Cassegrain reflector antenna of 2 m diameter in a dual stage scanning system. The dual-stage system consists of a slow momentum-compensated azimuth mechanism and fast scanning subreflector scanning system to provide both wide-area synoptic coverage and fast regional coverage with adaptive scan capabilities. The 2 m antenna will provide ~ 16 km horizontal subsatellite resolution at the highest GMS frequency. As of 2003, GMS is candidate instrument on GOES-R (2014). - A GOMAS antenna of about 3 to 3.5 m diameter can provide spatial resolutions ranging from 10 km (for precipitation) to 20 km (for water vapor and cloud liquid/ice water) and 30 km (for temperature). A GOMAS demonstration mission is proposed for the timeframe 2007-2009.

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\(^{437}\) B. Bizzarri, “MW/Sub-mm sounding from geostationary orbit.”, Report to EUMETSAT Science W. G., EUM/STG/SWG/9/00/DOC/11, pp.11—, 2000

\(^{438}\) http://www.etl.noaa.gov/et1/radiometry/gem/ITSC_GEM_Presentation_022802.pdf


An airborne campaign in Europe is to verify the concepts of GOMAS [use of the M-55 Geophysica of Russia in the timeframe Oct. 2003 to April 2004; and PSR (Polarimetric Scanning Radiometer) of NOAA].

- AMIGO (Advanced Microwave Interferometer from GEO), \(^{441}\) an ESA/EADS study which transposes the concepts of the LEO SMOS mission, namely the Y-shape MIRAS (sparse array instrument), into GEO. The aim is at sounding the Oxygen line in the 54/57 GHz region. Some key features of the GEO orbit favor the concept: a 4 \(\lambda\) antenna covers the Earth disk, and the integration time goes up to 30 min. Such a radiometer becomes realistic because of progress in MMIC (Millimeter-wave Monolithic Integrated Circuit) technology for the receiver and because of the next generation of low power space qualified ASIC’s for the correlator.

1.2.5 Optical Region, Active Observations (LIDARs)

Laser radars (active instruments), or LIDARs (Light Detection and Ranging), combine the principles of submillimeterwave radar and optics. A lidar instrument consists of the following basic elements:

- **Laser transmitter.** By far the most effective approach in all forms of active lidar systems is the use of laser energy in high intensity pulsed form, although range information can also be derived from continuous wave (CW) transmissions.
- **Collector (receiving telescope).** The telescope acts as an optical antenna (analogous to radar) with a corresponding detector system (heterodyne, etc.) in the focal plane.
- **Electronics and data processing resources.**

In this measurement technique, a sequence of monochromatic laser pulses are being generated and transmitted outward into a medium [this may for instance be the atmosphere, or a celestial body (the moon), or the surface of Earth from a spaceborne lidar] — an analysis of the return signals (echoes) provides information about the laser pulse interaction with the backscattering medium. A number of parameters may be derived from the analysis, such as: distance (range), physical state, or chemical composition (LIDAR spectroscopy). The LIDAR concept is generally applied in the optical (and IR) regions of the electromagnetic spectrum, specifically to the spectral range of 0.3\( \mu \text{m} \) to about 10\( \mu \text{m} \), or the equivalent frequency range of 1000 - 30 THz. This wave spectrum (shorter wavelengths than the microwave spectrum) implies and promises to be the next level of observation technology and of information interpretation (in the number of phenomena as well as in detail and accuracy, the targets can be much smaller), due to the use of a much finer scale of measurement. *In Earth observation, the LIDAR measurement technique provides the capability to study the following fine-scale phenomena of the atmosphere [with respect to structure, dynamics (transport and mixing), models and climatology], the Earth's surface (texture, terrain profiling, shallow water depth sounding, etc.), as well as ocean surfaces.*

- **For atmospheric profiling,** a lidar detects the laser energies backscattered from the atmospheric aerosols and molecules. The backscattered laser energies may be used to analyze the geophysical parameters such as aerosol concentrations and spatial distribution profiles, atmosphere wind profiles and trace gas profiles.

- **For terrain profiling,** lidar systems derive the terrain surface ranges and vegetation density/height profiles using surface backscattered laser signals. In addition to these range derived terrain profiles, the backscattered laser signal amplitudes can be used to derive the surface reflectivity profiles for classification of different surface types.

- **For the ocean profiling,** the lidar profiles the water surfaces by detecting laser backscattered energies from the ocean surface as a function of laser energy flight time and backscattered laser signal amplitudes. For this ocean surface application, a lidar functions similar to a microwave altimeter. However, in this altimeter mode, the laser footprints on the water surface are orders of magnitudes smaller than a typical microwave altimeter. 442)

- **The highly accurate ranging capability of the lidar technique was initially introduced in the 1960s in ground-based lidar systems, referred to as SLR (Satellite Laser Ranging), to measure the distance to retroreflectors mounted on spacecraft (see chapter 1.8.3.5). The precise analysis of the orbit (measured by the lidar technique), permitted in turn the study of crustal dynamics and plate tectonics.**

- **The last three Apollo missions of NASA in the early 1970s [Apollo-15 launch July 26, 1971, Apollo-16 launch April 16, 1972, Apollo-17 launch Dec. 7, 1972] carried each a lidar altimeter to map the terrain elevations around prospective landing sites of the moon.**

Some lidar detection / ranging techniques employed are:

- **CDL** (Coherent Doppler Lidar) for wind observations [also referred to as DWL (Doppler Wind Lidar)]. CDL measures wind by determining the Doppler shift of backscattered radiation (light backscattered from aerosol particles transported by the wind) that has been originally transmitted (by the primary laser). The collected, backscattered light is mixed with that from another laser, called the local oscillator (LO) onto a light-sensitive detector (this mixing technique is referred to as heterodyning). CDL heterodyne systems combine the weak (observed) optical signal at nominal frequency $f_1$ with a strong optical reference beam, the frequency-stable LO at frequency $f_2$, on a wideband square-law detector, thereby producing radio frequency beats at the frequency difference $f_1 - f_2$. The resultant beat-frequency signal is analyzed in a post-detection step to provide the Doppler frequency.

- **IBL** (Incoherent Backscatter Lidar). Incoherent-detection heterodyning refers to direct detection of an optical signal on an optical detector, with no LO present. The backscattered optical signal field is analyzed and dispersed in an interferometric filter (or in diffraction grating) prior to detection. The measurement accuracy of a direct-detection interferometric system depends only on the total scattered signal, it is not dependent on the energy of individual pulses, but on the total laser energy. The IBL detection scheme of the wind speed Doppler shift, using optical interferometry, is an emerging and alternate approach to obtain global wind measurements.

- **DIAL** (Differential Absorption Lidar). The objective is generally to measure the distribution/concentration of atmospheric constituents (such as ozone or aerosols). DIAL is a path absorption technique (by exploiting the fact that a gas will absorb light emitted at a certain laser wavelength while transmitting light at most others); information is derived relating to the path along which energy is transmitted or received by comparing the lidar echoes in a tuneable multiwavelength laser system (measurement of the differential ratios of the lidar returns with those of the transmitted ratios by tuning the laser wavelength to the specific absorption features of atmospheric trace constituents). The technique offers the capability to determine the densities of specific atmospheric constituents as well as water vapor and temperature profiles at better accuracies than obtainable with passive sounders. DIAL measurements are made at two different wavelengths. One wavelength, $f_{on}$ (for the DIAL on-line laser beam), is chosen in a region of high absorption cross-section of the gaseous constituent under study, whereas at the second wavelength, $f_{off}$ (for the DIAL off-line wavelength), the gaseous absorption should be minimal.

- **Laser altimetry** [the time-of-flight (TOF) of an echoed pulse determines the range of a surface (point) being detected; a sequence of pulses provides a point-wise sampling scheme]. Laser ranging and altimetry can provide accurate measurements of the distance from a reference height (i.e. the satellite orbital height) to precise locations on the Earth’s surface. The technique is being used to study many processes and phenomena in such solid Earth Sciences such as geodesy, geodynamics, ice dynamics, land topography, and Earth resources. Most laser altimeters provide exact height measurements over oceans, land, and ice.

Airborne lidars are flown since about 1977 [AOL (1977), CALS 1979), ALEX (1979), ALPH-A-1 (1979), etc.], most instruments were developed during the latter 1980s and the 1990s. MACAWS of NASA/MSFC (since 1995) is the first airborne 'coherent atmospheric wind lidar' measuring 2-D, 3-D or vertical wind fields.

On the spaceborne side, the first lidars were introduced in 1994 for atmospheric applications (detection of stratospheric and tropospheric aerosols; measurement of the planetary boundary layer, cloud top heights, atmospheric temperature and density); these were followed by lidar altimeters, mainly used for ocean surface or terrestrial surface monitoring.

- Atmospheric lidars: LITE (Lidar In-Space Technology Experiment) of NASA/LaRC, a triple wavelength lidar, was test-flown on Shuttle (STS-64) in Sept. 1994. Balkan-1 of Atmo-
spheric Optics, Tomsk (Russia), flown on the MIR/Spektr module (launch May 20, 1995). ALISSA, a CNES-developed lidar flown on MIR/Priroda (launch April 23, 1996).

The collaborative CALIPSO mission of NASA/CNES (launch Apr. 28, 2006) includes CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), providing vertical profiles of aerosol backscatter. As of 2002, NASA is defining a mission called OCO (Orbiting Carbon Observatory) with a projected launch in 2007. The OCO objective is to provide global measurements of atmospheric carbon dioxide (CO₂) needed to describe the geographic distribution and variability of carbon dioxide sources and sinks.  

In Europe, the instruments ATLID (Atmospheric Lidar) of the EarthCARE (Earth Clouds Aerosol and Radiation Explorer) S/C and ALADIN (Atmospheric Laser and Doppler Instrument) of ADM-Aeolus (Atmospheric Dynamics Mission) are part of ESA's spaceborne lidar program (launch of ADM-Aeolus in 2008). Of the latter two sensors, ALADIN will be the first spaceborne instrument in a sustained mission using the incoherent DWL (Doppler Wind Lidar) technique of direct detection of wind profiles on an optical detector (with no LO). In this measurement scheme the backscattered optical signal field is analyzed and dispersed in a Rayleigh receiver consisting of a dual filter (double-edge Fabry-Perot interferometer) prior to detection (a combined Mie and Rayleigh backscattering fringe-imaging receiver is employed to analyze aerosol and cloud backscatter).

Note: Mie scattering is named after Gustav Mie (German physicist, 1868-1957). In 1908 Mie presented a description of light scattering from particles that are not small compared to the wavelength of light, taking account of particle shape and the difference in refractive index between the particles and the supporting medium. Gustav Mie was the first to use the Maxwell equations to compute the scattering properties of small spheres suspended in a medium of another index of refraction. Gustav Mie’s work, along with the work of Peter Debye (Dutch physicist, 1884-1966), is now generally referred to as the “Mie theory.”

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<th>Instrument name</th>
<th>LITE</th>
<th>Balkan-1</th>
<th>ALISSA</th>
<th>ALADIN</th>
<th>ATLID (ESA)</th>
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<td>MIR/Spektr</td>
<td>MIR/Priroda</td>
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<td>3000 W</td>
<td>304 W</td>
<td>520 W</td>
</tr>
</tbody>
</table>

Table 27: System performance parameters of spaceborne atmospheric lidars

- Altimeter lidars: 444) 445) 446) SLA-1 (Shuttle Laser Altimeter), was flown on STS-72 (Jan. 11-20, 1996), SLA-2 was flown on STS-85 (Aug. 7-19, 1997) to acquire altimetric samples of land topography (see J.19). GLAS (Geoscience Laser Altimeter System) has been built by NASA/GSFC and is flown on the ICESat mission (launch Jan. 13 2003, see D.21) to determine the mass balance of the polar ice sheets and their contributions to global sea level change. ICESat is considered to be the first free-flying and long-term lidar mission. GLAS is intended as a laser sensor filling complementary requirements for both surface and atmospheric measurements. In addition to a high-resolution altimetry channel, GLAS contains

446) Courtesy of A. Ginati of OHB-System, Bremen
both 1064 and 532 nm backscatter lidar channels for atmospheric profiling. — Advantages of the laser technology include small footprint size, individual pulse processing of surface elevations, and dense ground sample spacing. The early EOS (Earth Observing System) program of NASA considered the development of LAWS (Lidar Atmospheric Wind Sounder), a coherent Doppler wind lidar with a carbon dioxide laser. However, the project was cancelled in 1994 due to severe budget cuts in the EOS program.
1.2.6 Sounding of the Atmosphere

The Earth’s atmosphere can conceptually be regarded as an optical filter for observational purposes. Such a filter attenuates and modulates the resolution and contrast of the measured radiation sources caused by such effects as gases, aerosols, fogs and precipitation, refractive turbulence, and background radiation. Everyday language and thinking uses atmospheric filter analogies. For example: spectral regions of high transmittance are referred to as “atmospheric windows;” the seeing conditions often use such terms as “visibility” and “visual range.”

Each of the gases that comprise the atmosphere has a different ability to absorb the radiation, or let it through, which varies with the radiation wavelength. Wavelength regions where absorption for the whole atmosphere is very low are called window regions and are obviously suitable for Earth-surface observation (such as the spectral regions: VNIR, SWIR, MWIR, TIR). Wavelength (or frequency) regions where a significant absorption of solar radiation occurs for some gas (or constituent) are called absorption bands for that particular gas and may be used to get information about it.

The general techniques for remote sensing (sounding) of the atmosphere include active instruments (such as millimeter-wave radars, SAR, lidars), passive absorption spectroscopy (e.g. solar occultation soundings) and passive emission spectroscopy. Among these techniques, emission spectroscopy, based on spontaneous thermal emissions of the gas, has important advantages. The technique can be applied continuously (day and night) and in all directions without depending on external sources as is the case of absorption spectroscopy. Naturally, emission measurements are only possible within those spectral regions, in which the atmosphere provides emission radiation of detectable intensity, which is generally the optical region of the spectrum (0.1-1000 μm or from the UV to the millimeter region), in particular the infrared region of the optical spectrum, and beyond in the microwave region. It is worth noticing that the wide infrared domain (of the optical region) is particularly suited to retrieve the concentration profiles of a large number of species. Passive emission instruments for atmospheric sounding include such devices as spectrometers, FTS (Fourier Transform Spectrometers), heterodyning instruments, radiometers, etc. Atmospheric sounders generally make passive measurements of the distribution of IR or microwave radiation emitted by the atmosphere, from which vertical profiles of temperature and humidity through the atmosphere may be obtained. An overview of some spaceborne instruments (alphabetic order) is given in Table 30.

The optical properties of the Earth’s atmosphere and its emission spectrum depend on both the temperature and the composition of the atmosphere. Each molecular species present in the atmosphere has characteristic transitions due to its rotational and vibrational spectrum. Good information is obtained from measurements made in a broad spectral range, so that numerous features are present, at a high spectral resolution and individually resolved. The FTS (Fourier Transform Spectrometer) technology combines these capabilities best among the various sounding instrument types. FTS instruments have the important capability of broadband measurements. The property permits observations of the full blackbody distribution of thermal emissions of the atmosphere and the measurement of the Earth’s radiation budget. In comparison to radiometers (which do not resolve the atmospheric windows), FTS instruments can resolve the signal made inside and outside the atmospheric windows and determine the contributions of the different altitudes to the outgoing radiation flux.

- Sounding (see also: Limb/occultation sounding in Glossary). Airborne and spaceborne Earth observation adapted fairly early the ancient technique of sounding (‘to find bottom’).

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originally used for the measurement of shallow water depths) into the development of suitable sensors (sounders) to measure conditions of the medium ‘atmosphere.’ Sounders provide profiles of state parameters (a series of measurements of temperature, pressure, moisture, trace gases, etc.) in a particular plane of observation (nadir or limb configuration) at various heights. The early sounder measurements were obtained from filter radiometers with a spectral resolving power \( \lambda/\Delta \lambda \) typically in the order of 100. At the start of the 21st century the spectral resolving power of typical radiometers is more in the range of 1000.

Later applications included also the sounding of aerosols, trace gas constituents (“absorptive” or “extinctive” occultation monitoring), and of wind components with a variety of instruments, employing such techniques as FTS (Fourier Transform Spectrometry) and Doppler. The technique of sounding has also been extended far beyond the Earth’s atmosphere to measure plasma densities of the solar wind. Active airborne sounders (namely lidars) are also used to fathom the depths of shallow waters (FLASH since 1989, SHOALS since 1994), to detect sea surface pollution, and to measure surface emissions. Naturally, the entire spectrum may be used for sounding measurements, but the microwave region is the traditional and dominant arena for sounders.

The presence of clouds in the field of view of sounders has a detrimental effect on the quality of a retrieval. The absorption properties of cloud droplets and ice particles at infrared sounding wavelengths are so strong that even thin clouds contaminate the measurement of radiances. As a result, a number of post-processing techniques have been developed to minimize the effects of clouds on soundings. These usually require some way of identifying cloudy scenes to arrive at an equivalent clear-sky radiance quantity. Methods accounting for the effects of clouds on the data are generally based on higher-resolution visible and infrared imaging data that are required to supplement the sounding channels.

- The first airborne devices used were self-registering instruments (referred to as sondes) on balloons to record meteorological data. The MTS (Microwave Temperature Sounder of GSFC) instrument was first flown on aircraft in 1976.
- There are two basic types of sounding instruments depending on the observation geometry, namely vertical and/or horizontal measurement concepts. Each technique requires different retrieval algorithms.

1) Vertical sounding observations. The instrument faces to nadir and senses the radiation coming both from the Earth’s surface as well as from the atmosphere. The BUV (Backscatter Ultraviolet) technique is mostly applied to vertical sounding observations (nadir viewing). In BUV, measurements are made of solar UV radiation entering the atmosphere (referred to as the irradiance) at a particular wavelength and of the solar UV that is either reflected from the surface or scattered back from the atmosphere (referred to as the radiance) at the same wavelength. Examples of BUV instruments are: SBUV (Solar Backscatter Ultraviolet) first flown on Nimbus-7 (later SBUV/2 flown on the POES series of NOAA), TOMS (Total Ozone Mapping Spectrometer), and GOME (Global Ozone Monitoring Experiment) flown on ERS-2 (launch Apr. 21, 1995).

2) Limb-viewing and occultation sounding systems (observations in horizontal direction). In these measurements the sounder (spectrometer) is carried on a spaceborne platform and probes the Earth’s limb at various depths in the atmosphere. Each observation is characterized by the altitude and the geolocation of the tangent point (that is, the point where the line of sight reaches the lowest altitude). A full set of measurements that cover the altitude interval of interest is usually referred to as a limb-scanning sequence. Limb-sounding measurements provide in effect a sampling grid of vertical profiles. The tangent altitudes of the measured spectra are generally in the 10 - 50 km range. Fine observation grids provide a high number of vertical layers within a sequence. A limb sounder may be oriented in a side-viewing direction, in a forward-view-
The sounder measures in general the infrared emission based on temperature and trace gas concentrations in the mesosphere, stratosphere and the upper troposphere. For species which absorb in the solar spectrum (for example ozone, water vapor and nitrogen dioxide, as well as aerosols) solar occultation instruments can be used to measure the extinction of sunlight through the atmospheric limb during satellite sunrise and sunset.

Note: All limb-viewing remote sensing measurements are sensitive to errors in pointing. Pointing errors result from spacecraft attitude errors, errors in correcting for the oblateness of the Earth, and errors in correcting for the time varying thermal expansion within the instrument or spacecraft.

### Table 28: Overview of limb-viewing spaceborne sounders

<table>
<thead>
<tr>
<th>Mission and launch date</th>
<th>Limb-viewing sounders</th>
<th>Spectral Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-C, NASA (Dec. 16, 1973)</td>
<td>UVNO (Ultraviolet Nitric-Oxide Experiment)</td>
<td>UV</td>
</tr>
<tr>
<td>Nimbus-7, NASA (Oct. 24, 1978)</td>
<td>LIMS (Limb Infrared Monitor of the Stratosphere)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>SAMS (Stratospheric and Mesospheric Sounder)</td>
<td>Infrared</td>
</tr>
<tr>
<td>ERBS, NASA (Oct. 5, 1984)</td>
<td>SAMS-II (Stratospheric and Mesospheric Sounder)</td>
<td>Infrared</td>
</tr>
<tr>
<td>UARS, NASA (Sept. 12, 1991)</td>
<td>CLAES (Cryogenic Limb Array Etalon Spectrometer)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>ISAMS (Improved Stratospheric &amp; Mesospheric Sounder)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>HALOE (Halogen Occultation Experiment)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>MLS (Microwave Limb Sounder)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>WINDII (Wind Doppler Imaging Interferometer)</td>
<td>VIS, NIR</td>
</tr>
<tr>
<td>SPOT-3, CNES (Sept. 26, 93)</td>
<td>POAM-II (Polar Ozone and Aerosol Measurement), NRL</td>
<td>UV, NIR</td>
</tr>
<tr>
<td>STS-66, NASA (Nov. 3-14, 94)</td>
<td>CRISTA (Cryogenic Infrared Spectrometers and Telescopes for Atmosphere)</td>
<td>Infrared</td>
</tr>
<tr>
<td>STS-85, NASA (Aug. 7-19, 97)</td>
<td>CRISTA</td>
<td>Infrared</td>
</tr>
<tr>
<td>ADEOS, NASA (Aug. 17,96)</td>
<td>ILAS (Improved Limb Atmospheric Spectrometer)</td>
<td>VIS, IR</td>
</tr>
<tr>
<td>SPOT-4, CNES (Mar. 24, 1998)</td>
<td>POAM-III (Polar Ozone and Aerosol Measurement) NRL</td>
<td>UV, NIR</td>
</tr>
<tr>
<td>Terra, NASA, (Dec. 18, 1999)</td>
<td>CERES (Clouds and the Earth’s Radiant Energy System)</td>
<td>VIS, IR</td>
</tr>
<tr>
<td>ODIN, Sweden, (Feb. 20, 2001)</td>
<td>SMR (Submillimeterwave Radiometer)</td>
<td>Sub-mm</td>
</tr>
<tr>
<td></td>
<td>OSIRIS (Optical Spectrograph &amp; Infrared Imaging System)</td>
<td>Infrared</td>
</tr>
<tr>
<td>TIMED, NASA (Dec. 7, 2001)</td>
<td>SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>TIDI (TIMED Doppler Interferometer)</td>
<td>UV</td>
</tr>
<tr>
<td></td>
<td>GUVI (Global Ultraviolet Imager)</td>
<td>UV</td>
</tr>
<tr>
<td>Meteor-3M-1, Russia (Dec. 10, 2001)</td>
<td>SAGE III (Stratospheric Aerosol and Gas Experiment III) NASA/LaRC</td>
<td>UV, VNIR</td>
</tr>
<tr>
<td>Envisat, ESA (Mar. 1, 2002)</td>
<td>MIPAS (Michelson Interferometer for Passive Atmospheric Sounding); GOMOS (Global Ozone Monitoring by Occultation of Stars); SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>Note: SCIAMACHY performs limb or nadir observations</td>
<td>UV, VIS</td>
</tr>
<tr>
<td>ADEOS-II, (Dec. 14, 2002)</td>
<td>ILAS-II (Improved Limb Atmospheric Spectrometer-II)</td>
<td>VIS, IR</td>
</tr>
<tr>
<td>Aura, NASA (July 15, 2004)</td>
<td>MLS (Microwave Limb Sounder), mm and sub-mm range</td>
<td>Sub-mm</td>
</tr>
<tr>
<td></td>
<td>HIRDLS (High-Resolution Dynamics Limb Sounder)</td>
<td>Infrared</td>
</tr>
<tr>
<td></td>
<td>TES (Tropospheric Emission Spectrometer), limb or nadir</td>
<td>UV, VNIR</td>
</tr>
<tr>
<td>NPP, NASA/IPO (2009)</td>
<td>OMPS (Ozone Mapping and Profile Suite) limb and nadir</td>
<td>UV, VNIR</td>
</tr>
<tr>
<td>NPOESS, IPO (2012)</td>
<td>OMPS (Ozone Mapping and Profile Suite) limb and nadir</td>
<td>UV, VNIR</td>
</tr>
</tbody>
</table>


Today’s sounders like AMSU (Advanced Microwave Sounding Unit), first flown on NOAA-15 (launch May 13, 1998), provide atmospheric temperature profiles with a sensitiv-
ity of about 1 K and a vertical resolution of about 2 km in the troposphere. SSMIS (Special Sensor Microwave Imager Sounder) of the DMSP series, first flown on F-16 (launch Oct. 18, 2003), features a similar performance as AMSU. Current generation sounder performance (AMSU, SSMIS) still falls short of the requirements for NWP (Numerical Weather Prediction). Some examples of next-generation sounders are: AIRS (Atmospheric Infrared Sounder) on Aqua (launch May 4, 2002), IASI (Improved Atmospheric Sounder Interferometer) on MetOp-A (launch Oct. 19, 2006), ATMS (Advanced Technology Microwave Sounder) and CrIS (Cross-track Infrared Sounder) on NPP (launch in 2009). Their data is planned to be used in NWP models and in many other applications. AIRS is in fact the first spaceborne instrument that employs hyperspectral sounding to give global coverage of temperature, water and ozone on a daily basis.

- **Measurement of global cloud profiles.** Clouds play an important role in climate modeling. The CPR (Cloud Profiling Radar) instrument of the NASA/CSA CloudSat mission (launch Apr. 28, 2006, see A.10) measures the vertical profiles of cloud structures [CloudSat formation flight with CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), to augment the data of CloudSat]. The quantitative evaluation/representation of clouds and cloud processes in global atmospheric circulation models is a major objective. *At 94 GHz (3 mm wavelength) the CPR instrument of CloudSat represents the first spaceborne millimeter-wave radar system.*

- **As of 2002/3,** a further CPR (Cloud Profiling Radar) instrument at 94.05 GHz is under joint development by JAXA (formerly NASDA) and CRL of Tokyo. The CPR is considered a core instrument of EarthCARE (Earth Clouds, Aerosol and Radiation Explorer), a joint ESA/JAXA candidate mission in ESA’s Earth Explorer Program with a planned launch in the time frame 2012. The entire sensor complement [ATLID (Atmospheric Lidar), CPR, MSI (Multispectral Imager), BBR (broadband Radiometer), and FTS (Fourier Transform Spectrometer)] of EarthCARE is dedicated to the study of clouds, aerosols and radiation parameters (determination of the global distribution of vertical profiles of cloud and aerosol field characteristics) to provide basic, essential input data for numerical modelling.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IASI (IASI pixel)</th>
<th>AMSU-A</th>
<th>MHS</th>
<th>AVHRR/3</th>
<th>HIRS/3 (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan type</td>
<td>Step and dwell</td>
<td>Step and dwell</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Step and dwell</td>
</tr>
<tr>
<td>Scan rate</td>
<td>8 s (8 s)</td>
<td>8 s</td>
<td>2.667 s</td>
<td>0.167 s</td>
<td>6.4 s</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>216 ms (216 ms)</td>
<td>200 ms</td>
<td>19 ms</td>
<td>0.025 ms</td>
<td>100 ms</td>
</tr>
<tr>
<td>Scan separation</td>
<td>52.69 km (23.81)</td>
<td>52.69 km</td>
<td>17.56 km</td>
<td>1.1 km</td>
<td>42.15 km</td>
</tr>
<tr>
<td>Pixels/scan</td>
<td>- (120)</td>
<td>30</td>
<td>90</td>
<td>2048</td>
<td>56</td>
</tr>
<tr>
<td>IFOV</td>
<td>3.33º (0.84º circular)</td>
<td>3.3º circular</td>
<td>1.1º circular</td>
<td>0.0745º square</td>
<td>0.69º circular</td>
</tr>
<tr>
<td>IFOV at nadir</td>
<td>47.63 km, (12 km)</td>
<td>47.63 km</td>
<td>15.88 km</td>
<td>1.1 km</td>
<td>10.0 km</td>
</tr>
<tr>
<td>IFOV edge cross-track (km)</td>
<td>146.89, (39.14)</td>
<td>146.89</td>
<td>52.83</td>
<td>6.15</td>
<td>33.27</td>
</tr>
<tr>
<td>IFOV edge along-track (km)</td>
<td>78.79, (20.31)</td>
<td>78.79</td>
<td>27.10</td>
<td>2.27</td>
<td>17.03</td>
</tr>
<tr>
<td>FOV</td>
<td>±48.33º (49.16º)</td>
<td>±48.33º</td>
<td>±49.44º</td>
<td>±55.37º</td>
<td>±49.5º</td>
</tr>
<tr>
<td>Swath (km)</td>
<td>2052, (1228)</td>
<td>2052</td>
<td>2134</td>
<td>2900</td>
<td>2160</td>
</tr>
</tbody>
</table>

Table 29: FOV and scan parameter comparison of major sounding instruments

- **Monitoring of atmospheric constituents (trace gases)** is in support of atmospheric chemistry and other environmental applications. The first spaceborne instrument of this genre, namely SAM (Stratospheric Aerosol Measurement) of NASA/LaRC, was flown on the US/Soviet mission ASTP (Apollo-Soyuz Test Project), July 15-24, 1975, to perform the

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first successful solar occultation measurement of stratospheric aerosol. This was followed by SAM-II on Nimbus-7 (launch Oct. 24, 1978). Since then considerable progress has been made in the design of new instruments and in the interpretation of the retrieved data.

- Aerosol monitoring plays an important role in global climate change. Spaceborne monitoring of aerosols started with SAM of NASA/LaRC [SAM (Stratospheric Aerosol Measurement) was flown on ASTP (Apollo-Soyuz Test Project), July 15-24, 1975, to perform the first successful solar occultation measurement of stratospheric aerosol], SAM II (launch Oct. 24, 1978 on Nimbus-7, see M.26.7), SAGE I, SAGE II). Both SAM and SAM-II were single spectral instruments measuring the aerosol extinction near the 1000 nm wavelength region. Multiple spectral measurements began with SAGE-I, with a launch on the AEM-2 (Application Explorer Mission-2) satellite, Feb. 18, 1979 (see A.5). SAGE-II is an advanced version of SAGE-I with 7 channels at 385, 448, 453, 525, 600, 940, and at 1020 nm. SAGE-II was flown on ERBS with a launch on Oct. 5, 1984 (see A.16). The measurements of SAM-II, SAGE-I and SAGE-II have provided long-term observations of aerosol and ozone for over 20 years. Note: The SAGE-II instrument continues to operate as of early 2004; its data were made available to the public as of Oct. 28, 2003.

SAGE-III is an Earth limb-scanning grating spectrometer (part of NASA's EOS mission) which is flown on Meteor-3M-1 (Russia) with a launch on Dec. 10, 2001. An important objective of SAGE-III is to characterize tropospheric and stratospheric aerosols and upper tropospheric and stratospheric clouds, and investigate their effects on the Earth’s environment, including radiative, microphysical, and chemical interactions. SAGE-III is also scheduled to fly on ISS in 2005. - Note: There is an inherent coverage weakness in the solar occultation technique by offering only two measurement opportunities per orbit. It has been estimated that six spaceborne SAGE-III instruments on various orbits would be needed to achieve a weekly coverage of the Earth.

- **SHS (Spatial Heterodyne Spectroscopy)**, see O.6.3 and J.18. The SHS technique provides the first practical approach to extend interference spectroscopy into the FUV (Far Ultraviolet, 1200-2000 Å) spectral range. SHS is a relative of the FTS (Fourier Transform Spectroscopy) concept, but has fundamental advantages over FTS in certain applications. In the SHS instrument, diffraction gratings replace the flat mirrors used in each arm of a conventional Michelson, and an imaging detector is used at the output to record a spatially heterodyned interferogram without any scanning elements. The mechanical simplicity of a diffraction grating is combined with the high light-gathering power of interference spectrometers.

In the basic SHS design, Fizeau fringes of wavenumber-dependent spatial frequency are produced by a modified Michelson interferometer in which the return mirrors are replaced by conventional blazed diffraction gratings (see Figure 14 part a). The fringes are recorded on a position sensitive detector and Fourier-transformed to recover the spectral content of the source. Zero spatial frequency corresponds to the Littrow wavenumber of the gratings, which can be chosen by adjustment of the interferometer. Since zero spatial frequency corresponds to a finite wavenumber, SHS measures differences between the source and alignment wavelengths, and high resolution spectra over a limited spectral range can be recovered with modest requirements on the spatial resolution of the detector. In this process, no element is mechanically scanned.

The resolving power of an SHS design is equal to the theoretical resolving power of the dispersive (i.e. grating) system while the field of view of the system is characteristic of interferometric spectrometers (conventional Michelson and Fabry-Perot). The interferometric field of view gives SHS systems a 100-fold gain in sensitivity for diffuse source spectroscopy over diffraction grating spectrometers of the same size and resolving power. Furthermore, field widening techniques can be applied to SHS systems which enable SHS to view even larger fields of view. Gains associated with field widening are typically two orders of magni-
tude in solid angle over conventional interferometers ($10^4$ larger than diffraction grating spectrometers).

![Diagram of SHS Configuration](image)

a) The beam splitter (BS) divides and recombines the incoming wavefront. Wavelength dependent Fizeau fringes produced by diffraction gratings G are recorded by a position sensitive detector.

b) The same SHS configuration but with field widening prisms P1 and P2 added to each arm. The prism angles are chosen so that from a geometrical optics point of view the gratings appear coincident.

Figure 14: Schematic diagram of the SHS configuration

The SHS technique appears to be offering high-resolution spaceborne spectroscopy applications in astronomy (detection of faint interstellar emission lines, study of the dynamics of hot interstellar gases) as well as in Earth observation. A first example in this field include the measurement of vertical density profiles of the hydroxyl (OH) radical in the middle atmosphere (30-100 km), study of the distribution of aerosols in the mesosphere, and to investigate the role of OH in the photochemistry of water vapor and ozone in the presence of aerosols in the mesosphere.

The SHS concept was first described in 1971 by Dohi and Susuki (they used holographic film as detectors). H. Butcher et al. (1989) developed SHS for astronomical telescopes. John Harlander and Fred Roesler (1990) developed practical SHS designs using CCD detectors. 450

NRL (Naval Research Laboratory) in Washington, DC has been cooperating with J. M. Harlander at UWM (University of Wisconsin-Madison) for the last years to develop an instrument. A first implementation of the SHS concept is realized in SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals). The instrument was flown on Shuttle flight STS-112 (Middeck), Oct.7-18, 2002. – Additional plans call for SHIMMER flights (im-

proved sensor versions) on STPSat-1 (Space Test Program Satellite-1), a USAF/AFRL mission with a launch on March 9, 2007. 451)

<table>
<thead>
<tr>
<th>Instrument/Agency</th>
<th>Mission/Platform, Coverage period</th>
<th>Species observed</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE-FTS (Atmospheric Chemistry Experiment - Fourier Transform Spectrometer)/CSA</td>
<td>SciSat-1/ACE of CSA (Aug. 13, 2003)</td>
<td>O$_3$, N$_2$O, CH$_4$, HNO$_3$, H$_2$O, HCl, H$_2$, NO, NO$_2$, ClNO$_3$, CO, CO$_2$, ClCl$_3$, ClCl$_2$F, ClCl$_2$F$_2$, and N$_2$O$_5$</td>
<td>Inclined orbit</td>
</tr>
<tr>
<td>ATMOS (Atmospheric Trace Molecule Spectrometer)/JPL</td>
<td>STS-51-B (1985), ATLAS-1, 2, 3 (1992, 93, 94)</td>
<td>O$_3$, NO, N$_2$O, ClO NO$ _2$, HCl, H$_2$, HF, CH$_4$, CFCs</td>
<td>Inclined orbits</td>
</tr>
<tr>
<td>ATSR (Along-Track Scanning Radiometer and Microwave Sounder)/ESA</td>
<td>ERS-1/2 (1991 to present)</td>
<td>Aerosols, clouds, SST (Sea Surface Temperature)</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>AVHRR (Advanced Very-High Resolution Radiometer (chan. 4/5))/NOAA</td>
<td>TIROS-N, NOAA-6 to -16 (1978 to present)</td>
<td>Smoke, fire, clouds, aerosols, vegetation</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>GOMOS (Global Ozone Monitoring by Occultation of Stars)/ESA</td>
<td>Envisat (2002 - )</td>
<td>O$_3$, NO$_2$, upper troposphere</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>HIRDLAS (High-Resolution Dynamics Limb Sounder)/U. of CO and Oxford University</td>
<td>Aura of NASA (July 15, 2004)</td>
<td>O$_3$, H$_2$O, CH$_4$, N$_2$O, NO$_2$, N$_2$O$_5$, HNO$_3$, ClF$_1$, ClF$_2$, ClF$_3$, NO$_2$, ClONO$_2$, and aerosols</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>IASI (Imaging Atmospheric Sounding Instrument)/CNES</td>
<td>MetOp-A (Oct. 19, 2006) of EUMETSAT</td>
<td>O$_3$, CO, CO$_2$, CH$_4$, N$_2$O, SO$_2$</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>ILAS-II (Improved Limb Atmospheric Spectrometer-II)/EA</td>
<td>ADEOS-II of JAXA (2002, formerly NASA)</td>
<td>O$_3$, HNO$_3$, NO$_2$, N$_2$O, CH$_4$, H$_2$O, CFC-11, CFC-12, ClONO$_2$, etc., aerosols, temp. pressure</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>LORAAS (Low Resolution Airglow/Aurora Spectrograph)</td>
<td>ARGOS of DoD (1999), see M.3</td>
<td>O$^+$, O, O$_2$, N$_2$, T</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>MERIS (Medium-Resolution Imaging Spectrometer for Passive Atmospheric Sounding) MIPAS (Michelson Interferometer for Passive Atmospheric Sounding)/ESA</td>
<td>Envisat of ESA (2002 - )</td>
<td>H$_2$O, clouds, aerosols</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>MLS (Microwave Limb Sounder)/JPL</td>
<td>UARS of NASA (1991 to present) (1991-1993)</td>
<td>O$_3$, ClO, H$_2$O$_2$, H$_2$O and pressure N$_2$O, NO, NO$_2$, HNO$_3$, CF$_4$, CF$_2$Cl$_2$, CFCl$_3$, HCl, N$_2$O, O$_3$, ClONO$_2$, CO$_2$, H$_2$O, ClO, CH$_4$, temperature CO, H$_2$O, CH$_4$, N$_2$O, NO, N$_2$O, O$_3$, HNO$_3$ and aerosols HF, HCl, CH$_4$, NO, H$_2$O, O$_3$, NO$_2$, and pressure</td>
<td>Inclined orbit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instrument/Agency</th>
<th>Mission/Platform, Coverage period</th>
<th>Species observed</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOPITT ((Measurement of Pollution in the Troposphere)/CSA</td>
<td>Terra of NASA (1999 - present)</td>
<td>Vertical profile of CO and total column of CH₄</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>OPU (Ozone and Pollution measuring UV Spectrometer)</td>
<td>GCOM-A1 of JAXA (2007)</td>
<td>SO₂, NO₂, BrO, OCIO</td>
<td>Inclined orbit</td>
</tr>
<tr>
<td>OMI (Ozone Monitoring Instrument) of NIVR and FMI</td>
<td>Aura of NASA (2004)</td>
<td>NO₂, SO₂, BrO, OCIO, and aerosol</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>SABER (Sounding of the Atmosphere using Broadband Emission Radiometer)/NASA</td>
<td>TIMED of NASA (2001)</td>
<td>O₂, O₃, H₂O, NO, NO₂, CO, CO₂, OH</td>
<td>Inclined orbit</td>
</tr>
<tr>
<td>SAGE-I/-II (Stratospheric Aerosol and Gas Experiment)/LaRC</td>
<td>AEM-2 of NASA (1979) ERBS of NASA (1984)</td>
<td>O₃, NO₂, (H₂O), aerosols</td>
<td>Inclined orbit</td>
</tr>
<tr>
<td>SAGE-III (Stratospheric Aerosol and Gas Experiment)/LaRC</td>
<td>Meteor-3M-1 of Rosaviakosmos (Dec. 10, 2001), ISS (2005)</td>
<td>O₃, NO₂, NO₃, OCIO, aerosols,</td>
<td>Polar sun-synchronous, Inclined 51.6°</td>
</tr>
<tr>
<td>SAM (Stratospheric Aerosol Measurement)/NASA</td>
<td>ASTP (Apollo-Soyuz Test Project), 1975, SAM-II on Nimbus-7, NASA (1978)</td>
<td>stratospheric aerosols</td>
<td>Inclined</td>
</tr>
<tr>
<td>SAMS (Stratospheric and Mesospheric Sounder)</td>
<td>Nimbus-7 of NASA (1978-1993)</td>
<td>O₃ profiles and total column amount</td>
<td>Polar sun-synchronous</td>
</tr>
<tr>
<td>SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography)/ESA</td>
<td>Envisat of ESA (2002)</td>
<td>O₂, O₃, O₄, NO, NO₂, N₂O, BrO, OCIO H₂CO, CO, CO₂, CH₄, H₂O, SO₂, HCHO, clouds, aerosols, pressure temperature,</td>
<td>Polar sun-synchronous</td>
</tr>
</tbody>
</table>

**Table 30:** Overview of some major spaceborne trace gas instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mission</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORA</td>
<td>EURECA-1 (1992 - 1993), ESA</td>
<td>Retrieving carrier platform</td>
</tr>
<tr>
<td>LITE</td>
<td>STS-64 (Sept. 9-20, 1994), NASA</td>
<td>Technology experiment</td>
</tr>
<tr>
<td>GOME</td>
<td>ERS-2 (launch Apr. 21, 1995), ESA</td>
<td>Spectral range of 240-790 nm for ozone, aerosols, etc.</td>
</tr>
</tbody>
</table>
### Table 31: Some aerosol-monitoring instruments of spaceborne missions

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mission</th>
<th>Swath (km)</th>
<th>Spatial resolution, nadir (km)</th>
<th>Spectral range (nm)</th>
<th>Global coverage</th>
<th>Polarization detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR-2</td>
<td>ERS-2</td>
<td>500</td>
<td>1 x 1</td>
<td>VNIR+TIR</td>
<td>3 days</td>
<td>No</td>
</tr>
<tr>
<td>AVHRR/3</td>
<td>NOAA-POES</td>
<td>&gt;2400</td>
<td>1.1 x 1.1</td>
<td>VNIR+TIR</td>
<td>1 day</td>
<td>No</td>
</tr>
<tr>
<td>GOME-2</td>
<td>MetOp-A</td>
<td>960</td>
<td>40 x 40 (40x5)</td>
<td>240 - 790</td>
<td>3 days</td>
<td>Yes</td>
</tr>
<tr>
<td>MERIS</td>
<td>Envisat</td>
<td>1150 km</td>
<td>0.26 x 0.3</td>
<td>390 - 1040</td>
<td>3 days</td>
<td>No</td>
</tr>
<tr>
<td>MISR</td>
<td>Terra</td>
<td>360</td>
<td>0.275 x 0.275</td>
<td>VIS+IR</td>
<td>9 days</td>
<td>No</td>
</tr>
<tr>
<td>MODIS</td>
<td>Terra</td>
<td>2330</td>
<td>0.25 x 0.25</td>
<td>400 - 14,500</td>
<td>1-2 days</td>
<td>No</td>
</tr>
<tr>
<td>POLDER-1</td>
<td>ADEOS</td>
<td>1140 x 2200</td>
<td>7 x 6</td>
<td>443 - 920</td>
<td>1 day</td>
<td>Yes</td>
</tr>
<tr>
<td>POLDER-2</td>
<td>ADEOS-II</td>
<td>1140 x 2200</td>
<td>7 x 6</td>
<td>443 - 920</td>
<td>1 day</td>
<td>Yes</td>
</tr>
<tr>
<td>POLDER-P</td>
<td>PARASOL</td>
<td>1160 x 2200</td>
<td>5.3 x 6.2</td>
<td>443 - 1030</td>
<td>1 day</td>
<td>Yes</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>Envisat</td>
<td>960</td>
<td>32 x 16</td>
<td>240 - 2380</td>
<td>3 day</td>
<td>Yes</td>
</tr>
<tr>
<td>TOMS</td>
<td>ADEOS</td>
<td>2795</td>
<td>50 x 50</td>
<td>UV</td>
<td>1 day</td>
<td>No</td>
</tr>
</tbody>
</table>

### Table 32: Observation characteristics of some aerosol instruments

1.2.6.1 Monitoring of ozone in the atmosphere

- Monitoring of ozone (global coverage). Detection of short-term and long-term (seasonal) changes in ozone (UV radiation) with measurements of total column amounts and stratospheric and tropospheric profiles of ozone. See also Table 627 for a survey of Shuttle flights with the SSBUV payload.

Atmospheric ozone has several environmental implications, it can be classified according to atmospheric layers (or altitude). Long-term trend measurements are of great importance. Ozone depletion leads to an increase in the intensity of UV radiation reaching the Earth surface in some regions of the world.
Stratosphere. About 90% of the atmospheric ozone is contained in the stratosphere. Ozone plays a critical role in absorbing UV radiation and preventing it from reaching Earth's surface. The so-called “ozone hole” is a consequence of stratospheric ozone depletion over the poles of the Earth.

Troposphere. In the upper and middle troposphere, ozone is a major greenhouse gas, causing inhomogeneous radiative forcing.

Troposphere. Ozone is an oxidizing power in the lower and middle troposphere.

Surface air. Ozone is a pollutant, toxic to humans and to vegetation.

- Airborne cloud investigations (properties, interactions, phases, droplets, microphysics, etc.) with radiometers, lidars, radars, hyperspectral imagers, etc. have been performed since the mid 1970s (with most observations in the 1990s) on various scales with a number of instruments, such as: ARES (NASA/JSC), AWSR (NOAA), AMMS, CALS and CAR (NASA/GSFC), CVI (MISU), Deimos and MARSS (UKMO), ALEX, OLEX, H₂O-DIAL and Microlidar (DLR), MPIR (SNL), CDL (LLNL), ELDORA/ASTRAIA (NCAR/CRPE), LASAL (GSFC), LEANDRE (CNRS/CNES), MCR and MIR (GSFC), MTP (JPL), NAILS (NCAR), OVID (MPI/Hamburg), RAMS (NASA/NOAA), MAKREL-2 and M2M (Tomsk), APDOR-95 (MIRSL).

- The first project to use in-service aircraft for trace-constituent data collection took place in 1968 with carbon monoxide (CO) measurements made from Lufthansa B-707 aircraft. A vertical CO gradient was observed in the tropopause, this resulted in an estimation of the size of the stratospheric CO sink. (The same group of researchers employed a manned laboratory inside a container on 10 German cargo service flights between 1981 and 1987 to measure CO).

- The meridional distribution of tropospheric ozone concentrations was studied by MPae (Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany) on 37 commercial flights between Northern Europe (Frankfurt) and South Africa (Cape Town) during the period 1970-1974.

- GASP (Global Atmospheric Sampling Program) was introduced by NASA in 1975 to measure trace gases on commercial airliners. Four B-747 (two Pan American, one United, and one Qantas) aircraft were equipped with instruments to routinely measure ozone, carbon monoxide, water vapor, aerosols, temperature, and horizontal winds. GASP was over the period 1975-1979 with over 6900 flights.

- The Japanese ASE (Automatic Air-Sampling Equipment) program with instrumentation on a Boeing 747 aircraft between Japan and Australia was introduced in 1993. It lasted until 1996.

- Also in 1993, the EU started its MOZAIC (Measurement of Ozone by Airbus In-Service Aircraft) program. During MOZAIC-I (1993-Sept. 1996), fully automated devices, developed by CNRS (France) and Forschungszentrum Jülich (Germany), were flown on five Airbus aircraft in normal airline service (Air France, Qantas, Lufthansa, Sabena). MOZAIC-II started in Oct. 1996 with the aim to continue the ozone and water vapor measurements, several new instruments were added to measure CO and NOₓ. Between Sept. 1994 and Dec. 1997, 7500 flights (54,00 flight hours) were made in the MOZAIC program over the continents (Europe, North America, Asia, South America, and Africa) and the Atlantic Ocean.

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A MOZAIC-III program is currently being carried out in the Fifth Framework Program of the EU.  

Table 33: Major spaceborne instruments for the global measurement of ozone

<table>
<thead>
<tr>
<th>Instrument (Agency)</th>
<th>Platform</th>
<th>Launch Date</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSSH-2 (DoD)</td>
<td>DMSP (DoD) series</td>
<td>Sep. 11, 1976</td>
<td>Starting with F1 satellite</td>
</tr>
<tr>
<td>SAGE-I (NASA)</td>
<td>AEM-2 (NASA)</td>
<td>Feb. 18, 1979</td>
<td></td>
</tr>
<tr>
<td>UVSP (NASA/MSFC)</td>
<td>SMM (NASA)</td>
<td>Feb. 14, 1980</td>
<td></td>
</tr>
<tr>
<td>UV Ozone Experiment Airglow Instrument Solar UV Monitor</td>
<td>SME (NASA)</td>
<td>Oct. 6, 1981</td>
<td></td>
</tr>
<tr>
<td>UV Spectrometer</td>
<td>EXOS-C (ISAS)</td>
<td>Feb. 14, 1984</td>
<td></td>
</tr>
<tr>
<td>SSBUV (NASA)</td>
<td>STS-34 (NASA)</td>
<td>Oct. 19, 1989</td>
<td>Coincident observations with SBUV/2 on NOAA-9 and NOAA-11</td>
</tr>
<tr>
<td>HALOE, MLS, CLAES, ISAMS</td>
<td>UARS (NASA)</td>
<td>Sep. 13, 1991</td>
<td>Sun occultation method (HALOE) Heterodyne limb sounder (MLS)</td>
</tr>
<tr>
<td>POAM-II (NRL)</td>
<td>SPOT-3 (CNES)</td>
<td>Sep. 26, 1993</td>
<td>SPOT-3 entered safehold Nov. 14, '97; Solar occultation through the Earth’s atmospheric limb</td>
</tr>
<tr>
<td>GOME (ESA) a scanning optical double spectrometer</td>
<td>ERS-2 (ESA)</td>
<td>Apr. 21, 1995</td>
<td>DOAS (Differential Optical Absorption Spectroscopy) measurement concept</td>
</tr>
<tr>
<td>Ozon-M</td>
<td>Priroda (Russia)</td>
<td>Apr. 23, 1996</td>
<td>Priroda, a module of the MIR station</td>
</tr>
<tr>
<td>MAHRSI (NRL)</td>
<td>CRISTA-SPAS-2</td>
<td>Aug. 7-19, 97</td>
<td>STS-85 Shuttle, OH interaction with ozone and other trace gases</td>
</tr>
<tr>
<td>POAM-III (NRL)</td>
<td>SPOT-4 (CNES)</td>
<td>Mar. 24, '98</td>
<td>Operational</td>
</tr>
<tr>
<td>OLME (FACH)</td>
<td>FASat-Bravo (Chile)</td>
<td>July 10, 1998</td>
<td>Total column ozone measurements</td>
</tr>
<tr>
<td>OM-2</td>
<td>TechSat/Gurwin-II</td>
<td>July 10, 1998</td>
<td>Technion (Israel Institute of Techn.,)</td>
</tr>
<tr>
<td>OSIRIS (CSA)</td>
<td>ODIN (Sweden)</td>
<td>Feb. 20, 2001</td>
<td>Detection of aerosols and trace gases</td>
</tr>
<tr>
<td>TOMS-5 (NASA)</td>
<td>QuikTOMS</td>
<td>Sep. 21, 2001</td>
<td>Failure of Taurus launch vehicle</td>
</tr>
<tr>
<td>SAGE-III (NASA)</td>
<td>Meteor-3M-1 (Russia)</td>
<td>Dec. 10, 2001</td>
<td>Self-calibrating solar and lunar occultations (9 spectral channels)</td>
</tr>
<tr>
<td>GLI, ILAS-II</td>
<td>ADEOS-II (JAXA)</td>
<td>Dec. 14, 2002</td>
<td>Swath width of 1600 km</td>
</tr>
<tr>
<td>GOMOS, SCIAMA-CHY (ESA)</td>
<td>Envisat (ESA)</td>
<td>Mar. 1, 2002</td>
<td>Star occultation measurement method, DOAS and BUV in parallel</td>
</tr>
<tr>
<td>HIRDLS, MLS, TES (NASA), OMI (NIVR)</td>
<td>Aura (EOS/CHEM) (NASA)</td>
<td>Jul. 15, 2004</td>
<td>Limb sounder (HiRDLs), FTS (TES), Hyperspectral capabilities of OMI</td>
</tr>
<tr>
<td>TANSO-FTS</td>
<td>GOSAT (JAXA)</td>
<td>planned 2008</td>
<td>FTS instrument</td>
</tr>
<tr>
<td>OMPS IPO/NASA</td>
<td>NPOESS (IPO)</td>
<td>planned 2012</td>
<td>Limb-viewing sensor suite</td>
</tr>
</tbody>
</table>

- **NOXAR** (Nitrogen Oxides and ozone measurements along Air Routes)\(^{459}\) was conducted aboard 540 flights of Swissair B-747 aircraft in the period from May 1995 to May 1996. The instruments recorded data at a temporal resolution of 3s.

- Another German program, CARIBIC (Civil Aircraft for Remote-Sensing and In-Situ-Measurements in Troposphere and Lower Stratosphere Based on the Instrumentation Container Concept), started in 1996.

### 1.2.6.2 Occultation measurements

The history of occultation observations must be as old as astronomy itself, ancient. An occultation occurs whenever a celestial object passes in front of another one, whereby the more distant object is hidden (eclipsed); occultation refers literally to the “obscuring-of-light event” of an astronomical body to an observer. One type of such an event is the occultation of stars by the moon or by any other object within the solar system. An eclipse of the sun takes place when the moon comes between the Earth and the sun so that the moon’s shadow sweeps over the face of the Earth. - The phenomenon of occultation helped ancient astronomers to determine the periods and motions of the sun and the moon. Historically, the eclipses of Jupiter’s moons Io, Europa, Ganymede, and Callisto (discovered by Galileo Galilei in 1610) are important, for they provided one of the earliest proofs of the finite speed of light. In 1675, the Danish astronomer Ole Rømer noticed discrepancies between the observed and calculated times of such eclipses, which he correctly explained as being due to the difference in the travel time of light when the Earth is nearest to Jupiter or farther away from it. Today’s astronomers use occultation measurements to determine for instance the variations in the length of the mean solar day or to estimate the diameter and size of a distant planet, even those of tiny asteroids.

Conceptually, occultations may also be observed by an instrument on a spacecraft in orbit and/or by a radio communication path interference between the spacecraft and the Earth. During the beginning and the end of such an occultation, signals sent out by the spacecraft’s communication system and received on Earth have penetrated the planet’s atmosphere. Occultation measurements employ generally the technique of passive absorption spectroscopy. In the early 1960s, this occultation technique was first employed by NASA/JPL in its planetary exploration program to Venus and Mars; the analysis of the data yielded information about atmospheric density and composition of Venus and Mars, respectively.

At the start of the 21st century, use of the occultation measurement principle for observing the Earth’s atmosphere and climate has become so broad as to exploit natural radiation sources such as the sun, the moon, and the stars, as well as man-made radio signals from the GNSS (Global Navigation Satellite System) constellations and other satellite constellations (crosslink signals), to employ the whole electromagnetic spectrum (from EUV/UV to VIS/IR to MW and radio waves), and to utilize all kinds of atmosphere-radiation interaction such as refraction, absorption, and scattering (see also Glossary and chapter O.2.1; there are also many occultation and limb/occultation sounding instances within the “history” itself). In general, good occultation monitoring coverage is obtained with a sufficient density of occultation sources. - The occultation measurement methods share the unique properties of self-calibration (via normalized intensities or time-standard reference), high accuracy and vertical resolution, global coverage, and an all-weather capability (due to the use of long wavelengths in the microwave region). The self-calibration property is particularly crucial for climate research and climate change monitoring applications, as it enables unique long-term stability in climatological datasets. Occultation measurements bear a great potential for such applications as operational meteorology, climate research, and many other fields.

Some examples are: 460)

- The occultation sounding of aerosols, trace gas constituents including ozone (“absorptive” or “extinctive” occultation monitoring), and of wind components with a variety of instruments (see 1.2.6).
- Refractive (or radio) occultation sounding of the GPS constellation. Earth-observation applications of navigation systems and use of GPS receivers as science instruments (in experimental state as of 2002). The goal is to use the meteorological occultation data to augment the data from other meteorological data sources (see 1.5.4)
- Bistatic ocean reflection measurements (see 1.5.6)
- Measurement of plasma densities of the solar wind

460) http://www.uni-graz.at/OPAC1Workshop-Sep2002/
1.2.7 Sounding of the Ionosphere

The ionosphere is a layer of the Earth’s atmosphere, between approximately 60 and 1000 km in altitude (a highly variable and complex physical system), that is partially ionized by solar x-rays, ultraviolet radiation, and energetic particles from space. The parameters of the ionospheric plasma are primarily controlled by the solar activity. Their sporadic perturbations usually appear as a response to perturbations in the solar wind and the magnetosphere. The interaction between the solar wind, the magnetosphere and the ionosphere is of great interest in solar-terrestrial physics studies. Spaceage observations reveal that the ionosphere locally reflects tropospheric phenomena (storms, upward shooting lightning, large cyclones and atmospheric fronts), anthropogenic factors (rocket launches, especially powerful ones, descent of spacecrafts, explosions, radio transmitter operations, etc.) and lithospheric processes (seismic activity, earthquakes, active fractures). The possibility to use these data for the prediction of earthquakes and monitoring of the anthropogenic and natural hazards is a new area of current research. 461) 462)

Ground-based echo sounding of the ionosphere has been conducted since about 1924/25 to obtain information about the upper atmosphere and the effects of solar emissions. By 1947, an instrument known as the “ionosonde” was routinely used to measure automatically the characteristics of the ionosphere. During the International Geophysical Year (IGY) of 1957/58, an international cooperative effort created a worldwide network of ionosondes to record vertical incidence measurements for the 1957/59 period of maximum solar activity. Since the IGY, a loosely coordinated worldwide network of vertical incidence ionosondes, varying between 100 and 200 sites, has been operated continuously. 463)

- Modern “bottomside” digital sounders 464) measure the frequency, time delay, amplitude, phase shift, Doppler shift and spread, polarization, and the return direction of echoes reflected off the underside of the earth’s ionosphere. These measurements are typically shown as ionograms and are regularly inverted to give plasma density, velocity, and even turbulence versus altitude. However, ionograms represent only a fraction of the information available to a modern sounder, but they do display the echoes from ionospheric structures in a clear and graphical format. Many of the advantages of modern sounders over earlier devices are due to increased use of digital signal processing and flexible software controlled designs. Radio sounding offers a way to simultaneously measure the largest and some of the smallest scales in the magnetosphere, plasmasphere, and boundary layers.

The ionosphere is divided into four broad regions called D, E, F, and topside. These regions may be further divided into several regularly occurring layers, such as F1 or F2. 465) 466)

- D-region: The region between about 75 - 95 km above the Earth in which the (relatively weak) ionization is mainly responsible for absorption of high-frequency radio waves.

461) Note: No single physical process can be made responsible for the diverse phenomena claimed to be associated with or indicators of impending earthquake activity. Transient termal anomalies and short-term ionospheric variations have different possibilities as pre-earthquake activity indicators.


464) Note: Ionograms are recorded tracings of reflected high frequency radio pulses generated by an ionosonde. Unique relationships exist between the sounding frequency and the ionization densities which can reflect it. As the sounder sweeps from lower to higher frequencies, the signal rises above the noise of commercial radio sources and records the return signal reflected from the different layers of the ionosphere. These echoes form characteristic patterns or “traces” that comprise the ionogram. Radio pulses travel more slowly within the ionosphere than in free space, therefore, the apparent or “virtual” height is recorded instead of a true height. For frequencies approaching the level of maximum plasma frequency in a layer, the virtual height tends to infinity, because the pulse must travel a finite distance at effectively zero speed. The frequencies at which this occurs are called critical frequencies. Characteristic values of virtual heights (designated h'E, h'F, and h'F2, etc.) and critical frequencies (designated foE, foF1, and foF2, etc.) of each layer are scaled, manually or by computer, from these ionograms.

465) http://www.ngdc.noaa.gov/stp/IONO/ionogram.html

466) http://www.wdcb.rssi.ru/WDCB/cat2ION.html
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--- E-region: The region between about 95 - 150 km above the Earth that marks the height of the regular daytime E layer. Other subdivisions isolating separate layers of irregular occurrence within this region are also labeled with an E prefix, such as the thick layer, E2, and a highly variable thin layer, sporadic E. Ions in this region are mainly O\(^{2+}\).

--- F-region: The region above about 150 km in which the important reflecting layer, F2, is found. Other layers within this region are also described using the prefix F, such as a temperate-latitude regular stratification, F1, and a low-latitude, semi-regular stratification, F1.5. Ions in the lower part of the F layer are mainly NO\(^{+}\) and are predominantly O\(^+\) in the upper part. The F layer is the region of primary interest for radio communications.

--- Topside region: This part of the ionosphere starts at the height of the maximum density of the F2 layer of the ionosphere and extends upward with decreasing density to a transition height where O\(^+\) ions become less numerous than H\(^+\) and He\(^+\) ions. The transition height varies but seldom drops below 500 km at night or 800 km in the daytime, although it may lie above 1000 km. Above the transition height, the weak ionization has little influence on transionospheric radio signals.

- Spaceborne soundings of the ionosphere started with the launch of Alouette-1 in 1962 (see below). A radio plasma sounder operates by emitting a series of pulses over a range of frequencies, and listening for returned echoes. The properties of the dielectric, the surrounding plasma in this case, dictate the wave modes which propagate and their dependence on the dielectric (plasma) parameters.

**Topside sounding of the ionosphere:**

The term refers to RF (Radio Frequency) sounders looking from a LEO spacecraft into the nadir direction for ionospheric electron density observations. Other ionospheric parameters such as TEC (Total Electron Content), critical frequency (\(f_{o}F2\)) and F2-layer peak height, plasma temperature, and ion composition may be derived from the topside ionograms. The ionosphere below the peak electron concentration is referred to as bottomside ionosphere, while the outer part of the ionosphere, extending to about 2000 km and further, is referred to as the topside ionosphere. A sounder, installed onboard a LEO satellite (generally in the 800-1500 km range) and practically immersed in the medium it is measuring, is able to see only the uppermost portion of the ionosphere down to about the peak electron height, i.e., the topside ionosphere; hence, such a sounder is referred to as a “topside sounder.”

An ionospheric topside sounder is a high frequency radar system that is located above the ionosphere, ideally onboard a polar orbiting satellite to provide global coverage. The sounder sweeps in frequency from around 0.3 to 15 MHz approximately every 32 seconds — its signals reflecting vertically off the upper F2 region of the ionosphere. The lowest frequency at which the signal passes through the ionosphere is called the critical frequency (\(f_{o}F2\)). Electrons are also stimulated at various lower frequencies causing resonances. The results from topside sounding are generally displayed as an ionogram, which is a display of reflections and resonances of the swept frequency against apparent range.

Following is a list in the early era of spaceflight of countries or agencies with various techniques of topside sounding implementations:

- The Canadian spacecraft **Alouette-1** (launch Sept. 29, 1962 from VAFB) can be regarded as the first satellite (with a circular orbit of 1000 km altitude and an inclination of

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80.5°) carrying a topside sounder to investigate the ionosphere (Canada/USA cooperative venture). The primary purpose of the Alouette-1 mission was to investigate the geographic, seasonal, and diurnal properties of the topside ionosphere up to 1000 km in altitude. Designed for a one-year life span, the satellite lasted 10 years producing more than 1 million images of the ionosphere. The Alouette-1 swept-frequency revealed that an equatorial anomaly extends high into the topside ionosphere; it also demonstrated its usefulness in observing HF electron resonances. The Alouette-1 topside sounder had the following parameters: Frequency range of 1-12 MHz, transmitter power of 100 W, pulse width of 100 µs, pulse repetition frequency of 62 Hz, and a frequency sweep rate of 1 MHz/s. In a supporting experiment, an untuned VLF receiver operated in the range of 400 Hz to 10 kHz. The VLF receiver permitted the measurement of relative ion abundances in conjunction with the sounder. A worldwide network of 22 ground receiving stations collected the sounding data of Alouette-1 and -2. Alouette-2 followed in 1965, also with a topside sounder. Each Alouette S/C produced topside ionograms for 10 years. 471) 472) 473)

- Explorer-20 of NASA (launch Aug. 25, 1964), the basic sounder instrumentation comprised a two-frequency transceiver coupled to an electrically short dipole antenna (three transceivers were used for sounding at six fixed frequencies between 1.5-7.22 MHz)

- Explorer-22 of NASA (launch Oct. 10, 1964)

- ISIS-1 (International Satellite for Ionospheric Studies-1) 474) 475) of NASA with a launch in 1969 (the ISIS program was actually an extension of the Alouette program), ISIS also demonstrated the ability to remotely sound the magnetospheric cusp.

- ISIS-2 of NASA (launch April 1, 1971). The ISIS satellites collected several million topside ionograms in the 1960s and 1970s (ISIS-1 and ISIS-2 collected for 21 and 19 years, respectively) with a multinational network of ground stations providing good global coverage. — — Note: ISIS-1 and — 2 are considered second generation topside sounder missions because they provided an onboard data storage capability and limited experimental control capability. These two topside sounders contained 4 track tape recorders with 550 m of tape to record telemetry, sounder and VLF information, along with reference tone & clock.

- SJ-2A (launch Sept. 20, 1970) of CAST, China, used two frequencies: 162 MHz and 40.5 MHz

- Cosmos-381 (launch in 1970) of the Soviet Union;

- ISS-A (Ionospheric Sounding Satellite-A) of NASA with a launch in 1976; ISS-B of NASA (launch Feb. 16, 1978). The missions were also referred to as Ume—1 and Ume—2. The ISS-B spacecraft had only memory for about 4 orbits (6 hours); hence, much of the available data was lost. It took nearly 4 months to build up one local time (LT) map of the Earth.

473) Note: Swept-frequency sounding is a technique in which a measurement is made of the frequency shift, phase shift, or time delay between the transmitted signal and its echo). Because of the Earth’s magnetic field, the ionosphere is birefringent with the result that a transmitted electromagnetic wave normally splits into two characteristic waves which travel independently at different velocities and different polarizations. These are called the ordinary (O) and the extraordinary (X) waves and are typically elliptically polarized. As the sounding frequency is increased, the electron number density required to reflect the transmitted signal increases until reflection occurs at a region or height of maximum ionization. Above the critical frequency corresponding to the electron number density at the peak of the F2-layer, reflection can no longer take place and the ionosphere becomes transparent to the sounding signal.
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- EXOS-B (Exospheric Satellite-B or Jikiken) of NASDA (launch Sept. 16, 1978)
- ISEE-1/-2 of NASA/ESA (launch Oct. 22, 1977)
- Intercosmos-19 spacecraft of the Soviet Union (launch Feb. 27, 1979). A digital topside sounder, IS-338, developed by IZMIRAN (Russian Institute of Terrestrial Magnetism, Ionosphere and Radiowave propagation) of Moscow, was flown. The spacecraft carried a computer to process data, having enough memory to record information from about 10 orbits (16 hours) of soundings recorded every 64 seconds.
- EXOS-C (Ohzora, launch Fe. 14, 1984) of NASDA
- Cosmos-1809 (launch Dec. 1986) of the Soviet Union. The spacecraft carried also the digital topside sounder IS–338.
- Coronas-I of Russia (launch March 2, 1994 from Plesetsk), and the orbital MIR Space Station (the topside sounder was installed on the Priroda module in 1998).

Topside sounding from a satellite reveals the response of the ionosphere to disturbances such as a geomagnetic storm. The pulses emitted by the sounder on consecutive frequencies are reflected on different heights depending on electron density height distribution. The time delay dependence of emitted pulses on the frequency is called the height-frequency characteristic of the ionosphere, referred to as the ionogram. With the help of a special algorithm, which takes into account the propagation characteristics of electromagnetic waves in magnetized plasma, the measurements are transformed into density height distributions from the satellite altitude down to the maximum F2-layer density distribution, which is usually located at altitudes of 250 to 350 km. In equatorial regions, especially in geomagnetically disturbed conditions, the F2-layer peak height may extend to altitudes of 500 km and even more. 476)

Direct observations of ionospheric features are crucial for various applications in the fields of communications, navigation, early earthquake warning, radar, etc. - In spite of the numerous early missions, topside global sounding of the ionosphere has not become an operational service at the turn of the 21 century, rather it can still be put into the experimental category of missions.

An overview of the history of seismo-ionospheric effects is provided in the following reference. 477) 478) 479) 480) A disturbance of ionospheric electromagnetic radiation in the range of 10 Hz - 1 kHz was for the first time observed by Gokhberg, 481) when the NASA satellite OGO-6 (Orbiting Geophysical Observatory-6; launch June 5, 1969 from VAFB, end of mission Oct. 12, 1979) had gone over the sources of strong earthquakes (M > 5.5). An ion density trough (about 20%) over the earthquake source was also observed when the data from the NASA satellites ISIS-2 (International Satellite for Ionospheric Studies-2, launch April 1, 1971) and AE-C (Atmospheric Explorer-C; launch Dec. 16, 1973) were analyzed. Additional disturbance effects were found from statistical data of the Intercosmos-19 mission (launch Feb. 27, 1979), and reported for the first time.

The phenomenon of ionospheric perturbations prior to strong earthquakes has been known for some time. But the problem is how to distinguish the perturbations caused by solar flares and magnetic storms from those that are genuinely due to seismic activity. The idea of using satellites to predict earthquakes is based on the fact that Earth’s crust emits characteristic electromagnetic signals a few hours before an impending quake.

The observed seismo-activity influence on the ionosphere is rather weak and is usually masked by the solar activity effects. The seismogenic disturbances are typically detected in the ionosphere under low solar activity conditions (Kp<4). Nevertheless, making use of modern signal processing methods there is a hope to extract them if the structural peculiarities of seismogenic “signals” can be reliably determined. This approach, however, requires a huge amount of experimental data as well as appropriate theoretical modeling.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Time frame</th>
<th>Mission</th>
<th>Time frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alouette-1 (Canada)</td>
<td>1964</td>
<td>Cosmos-274 (USSR)</td>
<td>1969</td>
</tr>
<tr>
<td>OGO-6 (NASA)</td>
<td>1969</td>
<td>OVI-17</td>
<td>1969</td>
</tr>
<tr>
<td>ISIS-2 (NASA)</td>
<td>1971</td>
<td>AE-C (NASA)</td>
<td>1973</td>
</tr>
<tr>
<td>GEOS-2 (NASA)</td>
<td>1978</td>
<td>Intercosmos-19 (USSR)</td>
<td>1979</td>
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<tr>
<td>Aureol-3 (CESR, France)</td>
<td>1981</td>
<td>Intercosmos-Bulgaria 1300</td>
<td>1982</td>
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<tr>
<td>Salyut-7 (USSR)</td>
<td>1985</td>
<td>Meteor-3 (USSR)</td>
<td>1986</td>
</tr>
<tr>
<td>Cosmos-1809 (USSR)</td>
<td>1987</td>
<td>ACTIVE (Intercosmos-24)</td>
<td>1987</td>
</tr>
<tr>
<td>TOPEX/Poseidon (NASA/CNES)</td>
<td>1996</td>
<td>MIR Space Station (Russia)</td>
<td>1994-1999</td>
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</tbody>
</table>

Table 34: Overview of seismo-ionospheric effects registered in missions (some a posteriori)

- Possible future applications of topside ionospheric monitoring may involve the capability to diagnose the effect of anomalous atmospheric electric fields that penetrate into the ionosphere. The data analysis from the topside sounder on the Intercosmos-19 (1979) spacecraft showed strong variations in the vertical structure of the ionosphere over regions of impending earthquakes. The ionosphere rises over a seismic active region forming a dome of density depletion. One of the main sources of atmosphere-ionosphere modification over the regions of preparing earthquakes is the emanation of various gases (radon, hydrogen and helium) from the ground as well as sub-micron aerosols. These may lead to the changes in the electrodynamic properties of the atmosphere-ionosphere that can be observed by the topside sounder.

- Seismo-ionospheric studies make use of atmospheric electricity distributions. The large-scale vertical electric field of high intensity (in the order of 1000 V/m), appearing over seismically active regions a few days prior to a strong earthquake, is due to the anisotro-

483) B. Nava, S. M. Radicella, S. Pulinets, V. Depuev, “Modelling Bottom and Topside Electron Density and TEC with Profile Data from Topside Ionograms,” Advances in Space Research, Vol. 27, No. 1, pp. 31-34, 2001
py of atmospheric conductivity at heights > 60 km. It normally penetrates into the ionosphere thereby creating the specific irregularities of electron concentrations. The resulting seismogenic variations in the ionospheric plasma represent a modification of the so-called magnetic-force-tube which is leaning into the direction of a developing earthquake region. The monitoring of the following parameters is of particular relevance in connection with corresponding models.

- F-layer maximum density (critical frequency)
- Measurements of the height of the F-layer maximum
- Vertical ionization profiles (both for topside and bottomside ionosphere)
- TEC (Total Electron Content)
- Measurement of ion composition
- Measurement of electron temperature.

- The COMPASS – 1 microsatellite (launch Dec. 10, 2001) of IZMIRAN is a new topside sounding mission dedicated to the study of the structure of the geodynamic processes (in particular above deep tectonic faults and earthquake regions). The sensor complement of the mission employs ionospheric tomography (monitoring of electromagnetic fields of various intensities and frequencies as well as heat distributions). The combined measurements are processed and analyzed in search of possible earthquake indicators. Note: The satellite experienced uncontrolled behavior ending in a loss of the mission shortly after deployment.

- The COMPASS – 2 microsatellite (launch May 26, 2006) of IZMIRAN is a topside sounding mission.

- Hyperspectral imaging of the global ionosphere is provided by the HIRAAS (High-Resolution Airglow/Aurora Spectroscopy) instrument package of NRL flown on the ARGOS satellite of DoD (launch Feb. 23, 1999, see M.3). The imagery of the ionosphere obtained is “hyperspectral” at wavelengths from 50 to 310 nm. The HIRAAS, GIMI (Global Imaging Monitor of the Ionosphere) and EUVIP (Extreme Ultraviolet Imaging Photometer) instruments on the ARGOS S/C provide a powerful remote sensing exploration of the global ionosphere. This unusual combination of hyperspectral imagers and imagers provides a unique database of global structure and variability of ionospheric structure.

- QuakeSat (launch June 30, 2003) is a research nanosatellite of the QuakeFinder Team and SSDL (Space Systems Development Laboratory) at Stanford University, Stanford, CA, with the objective of earthquake signature detection. QuakeSat’s primary scientific mission is to detect, record, and downlink ELF (Extremely Low Frequency) magnetic signal data, which may lead to groundbreaking techniques to predict earthquake activity. QuakeSat flies a very sensitive magnetometer. As of July 2004, a total of nearly 2000 magnetometer collections were made of all modes, primarily in the mode 2 configuration (10 to 150 Hz), roughly 500 MB raw binary uncompressed data.

- The DEMETER microsatellite mission of CNES (see M.25.1), with a launch June 29, 2004, has the objective to: a) study the ionospheric disturbances in relation to the seismic activity, b) estimate the ionospheric disturbances in relation to the human activity, c) study the post-seismic effects in the ionosphere.

- The Russian/Ukrainian multi-purpose Sich-1M spacecraft (launch Dec. 24, 2004) carries the instrument package Variant (“version”) to investigate the coupling of the lithosphere-atmosphere-ionosphere-magnetosphere, and to study space weather and fine seismogenic effects in the ionosphere. Variant is an international joint scientific project of Great Britain, Poland, France, Russia, and Ukraine. The Variant scientific payload includes three instruments for registration of space current density: a split Langmuir probe, a Rogovsky coil and a Faraday cup. The first two of these instruments are dedicated to measure

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current density variations and the last the particle fluxes. The equipment also includes sensors for measurements of the electric and magnetic field fluctuations in the frequency range from 0.1 Hz to 40 kHz.

- Project Vulkan (Volcano) is being funded by Rosaviakosmos for a launch of the minisatellite constellation in 2006. The satellites are being built by NIIEM of Istra; the scientific package is being developed by IZMIRAN of Troitsk and IKI of Moscow. The Vulkan orbital constellation will comprise two types of spacecraft (each of about 300 kg) built around the same multipurpose satellite bus: a) Vulkan-N at altitudes of 500-550 km, b) Vulkan-V at altitudes of 900-950 km. Monitoring of the following ionospheric phenomena/characteristics:

- Waveform of electromagnetic oscillations by electric and magnetic components within the 0.1 Hz to 5 kHz frequency band
- Spectral density of electromagnetic oscillations within the 1 Hz to 15 kHz band
- Electromagnetic field oscillation spectrum within the 15 kHz to 15 MHz band
- Quasi-constant electric field within the 0-1 Hz band
- Magnetic flux density within the band: -60 μT to +60 μT
- Parameters of the ionospheric plasma
- The satellites will also measure characteristics of the underlying terrain and vertical profiles of aerosols.

- Ionospheric sounding from GEO (Geostationary Orbit). The IMAGER (Ionospheric Mapping and Geocoronal Experiment) instrument of NRL is planned to fly on the EO-3 (Earth Observing-3) mission in 2006 (of NASA, US Navy and NOAA). The overall objective is to demonstrate real-time tracking of ionospheric irregularities and scintillation storms. The tracking of these storms provides advanced warnings of navigation and satellite communication outages.

1.2.8 Some Instrument/Observation Techniques

- **DOAS (Differential Optical Absorption Spectroscopy).** A measurement technique that identifies and quantifies trace gas abundances with narrow band absorption structures in the near UV and visible region of the spectrum. The atmospheric spectra technique was first developed by Dieter Perner at KFA Jülich (now Forschungszentrum Jülich, Germany) in the early 1970s for the analysis of spectral windows. The distinguishing feature of DOAS (as compared to other spectrometers measuring atmospheric constituents) is that it aims to measure differential rather than absolute spectra. This means that broadband absorption or scattering effects arising from aerosols or gases can be separated (in ground analysis) from differential features which are characteristic of the trace gases absorbing in a given window. The distinguishing feature of a DOAS instrument is that it records simultaneously the entire spectrum of a selected spectral window. 492) 493) 494)

The DOAS technique was first applied to long-path tropospheric investigations by D. Perner, U. Platt and co-workers. This resulted in an experimental ground-based DOAS-UV and VIS spectrograph installation at KFA Jülich in 1978, Germany (measurement of atmospheric CH$_2$O, O$_3$, and NO$_2$). Further ground-based DOAS instruments were built. Two airborne instruments, DOAS-VIS, developed by the Institute of Environmental Physics at the University of Heidelberg, and DOAS-UV of MPI for Chemistry (MPICh), Mainz, are flown since Jan. 1991 on a C160 Transall aircraft. A DOAS-type experiment by the name of “Mapping Atmospheric Pollution” was first proposed to ESA in March 1985 by J. P. Burrows, D. Perner, and P. J. Crutzen to fly on the EURECA free-flyer platform (EURECA was launched on STS-46 on July 31, 1992 and retrieved with STS-57 on July 1, 1993). - First spaceborne DOAS instruments are GOME (Global Ozone Monitoring Experiment) flown on ERS-2 (launch April 21, 1995), OSIRIS (Optical Spectrograph and Infrared Imaging System) flown on Odin (launch Feb 20, 2001), SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) flown on Envisat of ESA (launch Mar. 1, 2002), OMI (Ozone Monitoring Instrument), a Dutch-Finish nadir-pointing instrument on the Aura mission of NASA (launch July 15, 2004), and GOME-2 on Metop-A of EUMETSAT (launch Oct. 19, 2006). Since the launch of ERS-2, there are also several ground-based DOAS stations in Europe providing ground truth measurements for GOME and SCIAMACHY.

- **TDLAS (Tunable Diode Laser Absorption Spectrometer)** is an open path spectroscopic technique that utilizes a diode laser as its light source [also referred to simply as TDL (Tunable Diode Laser) technique]. TDLAS is an alternate technique (to DOAS) of measuring atmospheric trace gases. The in-situ measurement technique makes use of the existence of rotational-vibrational molecule transitions in the mid IR spectrum and monitors a single absorption line. TDLAS has an advantage over other spectroscopic methods in that the diode laser can be operated in a relatively high-frequency modulation regime, where its noise contribution is very low. The airborne instrument FAST (Frequency-modulated Absorption Spectroscopy by TDLAS) of MPICh (Max-Planck-Institut für Chemie) of Mainz, Germany, flown since 1992, is an example of the TDLAS instrument technique. NASA utilized the TDL technique in particular to improve water vapor measurements in the upper atmosphere. The ALIAS (Aircraft Laser Infrared Absorption Spectrometer) instrument, developed in the 1980s, was flown on the ER-2 aircraft with over 50 flights completed by the end of 1993. At the start of the 21st century, TDL instrument technology is being used for a wide range of applications, such as monitoring the exchange of CO$_2$ between specific eco-


systems. In 2000, NASA/JPL licensed its TDL technology to SpectraSensors Inc. of Altadena, CA, for commercial exploitation (air pollution emissions, etc.).

- **Wedge Imaging Spectrometer (WIS) technology.** WIS is a spectral separation technique in which the spectral separation filters are mated to the detector array to achieve two-dimensional sampling of the combined spatial/spectral information passed by the filter. The technique obviates the need for a complex aft-optics assembly; it was developed by Hughes SBRC and sponsored by ARPA (introduced in 1992, see chapter P.209). The technology (hyperspectral imaging in the VNIR and SWIR regions) was initially flown on airborne sensors (WIS). It is also employed for the spaceborne sensor AC (Atmospheric Corrector) of the EO-1 mission (launch Nov. 21, 2000).

- **Supermode acquisition of imagery.** The term “supermode” refers to an acquisition process, introduced by CNES for the HRG (High Resolution Geometric) instrument of SPOT-5 (launch May 4, 2002), through which an image, sampled at 2.5 m, may be obtained from two 5 m resolution panchromatic images acquired simultaneously, keeping within the same borders as the two 5 m resolution images. See chapter D.46.3.

The new sampling concept of imagery, technically referred to as quincunx sampling pattern (an arrangement of five things with one at each corner and one in the middle of an area), employs a linear dual-array CCD detector in the focal plane, offset by one half pixel in one direction and 3.5 pixels in the other to avoid overlapping. This configuration is sufficient to improve the sampling grid without doubling each array’s acquisition rate. The new sampling concept is based on Claude E. Shannon’s theory of information which states that “the sampling frequency must be equal to or greater than twice the maximum signal frequency” to obtain clean images. 495) A specific image processing software, developed by CNES, is used to reconstruct the final image after three processing steps: interleaving, interpolation and restoration (involving de-noising and de-convolution). The quincunx sampling mode is also referred to as THR (Très Haute Résolution) or very high resolution mode. 496) CNES intends to implement the THR ground processing mode also within the framework of its Pleiades program delivering panchromatic data at 70 cm and MS data at 2.8 m resolution. Note: In Oct. 2003, the French government gave its final approval and go-ahead to the Pleiades program.

### 1.2.8.1 QWIP (Quantum-Well Infrared Photodetector)

QWIP 497) 498) 499) 500) 501) 502) represents a new passive infrared photoconductive solid-state detection technology (using 2-D focal plane arrays), holding great promise for a variety of infrared imaging applications in the spectral region of 6-20 μm which includes TIR [Thermal Infrared = 6-14 μm (an atmospheric window) - great efforts are being made to extend the QWIP observation coverage in the infrared range beyond the 25 μm range). Operating principle: QWIPs operate by photoexcitation of electrons between ground and first...

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excited state subbands of multi-quantum wells which are artificially fabricated by placing thin layers of two different high-bandgap semiconductor materials alternatively. The bandgap discontinuity of two materials creates quantized subbands in the potential wells, associated with conduction bands or valence bands. The structure parameters are designed so that the photo-excited carriers can escape from the potential wells and be collected as photocurrent.  

The QWIP technology employs large-bandgap III-V compound semiconductor materials such as GaAs (Gallium Arsenide) and AlGaAs (Aluminum Gallium Arsenide) with different aluminum compositions. The potential advantages of QWIP manufacturing (GaAs and AlGaAs) include the use of standard manufacturing methods based on GaAs growth and processing techniques. Some QWIP technology applications require low-temperature cooling for good spectral performance (higher sensitivity and speed). Note: Infrared detection may also be implemented on QWIP structures operated in photovoltaic mode (as opposed to photoconductive mode). QWIPs are ideal due to their tunable, narrowband response, obtained in point detectors and focal plane arrays. - QWIP structures are intrinsically very fast photodetectors since the re-capture time of optically excited carriers is very short, in the order of a few picoseconds (ps). Besides infrared imaging applications, QWIP structures are also interesting for heterodyne applications, where the high electrical bandwidth results in an improved spectral range of a heterodyne spectrometer.

Background: Initial work on QWIP technology started in the early 1980s at AT&T Bell Laboratories in Murray Hill, NJ (funded by BMDO, NASA and the US Army). The project goals were to produce a highly sensitive infrared photodetector addressing such issues as cost, fabrication technique, wavelength response, and large array size [the QWIP technology is actually a product/result out of Ronald Reagan’s SDI (Strategic Defense Initiative) program to remotely detect the “signature” (i.e. slight changes in heat) of a ballistic missile launch, allowing for better tracking of a projectile]. The first experimental demonstration of a staring 2-D QWIP imaging array took place in 1985. The first demonstration model of a QWIP FPA camera with a 128 x 128 pixel array was developed by B. F. Levine and his colleagues at Bell Labs in 1991. This included the successful demonstration of the first bound-to-continuum GaAs/Al_x Ga_{1-x}As indirect bandgap QWIP operating at a cutoff wavelength of 4.2 μm. Semiconductor nanostructures, especially quantum wells and dots made of GaAs and InP related compounds, have enabled several unique infrared devices. Two prime examples are: QWIP devices and the QCL (Quantum Cascade Laser).

With the advent of QWIP technology, large format and high uniformity single- and two-color QWIP FPAs have been developed for IR imaging applications. The first multicolor FPAs are being developed at the start of the 21st century by a number of manufactures, capable to detect three and four color ranges of the spectrum simultaneously, thereby offering more detailed views of the spectrum resulting in a wider range of applications [Earth observation (infrared imaging, hot spots), medicine, astronomy, atmospheric studies (IR spectroscopy for chemical sensing, pollution monitoring, smog detection), surveillance, ...]

506) http://csmt.jpl.nasa.gov/spacemicro/QWIP_PAPER
507) Note: The SDI program implementation was stopped in the 1980s because of technological shortcomings.
navigation aids for pilots (night vision), commercial and industrial applications, traffic safety, etc.].

Some early imaging instruments of the QWIP technology are:

- In 1994, CSMT (Center for Space Microelectronics Technology) of NASA/JPL demonstrated a QWIP prototype camera with a detector array of 128 x 128 pixels (size of 38 \( \mu m \) x 38 \( \mu m \)), a cutoff wavelength of 14.9 \( \mu m \) (spectral bandwidth of 2 \( \mu m \)), and a frame rate of 5-210 Hz.
- In 1996, NASA/JPL and Amber (of Raytheon) demonstrated the QWIP technology with the development of a hand-held infrared camera (256 x 256 pixel FPA of QWIPs to detect radiation at 8.5 \( \mu m \), frame rate of 60 Hz, camera mass of 4.5 kg).
- In 1997, FhG/IAF (Fraunhofer Gesellschaft / Institut für Angewandte Festkörperphysik) of Freiburg, Germany, in partnership with AIM (AEG Infrarot Module) GmbH of Heilbronn, Germany, demonstrated also a QWIP-based camera system (256 x 256 pixel FPA with a peak wavelength of 8.1 \( \mu m \), the FPA is cooled to 65 K. - (Note: Objects at room temperature glow brightest in the wavelength range of 8-10 \( \mu m \)). The camera exhibits extremely low noise levels corresponding to NEDT (Noise Equivalent Differential Temperature) of 9.5 mK over the entire array. The research was supported by the German Ministry of Defence. The same camera, with the name of AIM-640Q, is also commercially available. 511)
- Another QWIP FPA camera with 640 x 512 pixels and 20 mK NEDT was developed by AIM in 1999/2000. The GaAs/AlGaAs QWIP FPA was fabricated at IAF. Detector size of 16.3 mm x 13.3 mm, frame rate of 50 Hz. The QWIP detector chips are hybridized to a silicon-based ROIC (Readout Integrated Circuit) by flip-chip bonding with In-bumps. A peak wavelength of 8.8 \( \mu m \) and a cutoff wavelength of 9.3 \( \mu m \) are chosen to match the dark current of the detector to the charge handling capacity of the readout circuit.

1.2.8.2 TDI (Time Delay Integration)

TDI is an observation concept of increasing the effective dwell time of CCD detector arrays, usually in a pushbroom imaging mode configuration, by accumulating multiple exposures

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510) http://www.iaf.fhg.de/ir/qwip/camera.html
of the same (moving) target line. In scanned infrared imaging systems, TDI is one of the most important functions performed by CCDs. It was developed along with the early CCD technology at several places in the US industry and at NRL (DoD) in the later 1970s as well as at RSRE (Royal Signal and Radar Establishment, Malvern, UK) in 1982. RSRE introduced TDI into an infrared detector system by the name of SPRITE (Signal Processing In The Element). The TDI technique refers to a cumulative exposure concept of each ground image line by a CCD detector array (or any equivalent array). In TDI operation, signals generated by a moving scene-segment in successive detector lines are sequentially added in a delayed fashion. In this arrangement, the object motion must be synchronized with the exposures to ensure a crisp image. The main TDI objective is to improve the SNR (signal-to-noise ratio) value which is one of the most important issues for high resolution imaging. [Since the total detector noise is given by the root mean summation while the total signal is given by a simple sum, an increase in SNR equal to the square root of the number of detector rows is obtained].

Some spaceborne instruments with TDI implementations are: The SeaWiFS instrument of SeaStar (the renamed OrbView-2 mission, launched Aug. 1, 1997), the ISIR sensor of NASA/GSFC flown on Shuttle flight STS-85 (Aug. 7-19, 1997), the OSA instrument of the Ikonos-2 satellite (launch Sept. 24, 1999), BGIS 2000 of QuickBird-1 (launch Nov. 20, 2000 - launch failure), PIC-2 of the EROS-B satellite program of ImageSat International, Cayman Islands - with a planned launch EROS-B1 in 2004), and MSRS (Multi-Spectral high Resolution System) of the Diamant satellite of OHB-System, Bremen (launch 2007) - are examples of more recent TDI implementations in 2-D CCD line-array technology in the visible range of the spectrum. Note: For extrinsic detector arrays (such as silicon detectors in the visible range) there are two possible observation approaches: TDI or “staring array.” (see also O.3.6).

An unconventional TDI implementation is provided with RALCam1 (Rutherford Appleton Laboratory Camera 1) on the TopSat (launch Oct. 27, 2005) spacecraft of the UK (QinetiQ, SSTL, RAL, Infoterra Ltd.). The S/C platform is capable of supporting TDI, an attitude mode where the S/C maneuvers to allow the camera to “look” at its target for a longer period of time - equivalent to increasing the exposure time on a camera. scanning effect. During TDI observations the pitch of the S/C is manipulated such that it stares at the target for a longer period.

### 1.2.8.3 Polarimetric radiometry, imaging polarimeters, SAR polarimeters

Polarimetry deals with the vector nature of polarized electromagnetic radiation throughout the frequency spectrum. The electromagnetic field is a traveling wave (at the velocity of light) with electric and magnetic vector fields (scattering matrix) perpendicular to each other and to the direction of wave travel. A change in the index of refraction (or permittivity, magnetic permeability, and conductivity) causes the polarization state of a single frequency wave to be transformed, i.e. to be repolarized. Hence, a reflected (scattered) polarized wave from an object such as a radar target must contain some innate information about the object. The interpretation of the behavior of these complex signatures (in particular the direction of the electric field vector of the reflected polarized radiation) is in effect a major objective in polarimetry. By its very nature, the “full polarimetric imaging” technique provides the total information content of a scene, far more than the conventional “intensity imaging” scheme can do, since it retrieves the full scattering matrix (without the loss of spatial or spectral resolution). Hence, polarimetry has the potential to improve the harvest of remotely sensed data considerably.

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Polarimetric radiometry refers to microwave and optical observations (imagery) and interpretation of polarized microwave/optical emission from natural surfaces. Polarimetry can be used to identify materials and to distinguish samples from a cluttered background. The polarimetric imaging technique represents an extension of the measurement of vertically and horizontally polarized microwave/optical brightness temperatures by considering, in addition, the third and fourth of Stokes parameters [Sir George Gabriel Stokes (1819-1903), British mathematician, Stokes’s theorem]. Collectively, the four Stokes parameters provide a complete characterization of the Gaussian-random electromagnetic field (scattering matrix).

The development of a full polarimetric optical imaging instrument technology is still in an early stage (complex and costly) at the start of the 21st century. It requires in particular substantial research efforts in high-speed and high-sensitivity detector technology. Examples of early instrument implementations are:

- **Airborne instruments:** 1) PSR (Polarimetric Scanning Radiometer), a multi-channel conical-scanning instrument of NOAA/ETL (Boulder, CO) and Georgia Tech, flown since 1997, providing fully polarimetric imagery in the microwave and optical regions (see P.171). PSR is being used for post-launch satellite calibration and validation (underflights) of a variety of current/future spaceborne passive microwave sensors (like WindSat on Coriolis, AMSR-E on Aqua, SSMIS on DMSP, CMIS and ATMS on NPOESS). 2) APMIR (Airborne Polarimetric Microwave Imaging Radiometer) of NRL provides four polarimetric channels. The first flight of APMIR took place in Dec. 2001.

- **Early examples of instruments with polarization capability on spaceborne platforms.**
  - **POLDER (Polarization and Directionality of the Earth’s Reflectances)** of CNES is flown on ADEOS (launch Aug. 17, 1996) and ADEOS-II (launch Dec. 14, 2002). POLDER is an example of a passive spaceborne multi-band polarimetric imaging radiometer in the optical region (use of telecentric lens, a rotating wheel supporting filters and polarizers, and a matrix CCD sensor). It measures the bidirectionality and polarization of the solar radiation reflected by the atmosphere: tropospheric aerosols (inversion of the physical properties); ocean color (accurate determination of sea surface reflectances); land surfaces (determination of surface BRDF and improvement in the correction of the surface bidirectional and atmospheric effects on vegetation indices).
  - **NICMOS (Near-Infrared Camera and Multi-Object Spectrometer)** was installed on HST (Hubble Space Telescope) in 1997. It contains optical elements which enable high spatial resolution, high sensitivity observations of linearly polarized light in the spectral range of 0.8 - 2.1 μm. The filter wheels for Camera 1 (NIC1) and Camera 2 (NIC2) each contain three polarizing elements sandwiched with bandpass filters. NICMOS is capable to retrieve three Stokes parameters, to derive the polarization intensity, the degree of polarization, and the position angle at each pixel.
  - **WindSat (Wind Microwave Radiometer)** flown on the Coriolis mission (launch Jan. 6, 2003) of NRL, is a 22 channel fully polarimetric microwave instrument retrieving all four Stokes parameters by measuring the six principal polarizations (see A.12). WindSat is also considered a precursor instrument to CMIS (Conical-scanning Microwave Imager/Sounder), a radiometric polarimeter to be flown on NPOESS (first launch in 2012).
  - **APS (Aerosol Polarimeter Sensor)** is also flown on NPOESS to retrieve aerosol and cloud parameters (operational products) for climate research using multispectral photopolarimetry.

- **Introduction of polarimetric measurements in the microwave (radar) region of the spectrum (retrieval of full scattering matrix).**

SAR polarimetry (microwave region): In addition to measuring the amplitude of the radar return from a target, a polarimetric radar measures the relative phase difference between the four linear polarizations. This allows calculation of the target scattering matrix that can be used to optimize the polarization combination of radar for various applications. In fact,
the new interpretation technique of POLinSAR (SAR Polarimetry and Polarimetric Interferometry) shows great potential for Earth surface analysis in such applications as forests canopies (biomassestimates), agriculture, ice, and other terrain types. The POLinSAR approach combines the analysis of polarization of SAR signals (polarimetry) with those for the analysis of phase differences between signals and to measure differential range (interferometry) using two or more images captured by SAR instruments. Taken together, polarimetry and interferometry offer the potential to summarize Earth surface characteristics in three dimensions with color. 515) 516) 517) 518)

First airborne radar (SAR) polarimeters started to be flown in the time frame 1988 to 1990 with such instruments as C/X-SAR (CCRS), ARMAR (NASA/JPL), DO-SAR (Dornier), HUTSCAT (HUT), MMW-SAR (MIT/LL), NUSCAT (NASA/JPL), P-3/SAR (ERIM), IMARC (NPO Vega), and RAMSES (ONERA).

Spaceborne polarimetric data were obtained from the L/C-band SAR (NASA/JPL) of the SIR-C/X-SAR Shuttle missions (SRL-1 in April 1994, SRL-2 in Sept/Oct. 1994). Further spaceborne missions with polarimetric SAR instruments are: Envisat with ASAR, ALOS with PALSAR (launch Jan. 24, 2006, polarimetric mode on an experimental basis), RADARSAT-2 with SAR (launch 2007), TerraSAR-X with TSX-SAR (launch June 15, 2007). See also Table 16.

1.2.8.4 FTS (Fourier Transform Spectrometer) instruments

FTS is a powerful observation technique which can be applied to the entire optical region extending from 0.01 - 1000 μm, i.e., from the UV to the FIR region inclusively, providing high spectral resolution and sensitivity for remote-sensing applications [conceptually, the FTS observation technique may of course also be applied to the microwave region]. FTS offers a very high throughput, or étendue, which is largely independent of the wavelength of the incident radiation. FTS at long wavelengths has obvious utility in two domains which are beyond the reach of standard heterodyne receivers: a) spectral measurements over very wide wavelength intervals, and b) observations of very broad individual spectral lines. Early FTS implementations suffered from the available detector technology. However, at the start of the 21st century, the FTS technology is very attractive for many remote-sensing applications due to the availability of a vastly improved detection technology, and onboard computational power.

The FTS method measures the interference pattern (i.e., the interferogram) as detector output (an intermediate product) which requires a Fourier transformation to obtain the measured radiance spectrum. The spectral resolution is governed by the OPD (Optical Path Difference). A comparison of FTS instrument technology with that of a conventional dispersive spectrometer brings out the following points:
- The throughput of an FTS instrument can be orders of magnitude greater than that of a dispersive spectrometer. Both methods have the capability to provide “hyperspectral data”
- The spectral resolution of an FTS instrument is usually much better than that of a dispersive spectrometer; it is in fact constant across the spectrum
- The frequency coverage of an FTS can be very large, 10:1 is routine. Dispersive spectrometers rarely cover more than 2:1

516) POLinSAR 2003 Workshop on Application of SAR Polarimetry and Polarimetric Interferometry,” ESA Earth Observation Quarterly, June 2003, pp. 16-18
- FTS instruments generate the interferogram (a frame as an intermediate product). Split spectrometers offer the image cube (spatial/spectral) directly.
- A high SNR occurs in the FTS concept due to the simultaneous observation of a wide spectral range. There is an increase in the accuracy of interferometry over dispersive spectrometry by a factor of square root ($N/2$), where $N$ is the number of samples taken. The SNR advantage is particularly noticeable for low-energy conditions or where scale expansion is required to bring out very weak signals.

A disadvantage of traditional spaceborne FTIR (Fourier Transform Infrared) spectrometers is that they obtain their optical delay by physically translating one or more optical components — the instrument has to go through all OPD positions to complete the measurement cycle of strokes (as discussed in chapter 1.2.2.1). This so-called translation mechanism usually dominates the risk, cost, power consumption, and performance of such FTS instruments.

- Introduction of FTS (Fourier Transform Spectrometer) technology in sensor development, usually in combination with an interferometer (Michelson, Sagnac, Fabry-Perot, Fizeau, etc.) for the measurement of the composition of the atmosphere (trace gases, air pollution monitoring, monitoring of accidental releases of toxic gases at industrial plants, etc.). See Tables 35 and 36 as well as chapter O.6.

The first spaceborne FTS instrument [sometimes also referred to as FTIR (Fourier Transform Infrared) spectrometer, due to the fact that most observation occurs in the IR region observing the Earth’s thermal emissions] flown in Earth observation was IRIS (Infrared Interferometer Spectrometer), a Michelson interferometer on Nimbus-3 (launch April 14, 1969) and on Nimbus-4 (launch April 8, 1970), followed by SI-1 (also referred to as SI-GDR) and SI-2 aboard the USSR satellites Meteor 25 (also referred to as Meteor-Priroda-2, launch May 15, 1976) and Meteor 28 (also referred to as Meteor-Priroda-3, launch June 29, 1976). ATMOS of NASA/JPL was an FTS sensor flown on the Shuttle (STS-17) in 1985. Mark-IV of JPL collected first ground-based spectra in April 1985, in 1987 the sensor was flown on a balloon and in aircraft campaigns.

In Table 36, FTHSI (Fourier Transform Hyperspectral Imager) of AFRL represents the first spaceborne instrument using a spatially modulated scheme. to obtain an instantaneous spatial and spectral interferogram. The optical instrument design concept overcomes the complexities of conventional interferometers (of sequential OPD generation) by splitting the input beam of the target into two mutually coherent beams that interfere and generate a spatially modulated (instantaneous) interference pattern that is recorded as an interferogram by a detector array (the amplitude of the interference pattern depends on the path difference). An image cube is formed by assembling the contiguous pushbroom stripes (in the cross-track) produced by the forward motion of the spacecraft to create the second spatial dimensions of data. Hence, each pixel element of a single pushbroom imaging action contains the spatial as well as the complete spectral information, collected simultaneously (i.e. within the dwell time of each stripe) across the entire imaging stripe. - The method of a spatially modulated interferometer (of simultaneous interferogram availability at the detector plane) is directly analogous to the imaging of the spectrum onto the detector array in a dispersive spectrometer. See also M.21.2 and O.6.2.

Some historical background on spatially modulated interferometers. The first spatially modulated interferometer was the one made in 1801/2 by Thomas Young (see O.9). However, the first “modern form” of Young’s interferometer was the one developed in 1965 by G. W. Stroke and A. T. Funkhouser. They replaced Young’s double slit with a beam splitter and they generated a spatially varying OPD (Optical Path Difference) by tilting the two mirrors.

in the arms of a Michelson interferometer. The two tilted wavefronts were focused onto a photographic plate to record the interference pattern. Another practical spatially modulated Sagnac interferometer design was developed by K. Yoshihara and A. Kitade of Japan in 1967. They were the first to generate static fringes at a pupil plane by using the triangle-path Sagnac interferometer. In 1984, T. Okamoto, S. Kawata and S. Minami were the first to use a digital detector array to scan the static interferogram. Since that time there have been many groups building static interferometers, all using variations of conventional interferometer layouts (Michelson, Sagnac, Mach-Zehnder, Wollaston Prisms, etc.). 521) 522) 523) 524)

A fairly early modern spatially modulated interferometer is SMIFTS (Spatially Modulated Imaging Fourier Transform Spectrometer), an airborne instrument developed at the Hawaii Institute of Geophysics and Planetology of the University of Hawaii at Manoa, and sponsored by the Office of Naval Research (ONR) and by DARPA. (see P.189). SMIFTS was first flown on a helicopter in March 1994.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Aircraft, Platform</th>
<th>Spectral Range</th>
<th>Observation Direction</th>
<th>Start of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIS (U. of Wisconsin)</td>
<td>ER-2</td>
<td>3.6-4.63 μm, 5.1-9.6 μm, 9.3-16.4 μm</td>
<td>Nadir viewing</td>
<td>1986</td>
</tr>
<tr>
<td>FIRS-2 (SAO)</td>
<td>Balloon</td>
<td>14-25 μm, 48-125 μm</td>
<td>Limb viewing</td>
<td>1987</td>
</tr>
<tr>
<td>MkIV (JPL)</td>
<td>Balloon, DC-8</td>
<td>1.8 -16 μm</td>
<td>Limb and zenith</td>
<td>1987</td>
</tr>
<tr>
<td>MIPAS-FT (KfK)</td>
<td>Transall</td>
<td>7.4 - 8.7 μm, 10.0 - 13.2 μm</td>
<td>Limb viewing</td>
<td>1991</td>
</tr>
<tr>
<td>MIPAS-B (KfK)</td>
<td>Balloon</td>
<td>7.25-8.45 μm, 10.3-13 μm</td>
<td>Limb viewing</td>
<td>1992</td>
</tr>
<tr>
<td>SMIFTS (U. of Hawaii)</td>
<td>Helicopter</td>
<td>1.0-5.2 μm</td>
<td>Nadir</td>
<td>1994</td>
</tr>
<tr>
<td>AES (JPL)</td>
<td>DC-8, P-3</td>
<td>2.4-15.4 μm</td>
<td>Nadir viewing</td>
<td>1994</td>
</tr>
<tr>
<td>FTS (NPL)</td>
<td>BAe Jetstream</td>
<td>3-13 μm</td>
<td></td>
<td>1994</td>
</tr>
<tr>
<td>FTVHSI (Kestrel)</td>
<td>Cessna TU-206</td>
<td>0.44-1.15 μm</td>
<td>Nadir viewing</td>
<td>1995</td>
</tr>
<tr>
<td>MIPAS-B2 (FZK)</td>
<td>Balloon</td>
<td>5.25-5.48 μm, 6.0-6.36 μm, 7.4-8.8 μm, 10.2-13.2 μm</td>
<td>Limb viewing</td>
<td>1995</td>
</tr>
<tr>
<td>MIPAS-STR (FZK)</td>
<td>Strato-2C</td>
<td>5.15 - 5.42 μm, 6.08 - 6.31 μm, 7.30 - 8.33 μm, 10.0 - 13.0 μm</td>
<td>Limb viewing</td>
<td>1996</td>
</tr>
<tr>
<td>MIROR (DLR)</td>
<td>VFW 614</td>
<td>2-18 μm</td>
<td>Aircraft jet engine</td>
<td>1995 (trace gas emissions)</td>
</tr>
<tr>
<td>SAFIRE-A (CNR/IOE)</td>
<td>Balloon, M-55</td>
<td>62.5-125 μm, 20-350 μm, future</td>
<td>Limb viewing</td>
<td>1996, polarizing FTS</td>
</tr>
</tbody>
</table>

Table 35: Survey of airborne Fourier Transform Spectrometer (FTS) instruments

- In 2000, NASA/JPL developed a new type of imaging interferometer featuring double the efficiency of conventional interferometers and only a fraction of the mass and volume; the instrument is referred to as SMPI (Spatially Modulated Prism Interferometer). SMPI

523) Information provided by Francis M. Reininger of NASA/JPL, Pasadena, CA
overcomes the complexities of traditional interferometers and the inherent limitations of diffraction gratings, dispersion prisms, and spectral selection filters. The design employs a prism triplet (a single-crystal material to maintain the same optical path length for both beams) providing 100% throughput of radiation. Applications include atmospheric sounding, geologic mapping, in-situ mineralogy, oceanography, pollution monitoring, poisonous gas detection, medical spectroscopic imaging, and industrial inspection. See O.6.2.

- The first FTS instrument to be flown in geostationary orbit is GIFTS (Geostationary Imaging Fourier Transform Spectrometer) on EO-3 (Earth Observing-3), a NASA/NOAA/DoD technology demonstration mission within NASA's NMP with a planned launch in 2006 (see M.11). GIFTS is in effect an infrared hyperspectral sounder and imager (spectral resolution: 0.6 cm\(^{-1}\); spectral range: MWIR = 4.4-6.06 \(\mu\)m, TIR = 8.85-14.6 \(\mu\)m). In parallel, a low visible light sensitive boresighted camera, using 512 x 512 active pixel detector arrays (APS), provides quasi-continuous imaging of clouds at 1 km spatial resolution. The GIFTS infrared measurement concept combines a number of advanced technologies, including LFPA [Large-area format Focal Plane detector Arrays (128 x 128)] and a compact, lightweight Fourier Transform Spectrometer (FTS) enabling atmospheric radiancespectra to be observed simultaneously for all LFPA detector elements, thereby providing high vertical resolution temperature and moisture sounding information. 525) 526) The GIFTS design offers high sounding resolutions, about 1-2 km in vertical resolution (for temperature and water vapor profiles) using rapid profile retrieval algorithms. The profiles are obtained on a 4 km grid over an instantaneous target area of 512 km x 512 km within a 10 s time interval (representing a single frame). Extended Earth coverage is achieved by step scanning the instrument FOV (Field of View) in a contiguous fashion across any desired portion of the visible Earth disk from GEO (the full disk or a regional map can be constructed from individual data frames; the seamless coverage of the Earth’s disk is made up of a frame matrix of 25 x 25). A star tracker provides real-time pointing information for GIFTS. The FOR (Field of Regard, 24º x 24º) dwell period of GIFTS will range between 0.125 and 11.0 s per frame, depending on the observation application (i.e., imaging or sounding).

The FTS approach for GEO satellite applications allows spectral resolution to be easily traded for greater area coverage or higher temporal resolution. - Dynamic observations of temperature, water vapor, wind profiles (with accuracies of 1 K, 15%, and 3 m/s, respectively), SST (Sea Surface Temperature) and emissivity, LST (Land Surface Temperature) and emissivity, enable a better understanding of climate physics, hydrology and the water cycle, the transport of chemical species, and weather processes. The GIFTS data have the potential to offer considerable advancement in meteorological observation capability which is expected to have dramatic impacts on weather forecasting capability. For example, the ability to observe water vapor flux and convergence and divergence patterns should enable meteorologists to view the formation of storm systems before clouds and rainfall are produced. - The GIFTS instrument will serve as the prototype of sounding systems to fly on future operational GEO satellites of NOAA. - Infrared hyperspectral sounding instruments with broad spectral coverage have the potential to provide unprecedented atmospheric profiling, surface characterization, cloud property and trace gas information.

Note: as of 2004 the launch of the GIFTS mission became uncertain due to DoD funding problems (Navy).


<table>
<thead>
<tr>
<th>Sensor</th>
<th>S/C or Platform</th>
<th>Spectral Range</th>
<th>Observation Direction</th>
<th>Start of Operation Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATMOS (NASA/ JPL)</td>
<td>Spacelab-2, 3, ATLAS-1, 2, 3</td>
<td>2.2-16.0 μm</td>
<td>Limb viewing</td>
<td>1985, (2) 92, 93, 94</td>
</tr>
<tr>
<td>CIRRIS (DoD/ USAF)</td>
<td>STS-39 Shuttle Discovery</td>
<td>2.5-25 μm</td>
<td>Limb viewing</td>
<td>Apr. 28 - May 6, 1991</td>
</tr>
<tr>
<td>IMG (NASDA, JAROS)</td>
<td>ADEOS</td>
<td>3.3-16.7 μm</td>
<td>Nadir viewing</td>
<td>launch, Aug. 17, 1996</td>
</tr>
<tr>
<td>MIRIAM (Free U. of Berlin)</td>
<td>MIR/Priroda</td>
<td>2.5-20 μm</td>
<td>Limb viewing</td>
<td>1996</td>
</tr>
<tr>
<td>SPIRIT-III (BMDO, USU)</td>
<td>MSX</td>
<td>2.5-28 μm</td>
<td>Limb viewing</td>
<td>launch, Apr. 24, 1996, FTS+ scanning radiometer</td>
</tr>
<tr>
<td>FTHSI (AFRL, Kestrel Corp.)</td>
<td>MightySat II.1</td>
<td>0.475-1.05 μm</td>
<td>Nadir viewing</td>
<td>launch July 19, 2000.</td>
</tr>
<tr>
<td>MIPAS (ESA,FZK)</td>
<td>Envisat</td>
<td>4.15-14.6 μm</td>
<td>Limb viewing rearwards &amp; sideways</td>
<td>launch Mar. 1, 2002</td>
</tr>
<tr>
<td>ACE-FTS (CSA) ACE-VNIR (CSA)</td>
<td>SciSat-1/ACE</td>
<td>2-14 μm, 0.5-1 μm</td>
<td>Limb viewing</td>
<td>launch Aug. 13, 2003</td>
</tr>
<tr>
<td>TES (JPL)</td>
<td>Aura (EOS/ Chem-1)</td>
<td>2.3-15.4 μm</td>
<td>Limb or nadir viewing</td>
<td>launch July 15, 2004</td>
</tr>
<tr>
<td>GIFTs (NASA/LaRC)</td>
<td>EO-3</td>
<td>4-14.6 μm</td>
<td>Nadir viewing (directional)</td>
<td>launch in 2006 (observation from GEO)</td>
</tr>
<tr>
<td>TANSO-FTS (JAXA)</td>
<td>GOSAT</td>
<td>0.75-14.3 μm</td>
<td>Nadir viewing</td>
<td>2008</td>
</tr>
<tr>
<td>CrIS (IPO)</td>
<td>NPP (NASA), NPOESS</td>
<td>4.63-15.3 μm</td>
<td>Nadir viewing</td>
<td>launch 2009, launch 2012</td>
</tr>
</tbody>
</table>

Table 36: Survey of spaceborne Fourier Transform Spectrometer (FTS) instruments

1.2.8.5 Onboard radiometric sensor calibration

The goal of any calibration procedure is to determine a functional relationship between the target source flux and the sensor output signal. Instrument calibration provides a means for consistent long-term data set interpretation by reducing the assumptions to be made (see Chapter 2 and Glossary). All instrument calibration involves generally extensive pre-flight calibration as well as repeated in-flight (or onboard) calibration in various time intervals. The discussion here is limited to onboard calibration. Most successful onboard calibration approaches employ a number of various targets including onboard calibrators, space targets (views to deep space, the sun, the moon, the stars, etc.), and/or ground targets (the reflectance-based approach relies on surface reflectance measurements of a selected site). All of these targets or calibrators have the objective to provide the instrument with a known reference. Many of these onboard calibration techniques are described with the sensor documentation of the various projects in the book.

The very early spaceborne instruments (cameras) didn’t provide a calibration capability. But the need for onboard calibration became evident from the very start of regular observations. Today’s sensor calibration involves usually comparing the detector of a particular spectral range against a known reference. For the VNIR region, a calibration source may be internal lamps or the sun (external source). In the infrared region, a suitable calibration reference may be an internal black body or an external source like deep (cold) space that may be viewed periodically. A calibration ‘period’ may be a scan sequence, each orbital eclipse period, the pass over a dedicated ground calibration site, or it may be a month or more, depending on need or opportunity. Some sensors employ several calibration techniques (for instance: GOME on ERS-2 retrieves ozone distributions by exploiting the traditional back-
scatter calibration approach, as well as by differential optical absorption spectroscopy). The ETM+ sensor on Landsat-7 uses three independent onboard calibration systems [the two new systems are: FAC (Full Aperture Calibrator), and PAC (Partial Aperture Calibrator), the ETM+ calibration system is a diffuser], representing a significant step forward in absolute radiometric calibration accuracy. The radiometric calibration of these systems not only helps characterize the operation of the sensors, but, more importantly, this calibration allows the full Landsat data set (the Landsat project has the longest data set of imagery anywhere since 1972) to be used in a quantitative sense for such applications as land use and land cover change. 527)

Long-term studies such as those needed for documenting and understanding global climate change require not only that a remote sensing instrument be accurately characterized and calibrated, but also that its characteristics and calibration be stable over the life of the mission.

A major (ideal) objective of the calibration of a sensor type (imager, radiometer) is to make the measurements independent of the instrument. This means that when a particular physical entity is to be measured at different times and places or with different instruments, the results should always be the same. It also means that attributes inferred by the measurements are target attributes and not instrument attributes.

- Another (rather costly) method of data calibration occasionally employed is that of airborne underflights of spaceborne missions. Many spaceborne sensors (in particular since the 1980s) have their airborne predecessors, which makes underflight calibrations a natural extension for independent parameter checks. Very important observations of a mission (proving a concept, etc.) are usually verified with parallel campaigns to compare spaceborne, airborne and ground-based observations. An example of such a scenario are the SRL-1/2 (Space Radar Laboratory) missions in 1994 (see SRL Campaigns). ESA's ERS-1 and Envisat missions are further examples of extensive underflight campaigns in the commissioning phase (prior to mission operations). A very special instrument among the airborne underflight sensors is NASIC (P.149), operated by NASA/GSFC since 1988 (built in 1980), capable of providing independent calibration data for several long-term satellite sensors, such as: AVHRR (on several NOAA satellites), TM (Landsat), VAS (GOES satellites), and CZCS (Nimbus-7).

- MOBY (Marine Optical Buoy) see P.140. MOBY is an important ocean-based remote sensing calibration station of NOAA, funded by NASA and NOAA, and deployed off the coast of Lanai, Hawaii, in 1994. 528) 529) 530) 531) 532) Its primary objective is to function as a calibration standard in support of spaceborne ocean color instruments. Typically, these instruments measure the received radiance in selected wavelength intervals from 410 to 870 nm to derive ocean color products such as the phytoplankton distribution of the ocean surface. However, the path of the radiance arriving at the spacecraft is very much dominated by atmospheric contributions. As it turns out, these ocean color sensors cannot be calibrated with sufficient accuracy before launch to meet the requirements for climate quality data products. Consequently, the calibration of ocean color instruments is performed during the mission with in situ spectral measurements of water-leaving radiance. MOBY is a 14 m long buoy system instrumented to measure upwelling radiance and downwelling irradiance at

529) http://orbit-net.nesdis.noaa.gov/orad/moby_index.html
the sea surface and at three deeper depths. Examples of the MOBY instrument calibration services are: SeaWiFS, MODIS, OCTS, POLDER, MOS, GLI, etc. The MOBY calibration reference is a key element in the international effort to develop a global, multi-year time series of consistently calibrated ocean color products using data from a wide variety of independent satellite sensors.

- Microwave radiometer calibration (absolute calibration). The SSM/I instrument, flown on the DMSP series since 1987, introduced a so-called “external calibration scheme” a total-power radiometer configuration, each scan consists of a cold reading, a warm load reading, and the scene stations. The cold reading utilizes a view to deep space (3 K black body radiation), the warm load temperature is variable over an orbit. Some other radiometer implementations employing the same technique are: SSM/T-2 (Special Sensor Microwave Water Vapor Profiler-2) first flown on DMSP F-11 (launch Nov. 28, 1991) and thereafter; TMI (TRMM Microwave Imager) on TRMM (launch Nov. 27, 1997); MTVZA (Microwave Imaging/Sounding Radiometer), a 26 channel conical-scanning microwave imagersounder in the range of 10.6-183.3 GHz on Meteor-3M-1 (launch Dec. 10, 2001); AMSR-E (Advanced Microwave Scanning Radiometer-EOS) on Aqua (launch May 4, 2002); AMSR on ADEOS-II (launch Dec. 14, 2002); and SSMIS (Special Sensor Microwave Imager Sounder), first flown on F-16 of the DMSP series (launch Oct. 18, 2003).

- Silicon photodiode self-calibrating technique. This technique became common in the 1980s permitting the development of 100% quantum-efficient silicon radiometers. In the 1990s, absolute cryogenic radiometers have become common in many national laboratories. 534)

1.2.8.6 Lightning detection instruments (event-based monitoring)

Lightning in the atmosphere is a transient, high-current carrying electric discharge event. It occurs when some region of the atmosphere reaches an electric charge sufficiently large so that the electric fields associated with the charge cause an electric breakdown in the air. 535) The optical detection of lightning events is based on the imaging of a specific spectral oxygen multiplet, which is excited during the lightning event. The lines are a triplet located at 777.4 nm, consisting of lines at 777.19 nm, 777.42 nm and, 777.54 nm. 536)

- Early detections of optical emissions by a spaceborne satellite of terrestrial lightning were first made by NASA’s OSO-2 (Orbiting Solar Observatory) with a launch Feb. 3, 1965. Since that time, additional optical observations of lightning have been made by the OSO, Vela, the spacecraft of the DMSP (Defense Meteorological Satellite Program) series, and the GPS satellite series. The Vela (detection of super bolts on Sept. 22, 1979), DMSP and GPS observations provided a time history of optical pulses produced by lightning. 537) 538) 539)

- Systematic spaceborne lightning studies were initiated by NASA/MSFC in the 1980s by using cameras aboard the Space Shuttle to make striking images of lightning from above the cloud tops. Later instruments on spaceborne missions with event-based monitoring capabilities revealed the extent of global lightning activities. Typically, more than 2,000 thunderstorms are active throughout the world at any given moment, producing on the order of 100

533) Note: The total-power observation/calibration scheme compares the atmospheric signal to the cold and hot loads.
536) NIST Atomic Spectra Database Lines, Data, http://physics.nist.gov/cgi-bin/AtData/main_asd
flashes per second (or > 8 million strikes/day). The length and duration of each lightning stroke vary, but typically average about 30 ms. The average peak power per stroke is about \(10^{12}\) W. An average bolt carries 20,000 A (ampere) of current, while the most powerful lightning bolts carry > 300,000 A. The most common types of lightning are: a) cloud-to-ground lightning, b) intra-cloud lightning, c) inter-cloud lightning.\(^{540}\)\(^{541}\)\(^{542}\)

The GHRC (Global Hydrology and Climate Center) in Huntsville, ALA, serves as the operational data processing and archive center for two satellite-based lightning instruments (OTD and LIS). Both instruments detect lightning in day and night conditions. Using the lightning detection software, the GHRC produces global daily, monthly, seasonal, and annual summaries of lightning strikes, providing the first truly global distribution maps of lightning. Lightning sensors in space and on the ground are showing the value of having a space-based network of sensors that could spot and track storms which are likely to spawn tornadoes.

- In the early 1980s, the NOSL (Night-time and daytime Optical Survey of Lightning) instrument of NASA/MSFC was flown in the Space Shuttle program on flights STS-2 (Nov. 12-14, 1981), STS-4 (Jun. 27-July 4, 1982) and STS-6 (Apr. 4-9, 1983).

- This was followed by MLE (Mesoscale Lightning Experiment) on Shuttle flights in the late 1980s (STS-26, Sept. 29-Oct. 3, 1988; STS-30, May 4-8, 1989; STS-34, Oct. 18-23, 1989; STS-32, Jan. 9-20, 1990). MLE used the Shuttle’s sensitive payload bay monochrome video cameras to record the Earth’s nighttime lightning activity from space. An analysis of the MLE video tapes positively identified two or three “upward lightning” events (i.e., sprites) in the stratosphere. The discovery of the phenomenon, now known as a sprite, was first documented on a video tape recorded the night of July 6, 1989 at the University of Minnesota (ground observations). \(^{543}\)\(^{544}\)

- OLS (Operational Linescan System) of the DMSP weather satellite series of DoD is also able to detect lightning activity (data sets exist starting from 1973, see G.1.1).

- An airborne sensor with a capability for lightning detection is LIP (NASA/MSFC, an upgraded instrument as of 1990). \(^{545}\)

- Another spaceborne sensor with a capability for lightning detection/distribution is Blackbeard (an RF experiment), flown on ALEXIS of LANL and SNL (launch of ALEXIS April 25, 1993).

- The OTD (Optical Transient Detector) of NASA/MSFC has been flown on Orb-View-1/Microlab-1 (launch April 3, 1995, B.11). The instrument is capable to gather lightning data under daytime conditions as well as at night. OTD collected a five-year record of lightning observations between April 1995 and April 2000.

- LIS (Lightning Imaging Sensor, NASA/MSFC) is flown on TRMM (launch Nov. 27, 1997, A.34). LIS is designed to study the distribution and variability of total lightning on a global basis. The staring imager which is optimized to locate and detect lightning with storm-scale resolution of 5-10 km over a large region (600 km x 600 km) of the Earth’s surface.

- FORTE: Simultaneous observations of optical and RF emissions (in the VHF spectrum) of lightning activity was observed with the instruments: OLS (Optical Lightning Sub-

\(^{540}\) http://thunder.nsstc.nasa.gov/

\(^{541}\) Note: Benjamin Franklin performed the first systematic, scientific study of lightning during the second half of the 18th century.


\(^{544}\) http://www.knology.net/~skeetv/myobs.htm

\(^{545}\) http://thunder.msfc.nasa.gov/ols/
system) and the RF-System (an advanced RF impulse-detection system), and an event classifier, all flown on the FORTE spacecraft of LANL/SNL (launch Aug. 29, 1997, A.18). OLS detects, locates, and characterizes lightning flashes. The event classifier consists of a set of adaptive processors that can distinguish lightning from man-made electromagnetic signals. It is a key technology in detecting secret nuclear weapons tests. The FORTE instruments provided a long-term assessment (> 3 years) of several million lightning events.

One of the major observations performed by FORTE are the so-called TIPP (Trans-Ionospheric Pulse Pairs) events, which are pairs of intense VHF electromagnetic energy pulses, the second one being the reflection of the first from the Earth’s surface. TIPPs are frequently associated with upper atmospheric discharges called “Sprites”, “Jets” and “Elves”, and with intense X-ray and gamma-ray energy bursts.

- The Andromède mission of CNES to ISS with a launch on Oct. 21, 2001 (on a Russian Soyuz-TM-33 flight) delivered LSO (Lightning and Sprite Observations) of CEA (Commissariat à l’Energie Atomique) with the objective to study emissions generated by lightning, sprites (very large luminous displays) and elves (rapidly moving optical flashes, <1 ms).

- The ROCSat-2/FormoSat-2 mission of NSPO (Taiwan, launch May 20, 2004) flies the instrument ISUAL (Imager of Sprite Upper Atmospheric Lightning) with the objective to observe the natural upward lightning discharge phenomena toward the ionosphere on top of the troposphere.

- VGLASS (VHF Global Lightning and Severe Storm) monitor is a proposed system of LANL (Los Alamos National Laboratory) to be flown on the upcoming Block-IIF/III GPS system in MEO. The conceptual design of VGLASS is based on a similar VHF receiver of LANL flown on the GPS satellite SVN 54 (launch Feb. 15, 2001).

- A demonstration instrument, LMS (Lightning Mapper Sensor) of NASA/MSFC is planned to be flown on the next-generation GOES-R spacecraft (launch 2014) of NOAA. The LMS on GOES represents the first lightning instrument to monitor lightning from GEO, permitting the continuous observation of the electrosphere over dimensions ranging from the Earth’s radius down to individual thunderstorms. 546)

- ASIM (Atmosphere—Space Interactions Monitor) is an instrument proposal of ESA (in Phase B as of 2006) to be flown on the Columbus External Platform Facility (CEPF) of the ISS (International Space Station). The objective is to observe TLEs (Transient Luminous Events) that occur in the Earth’s upper atmosphere accompanied by thunderstorms in the lower atmosphere. These events are known as blue jets, sprites and elves, the phenomena were first observed in 1989 [MLE (Mesoscale Lightning Experiment) of NASA/MSFC on Shuttle flights]. Plans are to launch ASIM in the timeframe 2010 on a Shuttle flight to ISS. 547) 548)

- EUMETSAT and ESA are studying instrument concepts to fly LMI (Lightning Monitoring Instrument) on the future Meteosat series in GEO (not before the middle of the next decade). 549)

1.2.8.7 Some telescopes for optical instruments

- TMA (Three Mirror Anastigmatic) telescope off-axis design method in optical instruments. The term ‘anastigmatic’ refers to lenses that are able to form approximately point images of target (object) points. The TMA concept provides within a slit-like wide FOV

546) http://thunder.msfc.nasa.gov/
547) http://www.esa.int/SPECIALS/CDF/SEMUIBJYDE2E_0.html
(Field of View) a diffraction-limited performance (this property is especially useful for pushbroom imaging spectrometers in remote sensing applications). TMA is normally the preferred optical design with emphasis on precise imaging applications. It also serves to provide flat image projections, free of first order aberrations. Normally, two of the mirrors are off-axis sections resulting in an obstruction-free aperture system.

Background: The first modern three-mirror telescope concept by M. Paul dates back to 1935. Paul recognized that a Mersenne telescope, a concave and convex paraboloid pair, was corrected for spherical aberration, coma and astigmatism. Knowledge of basic aberration theory led to a three-mirror design, corrected for these three aberrations, in which both the secondary and tertiary mirrors are spherical. J. G. Baker and R. V. Willstrop refined the Paul design in 1969 and 1984, respectively, to create telescopes with larger fields of view. \textsuperscript{550} \textsuperscript{551}

Since 1980, an optimized optical telescope configuration is increasingly being used from a family of TMAs discovered by Dietrich G. Korsch of Korsch Optics, Inc., Huntsville, AL. \textsuperscript{552} \textsuperscript{553} \textsuperscript{554} The design uses a tertiary mirror to correct and relay a real Cassegrain image onto the final focal surface. Korsch designs a three-mirror telescope by applying aplanatic conditions (constant optical path length and the Abbé Sine condition) to two mirrors of his three-mirror system. The shape of the third mirror is then optimized to minimize all other aberrations. - Korsch telescopes are increasingly being introduced in various high-performance astronomical as well as in Earth observation instruments. Some examples of Korsch-type TMA instruments flown or considered in spaceborne EO missions are:

- OSA (Optical Sensor Assembly) is flown on Ikonos-2 of Space Imaging Inc. of Thornton, CO (launch Sept. 24, 1999). The TMA concept in combination with a Korsch-Cassegrain type telescope design.
- Hyperion and ALI (Advanced Land Imager) of the EO-1 (Earth Observing-1) mission of NASA (launch Nov. 21, 2000).
- The BHRC 60 (Ball High Resolution Camera 60) instrument of Ball Aerospace is flown on QuickBird-1 (launch Nov. 20, 2000).
- The MTI mission of DOE (LANL, SNL) with a launch March 12, 2000 is flying the MTI (Multispectral Thermal Imager) instrument.
- OHRIS (OrbView High Resolution Imaging System) of ORBIMAGE is flown on OrbView-3 (launch June 26, 2003).
- The RALCam1 (Rutherford Appleton Laboratory Camera 1) of the UK TopSat mission (launch Oct. 27, 2005). While the camera optics are capable of a a 25 km FOV at 600 km altitude, a 15 km FOV was selected as a result of CCD and data throughput limits.
- The RSI (Remote Sensing Instrument), built by EADS Astrium SAS, France is flown on the FormoSat-2 mission of NSPO, Taiwan (launch May 20, 2004). RSI uses a TMA optics design with an all—reflective Korsch telescope of 600 mm aperture. The Pan camera of the THEOS spacecraft of GISTDA, Thailand (launch 2007), built by EADS Astrium, uses a Korsch telescope of 600 mm aperture. The NAOMI imager of the AlSat—2 mission of CNTS, Algeria (launch 2008), built by EADS Astrium, uses a Korsch telescope of 200 mm diameter.

\textsuperscript{554} D. Korsch, “Comparison of large aperture telescopes with parabolic and spherical primaries,” Optical Engineering, Vol. 25, No 9, Sept. 1986
- The imager of the CNES Pleiades spacecraft, referred to as OHRI (Optical High-Resolution Imager), employs TMA concepts (launch in 2009) in combination with a Korsch telescope. The primary mirror has a diameter of 650 mm.

1.2.8.8 Adaptive optics (AO)

AO is a technology referring to the physical modification of components of an optical system for the purpose of compensating for the distortion of electromagnetic radiation (refractive index variations) as it passes through the turbulent atmosphere and the optical system. In particular, infrared radiation is degraded by atmospheric turbulence to resolve fine detail by at least a factor of 10. Although the problem of aberration was long recognized in the field of optics (in particular in astronomy), two initial solutions were proposed by Horace W. Babcock (1953, USA) and by Vladimir P. Linnik (1957, USSR). They independently published papers with the conjecture that the aberrations caused by atmospheric turbulence could be corrected in real-time by (what became later known as) an “adaptive optical system.”

Principle: Adaptive optics is a technique which measures the wavefront phase errors generated by the variations in the index of refraction in the atmosphere and corrects the resulting image in real-time to achieve an angular resolution close to the diffraction limit of the telescope. For unresolved sources, adaptive optics attempts to put as many photons in as small an image area as possible, thus enhancing the image against the background, improving the resolution of spectroscopy, and allowing better interferometric imaging with a telescope array. For resolved sources, the improved resolution extends imaging to fainter and more complex objects.

AO systems unite several advanced technologies to remove noise from optical signals: precision optics, wavefront sensors, deformable mirrors, and lasers, tied together by high-speed control systems. Light entering an AO system is reflected off a special adaptive optical element called a deformable mirror that applies anti-noise to the beam, canceling aberrations on the incoming beam.

Essential elements of an AO system are: a high-speed wavefront sensor (sensing the turbulence-induced aberrations), a thin flexible mirror whose surface can be electronically controlled to correct for aberrations, and a computer controller that converts the wavefront measurements into deformable mirror commands.

The mirror is physically deformed in real-time by a large number of actuators (piezoelectric devices, liquid crystal devices, etc.). The device that measures the distortions in the incoming wavefront of light is called a “wavefront sensor” (analysis of wavefront, estimation of the shape of the original wavefront, derivation of the correction signals for the deformable mirror). High update rates are an essential ingredient for distortion removal. The MEMS technology is enabling the production of low-cost deformable mirrors. In addition, the APS/CMOS imaging technology permits the production of low-cost high-speed wavefront sensors.

556) V. P. Linnik, ”About a basic opportunity of reduction of influence of an atmosphere on the star image,” Optics and Spectroscopy, Vol. 25, No. 4,1957, pp.401-402
560) http://www.pha.jhu.edu/~jlotz/aoptics/node4.html
Background: In the field of astronomy there exists already extensive experience in building large segmented actively controlled mirrors for ground-based telescopes. Astronomical imagery taken from ground-based Earth observatories equipped with AO rival the quality of those taken by the Hubble Space Telescope (HST) from outside the Earth’s atmosphere. This use of AO is the most revolutionary development in astronomy since Galileo Galilei invented the telescope in 1609-1611. These new ground-based astronomy telescopes have led the way in showing how to use adaptive optics to maintain figure (shape) at low temporal bandwidth in the presence of wind, gravity, and structural disturbances. Additionally, most ground-based systems also use these technologies to correct higher frequency effects from atmospheric turbulence. However, adaptive astronomical telescopes have a relatively narrow FOV (Field-of-View) of about 1 arcmin when compared with high-resolution Earth observing telescopes (~ 2º).

Some examples of installations using AO technology in the field of ground-based astronomy are:

- In the 1980’s ESO (European Southern Observatory) developed a 1 m diameter, 20 mm thick active mirror which served as demonstration model for the 3.5 m diameter mirror of the NTT (New Technology Telescope) in operation in Chile since 1989.

- The SOR (Starfire Optical Range) at Kirtland AFB, Albuquerque, NM, houses two telescopes with adaptive optics systems: 564) 1) the 1.5 m telescope was installed in 1991 (first operational AO system anywhere). 2) a 3.5 meter telescope equipped with adaptive optics. Both telescopes are of Cassegrain design, they are being used to develop methods for atmospheric compensation using adaptive optics and laser guide stars (they are also being used for satellite tracking). The first light on the 3.5 m telescope with the adaptive optics installed was achieved in September of 1997.

- In 1997, a 3.5 m telescope by the name of ALFA (Adaptive optics with a Laser For Astronomy system), a cooperative project of MPIA Heidelberg and MPE Garching, was installed at the Calar Alto Observatory in Almería (Southern Spain). The AO system of ALFA was developed by Adaptive Optics Associates, Inc. of Cambridge, MA, USA.

- In 1997/8, some demonstrations of the adaptive optics technique were conducted in the field of astronomy with MMT (Multiple Mirror Telescope) Observatory on Mount Hopkins (AZ), a joint facility of the University of Arizona and the Smithsonian Institution (the MMT consisted of six 1.83 m telescopes in a common mount, a circle of 5.04 m diameter). In Nov. 2002 and in Jan. 2003, astronomers were very successful in demonstrating the removal of atmospheric blurring with a new and integrated adaptive optics system in a flexible secondary mirror (2 mm thick) telescope of 6.5 m diameter (the adaptive optics system is part of the telescope). 565) 566)

- An adaptive optics system was introduced on the segmented 10 m primary mirror of the Keck Observatory on Mount Kea, Hawaii, in operation since 1999.

- The ground-based VLT (Very Large Telescope) interferometer of ESO uses four 8.2 m diameter, 175 mm thick segmented primary mirrors, controlled by 150 actuators. First light for the MACAO (Multi Application Curvature Adaptive Optics) of VLT at the Paranal Observatory, Chile, occurred on April 18, 2003. VLTI consists of four MACAO units. MACAO in turn consists of a 60 element curvature system (vibrating membrane, radial geometry microlenses, bimorph deformable mirror and Tip-Tilt mount). The wavefront sensor employs an APD (Avalanche Photodiode) detector. At present, just one of the four telescopes is equipped with AO, but plans call for the eventual addition of AO for all four telescopes. Nothing less than a revolution in VLT interferometry is expected. An enormous gain in efficiency will result, because of the associated 100-fold gain in sensitivity of the VLT.

564) http://www.de.afrl.af.mil/sor/
At the start of the 21st century, the technology of lightweight adaptive optics is also being **considered for Earth observation (EO) instruments** (looking from space toward Earth). However, for EO instruments, the required response times are much shorter than those of astronomical instruments. The latter have long exposure times while EO instruments have dwell times in the order of microseconds. In particular, an adaptive optical system, designed for narrow-field applications (as in astronomy), is not sufficient for WFOV systems needed in EO applications. To address these needs, a new WFOV adaptive optics theory and a new error function were developed. Modeling and experimental results demonstrate the validity of the WFOV adaptive optics theory and new error function. This new error function, which is an extension of conventional adaptive optics, lead to the development of three new types of imaging systems: WFOV, selectable FOV, and steerable FOV. These new systems can have nearly diffraction-limited performance across the entire FOV or a narrow movable region of high-resolution imaging.  

A first attempt to develop an EO imager based on the AO technique (a deformable mirror design to correct for residual wavefront errors in a large segmented aperture optical system) was proposed by NASA in the late 1990s. This was the so-called **RedEye** (Regional Environmental Dynamics Active-aperture Infrared Imager) instrument, considered to be flown on the EO-3 mission (Earth Observing-3, launch in 2006) in geostationary orbit. However, as of spring 2000 the RedEye proposal was not accepted by NASA management for realization. - In the meantime, many advancements occurred [such as: high-resolution wavefront control with optically addressed liquid crystal (LC) spatial light modulators], making the AO technique a key enabling technology for a great variety of future imaging applications.

Not all adaptive optics implementations are used to correct for atmospheric turbulence. The technique is also being used to compensate in general for optical aberrations in the design of very small and light-weight optical systems to improve the optical characteristics (including focal length, aberrations, removal of misalignments, improvement of wider FOV, etc.) of a system subjected to space environment variations. Not all adaptive optics implementations use piezoelectric actuators in combination with computers for mirror control.

Adaptive optics 568) must also be seen in the context of FSO (Free-Space Optics) communications, (see 1.4.7.3) in reducing the bit error rate of a transmission. FSO is considered a valuable technology for many applications such as short-distance fiber-optic links, for mobile high-bandwidth data transfer as needed in military and industrial applications, or for long-range ground-to-satellite communication and vice versa.

Newer adaptive optics instrument designs (21st century) employ so-called **MOEMS** (Micro-Opto-Electro-Mechanical System) devices, microchips, able to physically react to a non-normal situation. In adaptive optics applications, **MMAs** (Micro Mirror Arrays) are a MOEMS sub-type, permitting the correction of distorted wavefronts and/or to compensate for optical imperfections in the micro mirrors themselves. MMAs are arrays of individually controllable micro mirrors, where each mirror can be adjusted to alter either the phase or direction of the light reflected back from that pixel (a light beam may also be spectrally modified). 569) 570) MMAs are fabricated by means of semiconductor process technology, they can form arrays with a large number of independent mirror elements, providing high spatial resolution. The technology is already being commercially exploited in such applications as

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high-definition TV sets, video devices, and in digital cinema projection systems. MMAs work on a pixel basis, they are rugged and compact devices with relatively low power requirements, providing update rates in the order of 1 kHz. The technology can be used to correct distortion and step errors on wavefronts. These devices look rather promising to allow future large telescopes to fly large lightweight apertures. - The MSA (Micro Shutter Array) device is another variant of MOEMS technology, permitting a redirection of light by individually controllable structures (MSAs may for instance be used as a programmable aperture mask for object selection devices in multi-object spectrometers).

A prominent candidate for these new technologies is the JWST (James Webb Space Telescope) mission (launch 2013 to Lagrangian point L2), a NASA/ESA collaboration - to succeed HST (Hubble Space Telescope). JWST features the following science instruments: NIRCam (Near Infrared Camera) provided by NASA, NIRSpec (Near Infrared Spectrograph) in the 0.6-5 μm range provided by ESA, and MIRI (Mid Infrared Instrument), comprising an imager and a spectrometer in the 5-27 μm range, provided by ESA and NASA, and FGS (Fine Guidance Sensor) provided by CSA.

ESA research into MMA technology examines two required MMA actuator functions for simultaneous support services: 572

1) Binary operated tilt mirrors - permitting some manipulation of the incident light (for instance discarding of those parts of the incoming wavefront causing interference). This is done by turning a mirror element optically “on” or “off” when below or above a threshold.

2) Analog-operated piston mirrors to be used for continuous phase-shifting operations. The principle of analog MMA wavefront correction is to compensate the local wavefront deviation averaged across the one micro mirror by appropriate height adjustment of that element.

- In June 2007, the LGS (Laser Guide Star) system started regular operations on the VLT (Very Large Telescope) of ESO at Paranal, Chile (one of the world’s most advanced large ground-based telescopes). The LGS system provides assistance for the adaptive optics instruments on the VLT and so allows astronomers to obtain images free from the blurring effect of the atmosphere, regardless of the brightness and the location on the sky of the observed target. – Two of the Adaptive Optics (AO) science instruments at the Paranal observatory, NACO and SINFONI, have been upgraded to work with the recently installed LGS and have delivered their first scientific results. 573  574

The LGS system installed at Paranal uses the PARSEC dye laser developed by MPE Garching and MPIA Heidelberg, while the launch telescope and the laser laboratory was developed by ESO. The first objects that were observed are interacting galaxies. The images obtained reveal exquisite details, and have a resolution comparable to that of the Hubble Space Telescope. In one case, it was possible to derive for the first time the motion of the stars in two merging galaxies, showing that there are two counter-rotating discs of stars.

The VLT Laser Guide Star system is the result of a collaborative work by a team of scientists and engineers from ESO and the Max Planck Institutes for Extraterrestrial Physics in Garching and for Astronomy in Heidelberg, Germany. NACO was built by a Consortium of French and German institutes and ESO. SINFONI was built by a consortium of German and Dutch Institutes and ESO.

571) http://ngst.gsfc.nasa.gov/ISIM/
1.2.8.9 Optical phased array (OPA) technology

At the start of the 21st century, OPA is an emerging and an enabling technology for rapid and accurate redirection (beam steering in 2-D) of the wavefront FOV (field of view) of an optical sensor. These non-mechanical beam steering devices operate in an analogous fashion to microwave frequency phased array radar antennas. - Optical phased arrays (imaging or tracking systems with a potentially large effective telescope/antenna area) provide an elegant means for an inertialess, high-speed, high-resolution and random-access electronic beam steering capability, required by numerous applications, including laser radar (laser radars may be used for such applications as target detection and wind profiling), laser communication (including high-speed and high bandwidth switching, intersatellite links), and laser projection display. For such applications, a phase profile is imposed on an optical beam as it is either transmitted through or reflected from the phase shifter array. The OPA technique is actually a promising approach for both sensing and transmitting functions. Current optical arrays are basically monolithic structures with no discrete elements, consisting of an array of phase shifters rather than individual transmit/receive modules; they are designed to use low-cost addressing electronics. Passive optical arrays consist solely of phase shifters, they are operated as space-fed arrays, meaning that an already formed beam is fed to the array of phase shifters, which then effects the steering of the beam. This contrasts to an active phased array, in which individual transmit modules form a beam as it exits a large array of transmitters (such as a laser phased array antenna).

![Figure 15: Schematic concept of a 1-D phased-array deflector arrangement](image)

The early generation (1990s) of optical device implementations are 1-D, space-fed, passive, phase-only, apertures (Note: the 1-D approach is selected to reduce the possible number of interconnections). An already formed beam is fed to the array of phase shifters, which then affects steering of the beam (analog beamforming of phased arrays). The imposed phase

578) Note: An OPA system can be composed of multiple liquid crystal or micro-mirror elements that modify the optical phase of an incident optical signal in transmission or reflection. These phase modifications can be used in beam steering and/or aberration correction. The liquid crystal elements, also referred to as “writeable gratings,” are solid state devices that are manufactured using semiconductor fabrication techniques. The dynamically-variable grating modifies the phase of an incident optical signal via a voltage-controlled index of refraction. Creation of a linear gradient in the optical path delay tilts the phase front and steers the optical beam. The realized linear gradient is actually folded, similar to a blazed grating. An OPA system can be flood illuminated by a single high power laser source or, alternatively, each element of the array can be fed by an individual laser. See URL: http://www.lbodaily.com/cbd/archive/2001/01(January)/18--Jan--2001/spmsc001.htm
profile steers, focuses, fans out, or corrects phase aberrations on the beam. High efficiency large-angle steering with phased arrays requires phase shifter spacing on the order of a wavelength or less; hence, addressing issues make 1-D optical arrays more practical than 2-D arrays. Generally, requirements call for a large number of addressable points, which in turn requires at least an equal number of independently controlled phase modulators in the array. Numerous line-management techniques have been explored to reduce the number of control lines required to regulate fully such a phased-array deflector while still providing continuous scan-angle control.

The optical phased array concepts are the direct functional analogs of the microwave phased array technology (that make possible agile and inertialess steering of microwave beams). However, due to the orders-of-magnitude difference in wavelengths between the microwave and the optical worlds, a different implementation approach is used for optical arrays. Future OPA implementations for airborne/spaceborne applications are distributed architectures providing a means for graceful degradation.

**LC (Liquid Crystal) optical phased array concept:** A promising implementation of an optical phased array is provided by the nematic-phase LC technology. A prism inserted into the aperture of an optical system introduces a linear gradient of OPD (Optical Path Delay) across the aperture, tilting the phase front and thereby steering the optical beam. For a given wavelength, a phase shift of $2\pi$ (OPD of one wavelength) can be subtracted periodically from the phase front without influencing the far-field pattern produced by the phase front. The “folded” phase profile represents a blazed grating. The phase ramp can be approximated by a series of small discrete phase steps.  

The application of a relatively low voltage (1-10 V) reorients the LC molecules and changes the effective index of refraction. The maximum phase shift available is proportional to the thickness of the LC layer. By using a cascaded coarse/fine beam steering architecture, full angular addressing flexibility is recovered.

LC optical phased array applications are also attractive optoelectronic components for simple, light weight and low-cost optical sensors. They have the potential to replace rotating or moving mirrors and prisms in many scanning devices. Liquid crystal phased arrays offer the following advantages over mechanical systems:

- Random access, rapid beam pointing
- Precise pointing stabilization
- Programmable multiple beams
- Potential for large aperture
- High optical damage threshold
- Low power consumption
- The use of optical phased arrays is a promising technology for laser radars
- Optoelectronic applications include a) laser free-space communications, b) 1- or 2-D photonic deflecting switches can be designed for optical interconnects to route optical signals from one fiber (or source) to another, c) optical phased arrays can be used as receivers for focal plane array detectors, d) optical wavefront correction and beam shaping (potential use in adaptive optics), (see Ref. 563).

Besides optical phased arrays (on LC technology) there are alternative options that realize rapid beam steering without the use of conventional mechanical systems. An example is: Cascaded microlens arrays consisting generally of a closely packed periodic array of miniature lenses. In this setup, beam steering is affected by translating one microlens array with respect to the other.

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580) http://www.bnonlinear.com/ArrayApp.html
Some background on OPA: In 1971, R. A. Meyer demonstrated a multichannel array of bulk lithium tantalate modulators for optical beam deflection. The deflector consisted of 46 phase shifters in a 1-D geometry; independent control lines were provided for each channel to obtain continuous scan control. Several fundamental concepts of optical phased-array deflection were verified by this simple single-stage device. In 1973, Y. Ninomiya demonstrated a phased array of bulk prism deflecting elements made with lithium niobate. This device exploited an array concept primarily to enhance the deflector resolution beyond that of a single deflecting element. Ninomiya also introduced a two-stage phased array arrangement that included offset phase electrodes set in front of each prismlike deflecting element. Later efforts (1979) led to the design of fast, high-performance 1-D phased-array beam deflectors that use integrated-optics AlGaAs channel waveguides. An optical solid-state phased array designed for potentially high-speed operation with PLZT (Lead Lanthanum Zirconium Titanate) technology was demonstrated in 1995. An optimal arrangement for cascading 1-D phased array deflectors is presented in reference 576). Cascading is required by high-resolution scanning systems to reduce the number of control lines significantly and can be achieved with phased arrays while still allowing for continuous deflection-angle control, restricted voltage requirements, and compensation for non-ideal optoelectronic behavior and aging effects.

1.2.8.10 Advanced telescope design - lightweight optics and structures

At the start of the 21st century, the prevailing observation technology in LEO and GEO provides global data sets to study seasonal and long-term changes of the Earth's environment. The problem: LEO missions can provide only periodic high-resolution snapshots of the Earth's environment at any given location. On the other hand, GEO missions (weather satellites) provide contiguous coverage over its viewing geometry, but only at moderate spatial resolutions (generally in the order of 1-2 km for VIS and 4-5 km for the TIR range). Hence, none of these current systems is sufficient, in temporal and spatial resolution, to monitor the development of dynamic environmental processes. While a single GEO observatory cannot provide global coverage, a high-resolution sensing capability from such a vantage point (GEO) can better reveal short term forcing processes on complex Earth ecosystems.

Conventional high-resolution and wide-FOV imagers in the optical region (0.1 < \( \lambda \) < 1000 \( \mu \)m) employ generally fairly heavy instrumentation, even with moderate aperture size (about 0.3 - 0.5 m) telescopes. The mass of these monolithic telescopes is mainly due to the optical components with solid glass lenses and mirrors (and aluminum coatings). Examples of conventional imagers are: ETM+ of Landsat-7 with a mass of 428 kg, ASTER of Terra with a mass of 421 kg, HRG of SPOT-5 with a mass of 356 kg, BGIS 2000 of the QuickBird-2 mission with a mass of 380 kg (telescope of 138 kg).

The performance requirements of future EO missions, in particular for higher-resolution imagery from GEO (or further out at L1), will lead to much larger aperture sizes. In order to obtain high-resolution VIS/TIR imagery from GEO, equivalent to that of conventional instruments in LEO (say, 30 m in VIS and 300 m in TIR), requires a telescope aperture of 4 m in diameter (see Airy diffraction limit in chapter 1.3). Hence, today's challenge is to pro-

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585) Note: An exception to this rule are the telescopes of lidar instruments. Examples are: a) the CALIPSO mission of NASA/CNES (launch Apr. 28, 2006) carries a lidar instrument with a telescope aperture diameter of 1 m; b) ALADIN (Atmospheric Laser Doppler Instrument), a lidar on ESA's ADM-Aeolus mission (launch 2008) has a telescope diameter of 1.5 m.
duce such a large-aperture and low-mass telescope at affordable costs. Possible design solutions for such systems may require concepts of deployed, semi-rigid segments with actively controlled mirrors. 586) In the field of space science and astronomy, future large-aperture telescopes will have apertures of 3-5 m diameter or much more. This will eventually require a segmented telescope design for the launch phase and a subsequent space deployment of the telescope instrument due to launcher fairing limitations. Obviously, a new design concept approach in lightweight manufacturing technology of optical systems (use of composite materials) is needed to reduce the instrument mass to tolerable levels. The advantages of large-aperture space telescopes are obvious -- the sensitivity increases (and observation time decreases) proportionately to aperture area; spatial resolution improves proportionately with aperture diameter; the orbital environment is generally stable and quiet. 587) • Lightweighted structures. SiC (Silicon Carbide) is an important composite material for precision applications in reflecting optics components, in semiconductor electronics technology, as well as in many other fields. 588) 589) SiC-type ceramic mirrors and structures are becoming state-of-the-art technology components in lightweight optomechanical systems (telescopes). Silicon carbide has several advantages as a primary mirror substrate material: SiC is isotropic, homogeneous, dimensionally stable when subjected to repeated temperature variations. SiC has a relatively high strength-to-weight ratio compared to other viable mirror materials. A major advantage of SiC is that it can be formed into complex shapes, allowing for optimal material usage. SiC is also useful as a mirror substrate because some forms of SiC can be polished to a high quality mirror finish using diamond grit. There are several different manufacturing processes for producing SiC. The processes include CVD (Chemical Vapor Deposition), Reaction-bonded SiC, Sintered SiC, Hot Pressed SiC,Foamed SiC, and C/SiC (Carbon fiber-reinforced/Silicon Carbide); the latter material is part of the CMC (Ceramic Matrix Composite) family, which replaces the previous organic, resin-carbon matrix family with a more stable, oxidation-resistant ceramic matrix, such as SiC. 590) 591) 592) The use of CMCs is highly desirable in a number of critical space components (telescopes, nozzles, thrust chambers, control surfaces, leading edges, sensors for combustion monitoring, wear-resistant brakes, etc.) to save weight, improve reuse capability, and increase performance (high temperature resistance). Of major interest to high-temperature applications are carbon-carbon (C/C), carbon-silicon carbide (C/SiC) and silicon carbide-silicon carbide (SiC/SiC) composites. Examples: a) the Space Shuttle has been demonstrating the maturity of carbon-carbon (C/C) nosecaps and leading edges for more than 20 years, b) CMCs have been developed by an ESA/NASA team for integration and flight demonstration on the X-38 Vehicle 201 (Jan. 2001), the prototype for the ISS (International Space Station) CRV (Crew Return Vehicle).

• A special form of SiC, namely C/SiC (Carbon fiber-reinforced Silicon Carbide), is composed of coated C-fibers and a SiC matrix. C/SiC materials benefit from the high-temperature capability of carbon fibers and high modulus and oxidation resistance of the SiC matrix. As a fiber-reinforced composite, the mechanical and thermal properties can be tailored by

adjusting fiber volume and placement (i.e., fiber architecture) to meet the needs of many applications. 593) The C/SiC technology is based on infiltration processing (without any shrinkage) of porous C/C-structures with molten silicon by capillary forces. Common C/SiC infiltration processes are: CVI (Chemical Vapor Infiltration), MI (Melt Infiltration), and PIP (Polymer Infiltration and Pyrolysis). The following list represents some of the C/SiC ceramic material characteristics:

- Very broad operating temperature range (4 to 1570 K)
- Low specific density (2.6-2.7 g/cm³) approximately the same as aluminum
- High stiffness (tunable stiffness 240-260 GPa) and strength (140-210 MPa)
- Low CTE (Coefficient of Thermal Expansion), CTE = 1.8 x 10⁻⁶ K⁻¹ at room temperature, and near zero below 150 K, (CTE about 4.1 x 10⁻⁶ K⁻¹ at 1000 °C)
- High thermal conductivity (125-135 W/mK), approaches that of aluminum
- Low electrical resistance (2 x 10⁻⁴ Ohm x m)
- Isotropic characteristics of CTE, thermal conductivity, mechanical properties, etc.
- Very high chemical and corrosion resistance
- No ageing or creep deformation under stress (stability of shape)
- No porosity, non-magnetic
- High quality optical surface layers (e.g. SiC, glass and Si, roughness: < 5 Å)
- Fast and low-cost machining (no special tools required)
- Short manufacturing times
- Considerable flexibility in structural design (including large structure scaling)
- Ultra-lightweight capability (small wall thickness and complex stiffeners)
- Composition of C/SiC material: SiC : Si : C = 50-60% : 20-30% : 10-20% (typical value)
- High hardness (>1500 N/mm) harder and stronger than most other optical materials.

CESIC® (Carbon—fiber reinforced Silicon Carbide) is a ceramic matrix composite material (made of SiC, Si and C) of high stiffness, high thermal conductivity, and low thermal expansion from room to cryogenic temperatures. This material is obtained from the transformation of the Carbon in SiC, due to the reaction at high temperature between C/C greenbody and liquid silicon. The use of C/C greenbody manufacturing is one of the key technologies of the CESIC process. CESIC is a product of ECM Ingenieur – Unternehmen, Munich, Germany (ESA provided funding for CESIC technology development). – CESIC is an ideal material to produce lightweight, stable structures and a range of high—precision optomechanical components, such as lightweight mirrors, focal planes, telescopes, instrument structures, and optical benches for both land— and space—based applications. 594)

Background: Classic materials in telescope design technology include fused silica, Zerodur, ULE, titanium, Invar 595), Pyrex, etc. However, at the start of the 21st century, carbon fiber composite materials (such as carbon-carbon or graphite cyanide ester) offer significant advantages over the classic materials in terms of: density, low thermal expansion, and high stiffness. Essential technology elements for lightweight and dimensionally stable telescopes are composite materials based on graphite and carbon fibers. Also, replication with fiber composite materials yields areal densities that approach the minimum possible for a free-standing optical surface.

- Schott Glas of Mainz, Germany, developed an essentially zero-expansion glass ceramic by the name of ZerodurRM in 1968. The material is machinable and is suitable for telescope mirrors, ring laser gyrosopes and other applications that demand high precision. A technique to fuse Zerodur allows to fabricate large lightweight mirrors that cannot be produced

595) Note: Invar is a nickel-steel alloy invented in the early 1900s by the Frenchman Charles Edouard Guillaume. Invar (derived from “invariable” due to its particular characteristics) was the ideal material for balances as its coefficient of expansion is 15 times lower than that of steel.
by traditional machining methods. Examples of Zerodur implementations: In 1991/93, the VLT (Very Large Telescope) of ESO (European Southern Observatory), a glass monolith produced in a centrifugal casting process, was built by Schott Glas consisting of a Zerodur mirror substrate with a diameter of 8.2 m. In fact, VLT has four main Zerodur mirrors, each of 8.2 m in diameter for the visible and near-infrared spectrum. When coupled together, they form a giant telescope with an effective diameter of 16 m. - The telescope of SOFIA (Stratospheric Observatory For Infrared Astronomy), a NASA/DLR long-term airborne observatory on a Boeing 747 aircraft (start in 2006), employs a Zerodur mirror substrate (a milled honeycomb structure on the backside; 2.7 m diameter, the primary mirror employs a rigid CFRP structure) thereby reducing the instrument mass from originally 4 tons to about 890 kg (see P.190).

- The ULE™ (Ultra-Low Expansion) glass, face sheets bonded to a honeycomb core, achieves about 85-90% lightweight. ULE of Corning Inc., Corning, NY, is a titanium silicate glass (consisting of 92.5% SiO₂ and 7.5% TiO₂). The material is characterized by superior dimensional stability, which results from the essentially zero expansion at room temperature. The HST (Hubble Space Telescope) of NASA (launch Apr. 24, 1990 on STS-31) features a ULE primary mirror of 2.4 m diameter (f/24 Ritchey-Chretien) and a 0.3 m Zerodur secondary mirror. The HST primary mirror was a lightweighted monolithic design (824 kg) by Perkin-Elmer (now Goodrich Inc.), Danbury, CN, using a lightweight, thick egg crate core sandwiched between two plates and fused together. - The Subaru infrared telescope of NAOJ (National Astronomical Observatory of Japan), atop Hawaii’s Mauna Kea, contains a primary mirror of 8.2 m, created from Corning’s ULE precision glass (telescope operation since 1999). Subaru employs also the monolithic mirror technology.

- Pyrex is a borosilicate glass (originally cookware and dishware consumer products) developed by Corning Glass Works between 1911 and 1914. Among other things, borosilicate glass resists thermal shock and expansion (changes in temperature make Pyrex expand and contract much less than ordinary glass). The first telescope of Mount Palomar, CA, ordered by George E. Hale (1868-1938), is a 5 m diameter Pyrex mirror, casted by Corning in 1934. Pyrex is being used today as a low-cost substrate material in moderate-size telescopes due to its outstanding thermal characteristics. 596)

- The AMSD (Advanced Mirror Systems Demonstrator) program is a jointly funded effort by the USAF, NASA/MSFC, and NRO (started in the late 1990s). The main objective of AMSD is to effect order of magnitude improvements for the JWST (James Web Space Telescope) as compared to HST. In this program, Eastman Kodak demonstrated the AWJ (Abrasice Water Jet) milling technique to fabricate thin walled, open-ended, honeycomb core structure out of bulk ULE glass. A honeycomb sandwich-type results by a fusion bonding process attaching the front and back faceplates. Mirror areal densities of about 15 kg/m² are being achieved using monolithic glass mirror designs. 597)

- At the start of the 21st century, new concepts in mirror design are being introduced with the so-called “active optics” technology by combining the elements of: a lightweight meniscus facesheet, figure control actuators, and computer technology, with mirror shape control. 598) The integrated “meniscus mirror design” approach (pioneered by Xinetics Inc., Devens, MA in 1995) provides a mirror construction, in which a maximum amount of weight can be removed without affecting the optical figure properties and the dimensional stability of the mirror surface. A thin meniscus facesheet is made from SiC (Silicon Carbide) or C/SiC (Carbon fiber-reinforced Silicon Carbide), using a near net shape casting process. In the implementation of Xinetics, the facesheet has a reflective front surface and a back surface, which contains an integral stiffening structure that mitigates the dimensional stability problems often associated with thin, flimsy mirrors. Formed directly within the web

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596) http://www.rfroyce.com/pyrex.htm
support ribs are cutouts, which enable the integration of high strain, solid-state electroceramic actuators.

<table>
<thead>
<tr>
<th>Product/Material (manufacturer)</th>
<th>Specific Density (ρ) (g/cm³)</th>
<th>Young’s Modulus of Elasticity (E) (GPa)</th>
<th>Coefficient of Thermal Expansion (α), (10⁻⁶/K)</th>
<th>Thermal Conductivity (k), (W/mK)</th>
<th>Specific Heat (c), J/(kg·K)</th>
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<td>1.31</td>
<td>776</td>
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<td>700</td>
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</tbody>
</table>

Table 37: Overview of some optical material properties

Some application examples of lightweight telescope mirror technology in spaceborne instruments (Earth observation and astrophysics missions):

- The SEVIRI (Spinning Enhanced Visible and Infrared Imager) radiometer on EU-METSAT’s MSG-1 mission (launch Aug. 28, 2002 into GEO) is employing a TMA (Three Mirror Anastigmatic) telescope design (5367 mm focal length) with Zerodur ceramic mirrors on a substructure. The primary elliptical plane mirror (M1) measures 830 mm x 530 mm. The secondary mirror is 500 mm in diameter; the tertiary mirror has a diameter of 60 mm. The mirror assembly has a total mass of 15.6 kg (mass reduction of 70% by milling honeycomb-shaped holes in the back of each mirror). The mirror micro-roughness is < 10 Å. Note: MSG-1 became Meteosat-8 on Jan. 29, 2004 when the mission was declared “operational” (commencement of routine operations). MSG-2 was launched on Dec. 22, 2005.

- The Japanese astronomical space mission IRIS (Infrared Imaging Surveyor) of JAXA is planned for a launch in 2003. IRIS is also the name of the telescope on this mission with a lightweight primary mirror of 700 mm diameter. It has a mass of 8.2 kg and is made of a sandwich-type SiC material, consisting of light porous SiC core and dense CVD (Chemical Vapor Deposition) SiC coat. The mirror is polished to high precision, it has an areal density of 20.7 kg/m².

- ATLID (Atmospheric Lidar) is an instrument technology development program of ESA since 1998. The instrument is being developed for EarthCARE (Earth Clouds, Aerosol and Radiation Explorer), a future cooperative mission of ESA/JAXA in planning. ATLID features a lightweight C/SiC telescope design of a lidar instrument (mirror diameter of 630 mm, mass = 6 kg including coating and mounting provision).

- The Herschel telescope of the ESA, to be flown on the HSO (Herschel Space Observatory) mission, uses a Ritchey-Chrétien type telescope with a primary mirror diameter of 3.5 m (the largest mirror built so far for space). A launch of HSO is planned for 2007 into an orbit at Lagrangian point L2. The telescope design employs a lightweight mirror (300 kg) consisting of silicon carbide (SiC) segments that are “braided” together to form a monolithic mirror that can be polished to “any” required accuracy. Requirements call for a total WFE (Wave Front Error) of < 6 μm corresponding to diffraction-limited operation at 90 μm during operations, and a very low emissivity. Since the accuracy of the manufacturing of the primary mirror is the driver in the overall telescope WFE budget, the control of this param-

599) http://sag-ssl.berkeley.edu/~mlampton/OTA9.ppt
600) http://www2.schott.com/magazine/english/download/info102/si102_07_satellite.pdf
The Herschel telescope is passively cooled to $< 90$ K and feeds three payload instruments inside a dewar (a helium tank of about 2560 l): 602) 603)

- SPIRE (Spectral & Photometric Imaging REceiver). SPIRE consists of a 3-band imaging photometer (wavelengths at 250, 350 and 500 $\mu$m) and a Mach-Zender FTS (Fourier Transform Spectrometer) in the spectral range of 200-670 $\mu$m, providing simultaneous imaging of the entire band.

- PACS 604) (Photoconductor Array Camera & Spectrometer), 60-210 $\mu$m spectral range. The PACS FPU (Focal Plane Unit) employs two Ge:Ga photoconductor arrays (spectroscopy mode) and two bolometer arrays (photometry mode). PACS features an accurate positioning cryogenic mechanism for positioning control (4 arcsec within 40º of arc). The detectors are cooled to liquid helium temperatures (4.2 K).

- HIFI (Heterodyne Instrument for Far Infrared). A high-resolution heterodyne spectrometer providing continuous coverage over the frequency range of 480 to 1250 GHz in five bands and 1410 to 1910 GHz in two additional bands.

- The JWST (James Webb Space Telescope, formerly NGST) of NASA has a planned launch in 2013 to L2. 605) The JWST telescope design will feature a figure-controlled (flexible) segmented lightweight primary mirror structure of about 6-8 m diameter controlled by an array of surface-mounted actuators (TMA design, and use of C/SiC technology). Requirements call for observations in the spectral region of 0.5 - 30 $\mu$m (VIS to FIR) and a telescope mass of $< 600$ kg with an areal density of $< 15$ kg/m$^2$. - The primary mirror architecture of Northrop Grumman Space Technologies (formerly TRW) features a 36-segment configuration with semi-rigid segments, each actuated in tilt, piston, and radius-of-curvature degrees of freedom.

- A further Japanese entry into the ring is SPICA 606) (Space Infrared Telescope for Cosmology and Astrophysics) of JAXA with a planned launch in 2010 to L2. The telescope aperture will have a diameter of 3.5 m and a segmented C/SiC mirror design. The requirements call for a spectral coverage of 5-200 $\mu$m with a diffraction limit at 5 $\mu$m. 607) 608)

- A complete new approach, away from the traditional polished glass technique, may eventually be realized in the future with deployable thin-film mirror technology. The lightweight thin film can be folded during the launch phase. The film mirror is subsequently being shaped into its correct form by an electron gun - resulting in an ultralight space telescope. The new mirror, which is composed of a piezoelectric material that expands and changes shape when an electric field is applied, uses a whole new technique of mirror fabrication. 609)

1.2.8.11 Deployable space structures

Deployable space structures (antennas, solar panels, booms, trusses, etc.) are structures capable of large configuration changes when deployed in an autonomous way (generally on orbital insertion after launch). Obvious advantages of deployable structures are savings in mass and launch volume. Also, a compact and tightly packaged configuration offers considerable stiffness to withstand the launch loads. In its deployed configuration, the spacecraft

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602) http://sci.esa.int/home/first/index.cfm
603) Note: ESA's HSO was formerly called FIRST (Far Infrared and Submillimeter Telescope), renaming in 2002 in honor of William Herschel (1738-1822)
606) http://www.ir.isas.ac.jp/SPICA/
607) http://space.gsfc.nasa.gov/astro/aasbeyond/contib/motohide/
608) http://space.gsfc.nasa.gov/astro/aasbeyond/
structure is only subjected to the orbital loads, which are considerably lower than those on Earth. An important issue in the design of quite a few deployable space structures is the true attainment of its deployed configuration with regard to shape and size, alignment, precision, and stiffness requirements in the deployed state (the variable on-orbit thermal and vibration environments must also be considered). These aspects are usually critical to the measurement performance of the mission.

Deployable space structures play an important part in the realization of practically all space missions, since the limited envelopes of the existing launchers constrain the payloads geometrically. From a historic point of view, deployable structures have been used since the very beginning of the space age. Eventually, an arsenal of lightweight space-deployable structures evolved for a variety of applications that include spacecraft stabilization, mobile communications, radiometry, active microwave sensing (deployable space frames like the apertures of SAR antennas, scatterometer fans), robotic manipulators, etc. Considerable research has been invested to study the dynamics and control of such deployable structures and to validate these concepts in space.

At the start of the 21st century, increasing demands, for example for energy supply, require more and more very large appendages on spacecraft. 610) Power generation of the International Space Station (ISS) is provided by eight deployable solar arrays, each spreading an area of approximately 32.6 m x 11.6 m. The 60 m long boom which was deployed and retracted in 2000 onboard of the Space Shuttle Endeavour during the Shuttle Radar Topography Mission (SRTM) is another prominent example. Presently, a clear trend for an increasing need can be identified for a number of future space structure applications like instrument booms, antennas and mesh reflectors, solar sails, deployable mirrors for large telescopes, and eventually huge solar space power systems.

1.2.8.12 Inflatable Space Structures

Large and low-mass in-orbit deployable structures, in particular effective apertures, are enabling elements for a wide spectrum of applications, ranging from remote sensing (radars, radiometers, interferometers, telescopes, etc.) to radio astronomy, communications, and wireless power transmissions (WPT). Large antenna reflectors for the next-generation space applications are characterized by a diameter in excess of 12-15 m which can be packed in a limited fairing envelope of the available launch systems. The challenge is to design antennas with a reliable deployment mechanism and with high contour accuracy and stiffness after deployment. The mass reduction potential of these advanced antennas enables an increasing payload instrumentation to be integrated on a mission (or the use of a smaller S/C). The principal design of available deployable structures can generally be divided into mechanically deployable structures as well as into inflatable structures.

Background: 611) 612) 613) At the start of the 21st century, the space inflatable structure technology is one of the emerging/enabling technologies that can potentially revolutionize the designs and applications of large space structural systems. Concepts of inflatable deployable space structures have been under development since the early 1960s when the ECHO balloon satellites of NASA were successfully sent into orbit. The inflatables were chosen because the launch capabilities of the early US space program were rather limited.

Major advantages of using inflatable elements in space are their high packaging efficiency, extremely lightweight, high deployment reliability, and low cost. 614)

Flexible inflatable composite materials are utilized in many applications today but perhaps may find their greatest benefit in space structures. The automobile tire is the best known example of a flexible inflatable composite structure. In this case, the flexible matrix material is reinforced with woven materials such as steel or Kevlar. The reinforcement materials aid in supporting the structural loads due to inflation and also increase the composite material’s puncture resistance. Inflatable structures for space use similar principles to achieve the same or better performance as rigid structures. As is the case with automotive tires, space inflatable structures have become more durable and robust with the advent of new materials. Advanced flexible polymers and high strength fibers such as Kevlar, Vectran, and Spectra, have enabled the fabrication of very low mass structures that are deployable from a densely packed state. 615)

Inflatable structures minimize mass and volume of a spacecraft, they are far less expensive and will become increasingly important in future space missions. The inflatable technology fulfills best the requirements of large-diameter space structures (antennas, etc.), followed by the mesh technology with straight or foldable ribs. Inflatable structures are classified into three categories, depending upon the type of inflation they require. The categories are:

- CI (Continuously Inflated) structures
- RI (Rigidized Inflatable) structures
- SI (Single-Inflation) devices

CI structures such as balloons, data collection antennas, rover tires and habitats require continuous inflation (pressurization) throughout a mission. Hence, leakage (attributable to flaws in materials and holes from micrometeorites) is a major disadvantage of these structures. Pure inflatable CI structures are used only for missions with short operational life and where the supply of make-up gas does not pose a problem. RI structures, including antennas, solar arrays, light sails and solar shields, are made of materials that harden when they are inflated and exposed to sunlight. RI structures provide long-term structural integrity (mission life of 10-15 years); today, they are being considered for a variety of space applications. SI and RI devices are only inflated once. SI devices, such as landing bags, are then discarded.

RI structures are fabricated from flexible composite laminates. The material can be folded and packaged; once in orbit, it is being rigidized in situ via some external influence (thermal heating is a proven rigidization method by exposure to sunlight). Typical shapes or building blocks of the material are: toroids, spheres, dish structures, tubes, etc., which can be assembled into the required final structures. Naturally, process control is a major issue in the deployment/inflation/rigidization procedure.

The use of inflatable technology in a deceleration system offers some great advantages because of its low storage volume, mass and cost. Due to these advantages inflatable deceleration technology can successfully be used for planetary exploration or to return a small payload from ISS (International Space Station).

- Inflatable spaceborne structures have been used since 1960 with the launch NASA’s ECHO series experimental communication and geodesy satellites. These balloon satellites


615) Note: Large mechanically deployable antennas have been in great demand over the past two decades for a variety of space applications, such as satellite/mobile communications, radiometry, SAR (Synthetic Aperture Radar), and VLBI (Very-Long-Baseline Interferometry). - In the summer 2000, NASA started a Gossamer Spacecraft Initiative. The overarching goal is to achieve breakthrough enhancements in mission capability and reductions in mission cost, primarily through revolutionary advances in structures, materials, optics, and adaptive and multifunctional systems. The enabling technology is in particular envisioned for such applications as: very large aperture telescopes, large inflatable antennas, solar sails, and large solar power collection. The field of Earth observation will also profit from this initiative.
of 30 m diameter (ECHO-1A launch Aug. 12, 1960 available until 1968, ECHO-2 launch Jan. 25, 1964 available until 1969) were deployed from a packing container 0.67 m in diameter using inflation gas. The deployment event of the balloon satellites was uncontrolled and depended only on the packing method used. The ECHO satellites were large metalized balloons (manufactured from a laminate of 1100-0 aluminum foil and polyester film) that served as passive reflectors of radio signals (unfortunately the reflected signal was rather weak, hence not attractive for commercial use). ECHO-2 remained in orbit for several years.

- The follow-up Explorer IX and XIX inflatable spacecraft of NASA were used for high altitude atmospheric studies. Explorer IX (launch Feb. 16, 1961 from Wallops Island, VA) was a 3.5 m diameter sphere after inflation at orbital altitude (966/2157 km) with a mass of 17 kg. Explorer XIX was launched on Dec. 19, 1963. The PAGEOS (Passive Geodetic Earth Orbiting Satellite) spacecraft of NASA (launch June 24, 1966 from VAFB) was an aluminum-coated Mylar balloon of 30 m diameter with a mass of 55 kg (2953 km perigee, 5207 km apogee). Over 30 launches of inflatable spheres occurred during the period from 1960 to 1971 with some remaining in orbit for over 11 years. Several of the early balloon satellites failed during the inflation event. Some of these failures were attributed to lack of control of the inflation process. Modifications were made to the packing and inflation procedure which lead to success with subsequent flights. Most of the early research on space inflatables centered on methods of making the structure rigid.

- Inflatable antenna structures. Inflatable structures have the advantages of low mass, low stored volume, and of low cost. They also have the potential to deploy much more reliably than the conventional mechanical systems used for deploying rigid structures. However, the deployment of high-performance antennas needs some supervision in form of antenna surface shape control to satisfy the requirements of surface accuracy. Inflatable structures have been analyzed and developed in the US by NASA/JPL and AFRL in cooperation with L'Garde, ILC Dover, etc.; in Europe by ESA in cooperation with Contraves, Switzerland, with EADS Astrium, etc. - Inflatable antennas may be used in various frequency ranges (in particular VHF, UHF, MW) for such diverse applications as measuring soil moisture and ocean salinity or communications and power generation for satellites. Following are some demonstrations of inflatable and of mechanically deployable structures. 617 618

- In 1996, the spaceborne NASA IAE (Inflatable Antenna Experiment) was flown on SPARTAN-207 of the Shuttle mission STS-77 (May 19 - 29, 1996), a small free-flying satellite, made up of four major components: lens, torus, struts, and body. The experiment was conceived to verify the accuracy of an inflatable off-axis parabolic lenticular antenna structure deployed in space and to demonstrate its performance. NASA and L'Garde Inc. of Tustin, CA, worked together in the IN-STEP (In-Space Technology Experiments Program) to conduct the experiment. 619 620 The inflated antenna (successfully deployed on May 20) consisted of a 14 m lenticular, supported around its perimeter by an inflatable torus. The antenna assembly was attached to the parent spacecraft, SPARTAN-207, by three 28 m inflatable struts. The entire deployment system had a mass of 60 kg. Antennas of this type have the potential to be used for such applications as for space and mobile communications, Earth observations, astronomical observations, and space-based radar.

- The Russian/Georgian EGS “Reflector” experiment at the MIR Space Station (successful deployments in the period, July 23-28, 1999).\(^{621}\)\(^{622}\) The objective was to demonstrate and validate the mechanical deployment (form creation process in the space environment) of a large deployable high-precision offset (mesh) antenna. The reflector construction included many novelties which make it different from all other presently known reflectors. The reflector structure is of parabolic design. The stowed transport package had dimensions of 620 mm x 1060 mm. Together with electrical and mechanical systems the reflector mass is 38 kg, while together with the interface and container its weight is 46.5 kg. The stowed pack was delivered by the cargo ship ”Progress M-42” to MIR on July 18, 1999. At the end of the experiment, the cosmonauts turned the reflector mounting ring around of the SOFORA mast (a 14 m mast structure on the Kvant-1 module) on MIR and jettisoned the antenna away from the orbital station.

<table>
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<th>Parameter</th>
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<td>Optics</td>
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Table 38: Characteristics of Reflector

- The USAFRL at Kirtland AFB, NM, launched an inflatable sphere, named OCSE (Optical Calibration Sphere Experiment, built by L’Garde), on the JAWSAT mission (launch Jan. 27, 2000 on a Minotaur launcher into LEO, see N.12) of Weber State University, Ogden, UT. The objective was to refine and support spacecraft SLR tracking from the ground. The balloon had a diameter of 3.5 m. After successfully completing its one year mission, OSCE reentered the Earth’s atmosphere on March 5, 2001.

- The ISAR (Inflatable SAR) antenna under development at NASA/JPL is an L-band radar that has an aperture size of 10 m x 3 m, an operating frequency of 1.25 GHz, dual-linear (vertical and horizontal) polarization, 80 MHz bandwidth, and electronic beam scanning. The antenna aperture consists of three layers of thin-film membranes that form the radiating plane, the ground plane, and the transmission line plane. The ISAR designs are lightweight (11-12 kg).

- IRDT (Inflatable Reentry and Descent Technology). IRDT is an inflatable reentry vehicle (cone-shaped shield) project, co-sponsored by ESA, EC and EADS Astrium GmbH, designed/developed by NPO Lavochkin in Moscow, and EADS Astrium GmbH (sensor package) in Bremen, Germany, and launched by Starsem (Russian/European launch company). The first demonstration flight was conducted Feb. 9, 2000 when IRDT successfully returned the Fregat upper stage of the Soyuz launch vehicle; a second one returned a small 15 kg ESA payload called “Mission 2000.” The reentry packages were returned to Earth about eight hours later, with the inflatable shields also doubling as drag devices and soft-landing “airbags” instead of using parachutes. The Mission 2000 payload used a 95 kg two-stage IRDT shield. The first stage was inflated to envelop the payload upon separation from the Fregat stage; the second was inflated at an altitude of about 20 km, after entering the atmosphere, to serve as an airbrake for landing. The second stage apparently malfunctioned, allowing the payload to land at 60 m/s instead of the planned 13 m/s. The payload was not damaged, however. - IRDT makes use of technologies originally developed by NPO Lavochkin within the Russian Mars program in 1996. The IRDT system presents a potential lightweight, economical method to return payloads to Earth. A goal of the demonstration is


to use the IRDT system in future autonomous small payload return flights (samples) from ISS (international Space Station).

- In the late 1990s, NASA was engaged in the development of TransHab, a large inflatable habitat in space who’s multi—layer shell was based on Kevlar high—strength fibers (TransHab requirements called for an inflated volume of 340 m$^3$, 11 m in length and 4.3 m in diameter, and a launch mass of 13,200 kg) for protection from orbital and meteoroid debris. TransHab was intended as a replacement for the already existing rigid International Space Station crew habitation module. However, the US Congress (and NASA) cancelled the TransHab project in 2000 due to budgetary constraints.

- In 2002, Bigelow Aerospace of Las Vegas, NV, bought the TransHab license from NASA and started to pursue a development scheme for a civilian space complex. This resulted in the launch of two technology demonstration missions, Genesis—1 and Genesis—2 with launches on July 12, 2006 and June 28, 2007, respectively, to evaluate inflatable/expansible space module technology. The privately built and financed habitable structures are intended to be available for research, manufacturing and other uses, including lodging for future space tourists. – Each Genesis spacecraft has a launch mass of about 1,360 kg and a size of 4.6 m in length and 1.6 m in diameter at launch. The spacecraft architecture features an expandable outer surface that is wrapped around a central core at launch and expanded through air inflation in orbit. The skin is made of several layers that include proprietary impact—resistant materials. The flexible structure is designed to double in diameter once in orbit. The one—third scale hardware is to produce important data regarding multiple features of a full—scale spacecraft. The goal/commitment is to develop and operate a privately—owned inflatable space complex commercially and to be of service to a community of customers interested in space exploration and space habitats.

- ARISE (Advanced Radio Interferometry between Space and Earth). A NASA/JPL astronomy satellite mission in planning consisting of a 25 m diameter radio telescope (an inflatable structure with a very thin reflecting surface that does all the work in collecting light from the cosmos) in a highly elliptical Earth orbit (HEO). The new lightweight telescope architecture is called DART (Dual Anamorphic Reflector Telescope). The DART concept makes use of two parabolic, cylindrical trough-shaped reflectors oriented with respect to each other to produce a point focus. Since each reflector contains only a single simple curve, the mirrors can be formed by tensioning a reflective foil over a frame that has a parabolic contour along one axis. The use of an extremely low-mass membrane for the reflective surfaces reduces the mass of the telescope. The orbiting telescope (inflatable antenna with a size of the 25 m diameter) is used in a SVLBI configuration with arrays of ground-based telescopes to image radio sources in the universe with a resolution of 10-20 microarcseconds. Lowering the cost and maximizing the antenna performance are the two primary goals of the mission. The ARISE design is an upscale version of the IN-STEP structure IAE (Inflatable Antenna Experiment).

- STR (Spring-Tape-Reinforced) booms. Besides antennas, inflatable structures may also be employed for other components of space structures such as: solar arrays, sunshades, solar concentrators, and telescope reflectors. The STR technology, invented at JPL, represents another enabling element of inflatable structures, including self-rigidizable booms made of stretched aluminum laminates. A typical boom consists of a tube, formed of aluminum laminate sheet, and sewed by a Kapton tape and two end caps. A number of distinct advantages of the STR booms have been identified and demonstrated during the development process. These include: simplicity of the design, self-rigidizable in space, high-load carrying capability, high packing efficiency, and low inflation deployment pressure. 623)

- HIA (Hybrid Inflatable Antenna) for Ka-band applications. JHU/APL and ILC Dover Inc. developed a hybrid antenna concept combining a fixed parabolic dish with an inflatable

reflector annulus that greatly increases antenna area. The objective is to provide a credible backup capability with the high-gain parabolic dish in the event of an inflation failure. In this scenario, the inflated annulus enhances the science return above the minimum level already provided by the existing rigid dish. The rigid reflector provides a guaranteed high-gain capability, and the inflated annulus provides a “bonus” science return. For instance, a 1 m diameter rigid dish acquires a 16 times greater data rate capability when the annulus is inflated to a 4 m diameter.  

1.2.8.13 MEMS (Micro-Electro-Mechanical System) technology

MEMS - also known as “microsystems” in Europe or “micromachines” in Japan. MEMS technology first emerged in the late 1960s and early 1970s. MEMS devices, tiny machines virtually invisible to the naked eye (they range in size from a few μm to mm), fashioned largely from silicon with techniques adapted from the microchip industry, are able to “touch” the physical world and act upon it. There is a trend toward complete microsystems - merging sensing, actuating, computing and communications. Microtechnology represents essentially a synergistic combination between thin film technology, semiconductor technology, silicon micromechanics, ultra precision engineering, LIGA technique, laser lithography, and several technologies for packaging and assembly. The new microsystems offer enhanced levels of perception, control, and performance (nanoscale design, low power quantum electronics, high bandwidth photonic devices, etc.). The evolving list of MEMS features includes: provision of inputs and outputs for information systems, permitting multiple and mixed technology integration (CMOS/MEMS integration, integrated trench technology, etc.); in particular, there is the ability to sense and measure changes of physical parameters on the micro-scale (atomic) level, orders of magnitude better, than traditional techniques. At the end of the 1990s, the technology of miniaturization experiences a tremendous growth. It is destined to become a natural pick for a divers number of applications in all fields, in particular for the design of new instruments in the space industry. The potential of MEMS as an enabling technology has a definite impact on new designs, similar to the impact of integrated circuits for the electronics industry during the 1960s and 1970s.  

At the start of the 21 century, RF and microwave frequency MEMS have indeed potentially enormous and widespread applications in the electronics and telecommunications industry. The MEMS technology is in particular an enabler for high-frequency switches (GHz range). Components based on MEMS technology such as switches, varactors, and phase shifters exhibit virtually no power consumption or loss. There are always two distinct functions to a MEMS switch or varactor, namely: 1) the actuation (or mechanical) function, and 2) the electrical function. The forces required for the mechanical movement can be obtained using electrostatic, magnetostatic, piezoelectric, or thermal designs. 

Some examples of MEMS space applications are:

- MEMS technology is being applied to a variety of optical applications, ranging from adaptive mirrors to integrated optical benches, grating spectrometers, optical scanners, fluid pumps, etc.

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629) Note: A varactor is a special semiconductor diode that exhibits change in capacitance with a change in applied voltage; used as a voltage-variable capacitor.  
630) Gabriel M. Rebeiz, “RF MEMS, Theory, Design, and Technology,” John Wiley & Sons, Inc. 2003, chapter 1
MEMS technology is making possible the development of many different types of thermal sensors for spaceborne instruments and operational hardware. At the start of the 21st century, these are becoming available with high performances and in the case of arrays (linear or matrix) make possible a new class of imaging and spectrographic instruments.

- Integrated microaccelerometers and gyros
- Uncooled infrared detectors
- MEMS technology is used to form miniature antennas for millimeter-wave applications
- MEMS technology is being applied to micropropulsion systems.
- MEMS technology is applied for distributed sensors and actuators (closed-loop control is a viable option)
- MEMS is being used for electromechanical signal processing
- In the early 1980s, the Institute of Microstructure Technology of KfK (Kernforschungszentrum Karlsruhe, Germany) initiated/developed a micromachining technology by the name of LIGA [Lithographie, Galvanof ormung und Abformung (lithography, electroplating and moulding)]. LIGA is widely used throughout industry and the research community for advanced MEMS applications. LIGA is a three-stage process which can be used for the manufacture of high aspect ratio, 3-D microstructures in a wide variety of materials (e.g. metals, polymers, ceramics and glasses). By using the penetrating power of x-rays from a synchrotron, LIGA allows the fabrication of structures which have vertical dimensions from hundreds of microns to millimeters and horizontal dimensions which can be as small as microns.

SUMMIT (Sandia Ultra-planar Multi-level MEMS Technology) is another fabrication process developed by SNL (Sandia National Laboratories).

In 1993 the term nanosatellite was first coined and defined by Siegfried W. Janson, Henry Helvajian, and Ernest Y. Robinson of the Center for Microtechnology at The Aerospace Corporation, El Segundo, CA. In this paper, the proposed nanosatellite architecture employs MEMS and ASIMs (Application Specific Integrated Microinstruments). The integration of MEMS with microelectronics for data processing, memory, signal conditioning, power conditioning and communications results in stand-alone ASIMs (chip-to-chip wireless integration). ASIMs with silicon or other semiconductor substrate can be applied to S/C systems, i.e. tiny instruments, for such functions as guidance, navigation and control, attitude sensing, attitude control, thermal control primary propulsion, power and communication. In this concept, the nanosatellite denotes a S/C built almost entirely of ASIMs. The silicon satellites are spacecraft that utilize single-crystal silicon wafers for electronic substrates, mechanical structure, thermal control system, and radiation shield. 631) 632)

1.2.8.14 Cryogenic cooling techniques of observation instruments

The accurate measurement of incoming radiation, a principle used in all passive observation sensors, requires thermal and structural (vibration) instrument stability, and in various applications cryogenic cooling (simply referred to as “cryocooling”), to obtain reproducible results. Cryocooling is needed to provide the required detector response, reduce preamplifier noise, and/or reduce background radiation. Cryogenic operation has been required for a number of spaceborne instruments, including infrared sensors (focal plane imaging arrays, filters, occasionally optics), x- and gamma-ray detectors, and a number of emerging superconducting technologies. The objective of cryocooling is always to improve the sensitivity of the sensing device by suppressing unwanted noise. Typical cooling temperatures in

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space systems range from the boiling point of liquid Nitrogen at 77.36 K, down to near the boiling point of liquid Helium at 4 K (Note: the boiling point of Helium 4 is a bit above 4 K while that of Helium 3 is 3.2 K).

All infrared radiation generates heat on detection requiring generally a cooling method of the detector system for accurate signal measurements. This unwanted side effect of infrared heating involves rather costly implementations of cryocooling to circumvent this nuisance. In general, a cryogenic cooler increases the mass, volume, and power consumption of the detector assembly by about an order of magnitude. A high price to pay for accuracy.

A number of technical approaches to meeting this need are possible and have been developed over the years.

- **Passive coolers** have been used for many years in space science applications due to their relatively high reliability and low vibration levels. These passive radiator systems have taken advantage of the inherent cold of deep space (however, they generally require large large radiator areas and shading from heat sources such as the sun and IR emission from the spacecraft and planetary surface).

![Cryogenic cooling methods in space](http://www.aero.org/publications/donabedian/donabedian-1.html)

On spacecraft, focal planes are sometimes cooled with passive radiators, the performance of which is highly dependent on mission parameters and spacecraft configuration. Passive radiative coolers are well developed and provide exceptional reliability for detector arrays. The size of these coolers is, however, governed by the first-order physics of Planck’s radiation law. The required minimum area for the radiative surface is governed by the relationship $W = AesT^4$, where $W$ is the radiated power, $A$ is the area of the radiator, $e$ is the effective emissivity of the radiator’s surface, $s$ is the Stefan-Boltzmann constant, and $T$ is abso-
lute temperature. This relationship can be expressed as $A = \frac{W}{(eST^4)}$. Thus, the area of the radiator needed to achieve a given cryogenic temperature depends directly upon the amount of cooling power required and upon the inverse fourth power of temperature. This is a highly nonlinear relationship; for example, it takes four times as much radiator area to reach 60 K as to reach 85 K. Consequently, application of this comparatively straightforward technology is limited to relatively modest levels of cooling power at temperatures of about 65 K or warmer. This is more than adequate for sensors such as MODIS, but passive cooling would be a challenge for a high-resolution pushbroom longwave infrared imager, for example.

Some examples of passive radiative cooling are:

1) The HgCdTe detectors of the MVIRI (Meteosat Visible and Infrared Imager) on the first-generation Meteosat series are radiatively cooled to 90 K by a passive system (launch of Meteosat-1 Nov. 23, 1977, launch of Meteosat-7 Sept. 3, 1997).

2) The ETM+ (Enhanced Thematic Mapper Plus) of Landsat-7 (launch Apr. 15, 1999) is radiatively cooled. The second focal plane is the cold focal plane which includes the optical filters, infrared detectors, and input stages for ETM+ spectral bands 5, 6, and 7. The temperature of the cold focal plane is maintained at 91 K using a radiative cooler.

3) The MODIS instrument of the Terra mission (launch Dec. 19, 1999) uses a high-performance passive radiative cooler to cool the infrared FPA to 83 K.

- **Dewars** [named after Sir James Dewar (1842–1923) who first liquefied hydrogen in the 1890s] containing liquid cryogen (stored coolants) have been flown. Typically, containment dewars are used for space systems that require cooling below 80 K. These open systems employ the latent heat of vaporization or sublimation for cooling. Although this technique has several advantages, such as the absence of exported vibration, the systems are massive, inconvenient to accommodate, and have limited lifetimes. The main applications are in infrared astronomy. Some examples:
  - The joint IRAS (Infrared Astronomical Satellite) mission of NASA, The Netherlands, and the UK (launch Jan. 25, 1983) employed a dewar for infrared observations (wavelengths of 8.5–15, 19–30, 40–80, and 83–119 µm) of the universe. The telescope of 0.57 m diameter was housed in the dewar, filled with 480 liter of liquid helium and contained a plane array of 62 detectors. The entire telescope was cooled to a temperature of about 4 K. IRAS operated for 10 months until the cryogen was depleted. In addition, there was a spectrometer in the range 7.4–23 µm, and a photometer in the range 4.1–8 µm.
  - SHOOT (Superfluid Helium On-Orbit Transfer), a NASA/GSFC cooling demonstration experiment, was part of the space shuttle STS-57 mission in June, 1993. The experiment objectives included: transfer of superfluid between two dewars connected by a tube in a low gravity environment at different flow rates; operation of two different liquid acquisition devices within the dewars; liquid/vapor phase separation for normal liquid helium as well as superfluid at varying venting rates; accurate mass gauging and flow metering; and autonomous control of the transfer process by an expert system aboard a computer on the Shuttle. 635) 636)
  - The NICMOS (Near Infrared Camera and Multi-Object Spectrometer) instrument of NASA, built by BATC, was flown to the HST (Hubble Space Telescope) on mission SM-2 [the second Hubble service flight on STS-82 (Feb. 11-21, 1997)]. NICMOS was designed to fit inside a cryogenic dewar, cooling the NICMOS detector with a block of solid nitrogen

634) http://www.nationalacademies.org/ssb/smallsatappendb.htm
636) http://cryowwwbaber.gsfc.nasa.gov/introduction/helium_space.html
However, due to unforeseen design problems, the dewar ran out of nitrogen coolant after less than two years, and had to stop operation (see NICMOS under item 5 below, “Reverse Brayton cycle cooler”).

- The Spitzer Space Telescope mission of NASA/JPL (formerly SIRTF, launch Aug. 25, 2003) employs a dewar of 335 liter of supercold liquid helium. The cryogen is used to cool the FPA (Focal Plane Array) of IRAC (Infrared Array Camera), IRS (Infrared Spectrograph), and MIPS (Multiband Infrared Photometer for Spitzer) to a temperature near absolute zero for highest-level sensitivity (the mission is to last until 2008/9). Observations are made in the range 3 – 160 µm.

- The payload of the GP-B (Gravity Probe-B) mission of NASA (launch April 20, 2004) is in effect a large ‘thermos bottle’ in space. The objective is to cool the science instrument constantly to 1.8 K to test Einstein’s relativity principle. The science payload consists of a superfluid helium dewar (2,440 l), within which a high-vacuum probe is installed, containing the SIA (Science Instrument Assembly), made up of a Quartz Block Assembly (QBA), which is optically contacted to a fused quartz Cassegrainian telescope. The SIA is maintained at a stable temperature of 1.8 K (over a period of 1 – 2 years) which provides the necessary stability of the precision alignment between the gyroscopes and the telescope. 637)

• **Active coolers** (referred to as cryocoolers, they are refrigerators used to reach cryogenic temperatures). Active coolers use closed thermodynamic cycles to transport heat up a temperature gradient to achieve lower cold—end temperatures at the cost of electrical input power. – Active cryogenic refrigerators offer an alternative to passive radiators. Active coolers offer greater capacity and provide additional freedom in packaging and locating the sensor on the spacecraft, since there are no preferred orientations or constraints on view factors. These benefits are provided at the expense of fairly high power consumption, added mass, and diminished reliability. Indeed, there is a crossover point in size/mass efficiency: Passive coolers tend to be the better choice for modest heat loads (<1 W) at temperatures above approximately 80 K; active coolers are more attractive for higher heat loads (>2 W) at temperatures of 65 K or colder. 638) 639) 640) 641) Depending on the temperatures required, several cooling schemes are commonly used to actively cool focal planes of optical detectors or other components. The general reliability requirement associated with the development of cryocoolers for space applications leads to the rule that a reliable cooler shall be simple, have no friction, or better have no moving parts. – At the start of the 21st century, cryocoolers represent an important enabling technology for many Earth and space science instruments. As a consequence, NASA started ACTDP (Advanced Cryocooler Technology Development Program) directed towards 6 K/180 K two—stage cooling with remote cold heads. The idea is to be able to commit to missions in the 2007–2015 timeframe. 642)

The following list gives short-descriptions of some cryocooler types and applications: 643)

1) **Stirling cycle engines**, named after the Scottish brothers, Robert and James Stirling. They invented the Stirling engine in 1816 (the original Stirling cycle was developed as a closed-cycle steam engine — and reversed for application to refrigeration by Kirk in 1874).
-- Stirling cycle coolers are based on causing a working gas to undergo a Stirling cycle which consists of 2 constant volume processes and two isothermal processes. Devices consist of a compressor pump and a displacer unit with a regenerative heat exchanger, known as a 'regenerator'. Stirling cycle coolers were the first active cooler to be used successfully in space and have proved to be reliable and efficient. -- Recent years have seen the development of two—stage devices (minimization of losses) which extend the lower temperature range from 60—80 K to 10 K (with a practical load). EADS Astrium and RAL, in fact, built such a machine in the late 1990s. A flight qualified model is expected in 2006 to reach around 6 K with no load. 644)

Examples of first-generation Stirling cycle cryocoolers are:

- The first long-life active cooler system (> 1 year in service) successfully operated in space was a cluster of four Stirling cycle machines launched Feb. 24, 1979 aboard the P—78—1 spacecraft of the USAF. 645) P-78-1, also referred to as “Solwind”, was the first satellite to carry a gamma-ray spectrometer and an X-ray monitor that were cooled by mechanical refrigerators (the X-ray monitor, referred to as NRL-606 or XMON, was a collaboration between the Naval Research Laboratory and Los Alamos National Laboratory). In addition, the payload consisted of a white—light spectrograph, an EUV (Extreme Ultraviolet) spectrometer, a high—latitude particle spectrometer, and an aerosol monitor.

The four Stirling cycle engines were developed by North American Philips Laboratories and by JHU/APL, Laurel, MD (the Stirling coolers were actually a development of an ongoing technology program developed by Philips Co. of Eindhoven, The Netherlands, since World War II). Each pair of coolers nominally consumed 30-35 W, produced 0.3 W of cooling at 75 K, and had a mass of 7.2 kg (including electronics). Although the cooler systems showed significant performance degradation on orbit, they operated sufficiently well to keep the payload operating until it was deliberately destroyed by the USAF during a successful test of an anti-satellite interceptor on Sept. 13, 1985. At least one cooler was still in operation when the spacecraft was destroyed in 1985. 646) 647) 648)

NASA considered the single-stage Stirling cryocooler of the North American Philips Laboratories in the most mature stage of development. This cooler incorporated linear motors and magnetically levitated moving parts (piston, displacer and counterbalancer) with clearance seals. 649) 650)

- Actually, the very first spaceborne Stirling cryocooler (and a Vuilleumier cooler) were flown on the Skylab missions in 1973. However, these were only fairly short-duration refrigerators (i.e. low duty cycles) during each Skylab occupancy by the astronauts. They were used to cool the S—191 (Visible-Infrared Spectrometer) and S-192 (Multispectral Optomechanical Scanner) instruments onboard Skylab.

- The Oxford cryocooler, designed and built by the University of Oxford, UK, was first flown on the NASA UARS mission (Upper Atmosphere Research Satellite, launch Sept. 12, 1991) to provide cooling for the ISAMS (Improved Stratospheric and Mesospheric Sounder) instrument, a limb-sounding radiometer of Oxford University, Oxford, UK. Its

645) http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/p78-1.html
646) http://www-atm.physics.ox.ac.uk/main/capabilities/mechanical_coolers.html
647) Information provided by Jaime Reed of EADS Astrium in Stevenage, UK (formerly of Cryogenics Group at the University of Oxford, UK)
design cooling power was 0.8 W at 80 K and its mass was about 4.3 kg. 651) Two coolers were installed for vibrational balance. [Note: the ISAMS cryocooler was a joint development by groups in the Physics and Engineering Departments at Oxford University and at the Rutherford Appleton Laboratory (RAL), UK].

The use of mechanical coolers in space was pioneered by this program. Already in 1990, BATC (Ball Aerospace & Technologies Corp.) of Boulder, CO, licensed the Oxford University/Rutherford Appleton Laboratory cryocooler technology. 652) In addition, the Oxford cryocooler technology was licensed by British Aerospace, now EADS Astrium Ltd., for use in Europe. A derivative of an Oxford cryocooler was part of the NRL HTSSE-II instrument flown on the ARGOS mission of DoD (launch Feb. 23, 1999). The MOPITT instrument coolers, flown on the Terra mission of NASA (launch Dec. 18, 1999), were built by British Aerospace/EADS Astrium Ltd.

- The CSE (Cryo System Experiment), 653) a hybrid cryogenic cooling system within NASA's IN-STEP (In–Space Technology Experiments Program), built by Hughes Aircraft Co., first flown on STS-63 (Feb. 3-11, 1995), provides 1.2 W of cooling at 65 K [it is the first US-built long life (1.5 years of continuous operation) Stirling cooler to operate in space]. In addition, there was an experimental diode oxygen heat pipe. The heat pipe enables large physical separation between the cryocooler and its thermal load, and provides on–off switching to limit reverse heat flow when the cooler is turned off. CSE achieved all of its objectives.

- The Terra mission of NASA (launch Dec. 19, 1999) is flying several Stirling coolers. The SWIR and TIR subsystems of the ASTER instrument of Japan are each cooled to 80 K (continuous operation of the cryocoolers, nominal cooling capacity of 1.2 W, design life of 50,000 h of operational service). 654) The MOPITT instrument of Terra, build by the University of Toronto, provides thermal control by an 80 K Stirling cycle cooler, capillary-pumped cold plate, and passive radiation.

2) Pulse tube systems. Pulse tube coolers are similar to the Stirling cycle coolers although the thermodynamic processes are quite different. They consist of a compressor and a fixed regenerator. Since there are no moving parts at the cold–end reliability is theoretically higher than Stirling cycle machines. Efficiencies approaching Stirling cycle coolers can be achieved and several recent missions have demonstrated their usefulness in space.

Pulse tube coolers are capable of achieving cryogenic temperatures of <20 K in the 0.5-3.5 W cooling capacity range. The principal benefits of a pulse tube cooler are greater reliability and lower cost compared to the Stirling cooler and an order of magnitude lower mass, lower cost, and longer life than the current state-of-the-art coolers. A pulse tube cooler is also more efficient than a TEC-type instrument, however, as a mechanical cooler, it is much larger than a TEC. In addition, mechanical coolers can produce vibrations that must be canceled or isolated. Examples:

- The Lewis satellite of NASA (launch Aug. 23, 1997 - however, the S/C was lost and re-entered the atmosphere Sept. 28, 1997) was the first spacecraft in civil Earth observation featuring pulse tube cryocooler technology (built by TRW) in its HSI (Hyper-Spectral Imager) for low-noise SWIR cooling. Already in 1994, TRW delivered its first pulse tube instrument, built under contract to the Air Force’s Phillips Laboratory.

- The MTI (Multispectral Thermal Imager) mission of DOE (LANL/SNL), launch March 12, 2000, employs a dual-load pulse tube cryocooler of the MTI instrument, built by

651) Oxford cryocooler information provided by Manny Tward of TRW, Redondo Beach, CA
653) http://www.infobloom.se/cesk/cryo.htm
TRW, now NGST (Northrop Grumman Space Technologies). This technique permits FPA cooling for MWIR (60 K) and TIR (35 K) observations with a total input < 125 W.

- Other instruments with pulse tube cooling technology are AIRS (Atmospheric Infrared Sounder) of NASA's Aqua satellite (launch May 4, 2002) and TES (Tropospheric Emission Spectrometer) on the Aura mission (launch July 15, 2004). 655)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Cooler type</th>
<th>Agency (mission)</th>
<th>Instrument (mission)</th>
<th>Launch date</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGST (TRW), Oxford Plc.</td>
<td>Mini Stirling</td>
<td>NRL (ARGOS)</td>
<td>HTSSE-II (ARGOS)</td>
<td>Feb. 23, 1999</td>
</tr>
<tr>
<td>NGST (TRW)</td>
<td>Mid-size pulse tube</td>
<td>SNL/LANL, (MTI)</td>
<td>MTI (Multispectral Thermal Imager),</td>
<td>Mar. 12, 2000</td>
</tr>
<tr>
<td>NGST (TRW)</td>
<td>Mini pulse tube</td>
<td>NASA/GSFC (EO-1)</td>
<td>Hyperion (EO-1)</td>
<td>Nov. 21, 2000</td>
</tr>
<tr>
<td>NGST (TRW)</td>
<td>Mini pulse tube</td>
<td>NASA/LaRC</td>
<td>SABER (TIMED)</td>
<td>Dec. 7, 2001</td>
</tr>
<tr>
<td>NGST (TRW)</td>
<td>Mid-size pulse tube</td>
<td>NASA/JPL</td>
<td>AIRS (Aqua), 2 units</td>
<td>May 4, 2002</td>
</tr>
</tbody>
</table>

Table 39: Some spaceborne cryocoolers with DoD/MDA (Missile Defense Agency) research funding 656)

3) Joule-Thompson coolers. These coolers work using the well known Joule-Thomson (or Joule-Kelvin) effect. A gas is forced through a thermally isolated porous plug or throttle valve by a mechanical compressor unit leading to isenthalpic cooling. Although this is an irreversible process, with correspondingly low efficiency, JT coolers are simple, reliable, and have low electrical and mechanical noise levels. Note: the JT cooler is actually an open-cycle expansion device. Examples:

- A JT cryocooler experiment of BATC (Ball Aerospace & Technologies Corp.) was successfully demonstrated on Shuttle flight STS—85 in Aug. 1997.

- A 4 K JT stage driven by a valved linear compressor (designed by RAL and EADS Astrium), similar to those used for Stirling cycle and Pulse Tube coolers, will be flown on the planned Herschel/Planck telescope mission of ESA (launch in 2009).

4) Peltier effect coolers. Solid–state Peltier coolers, or TEC (Thermo–Electric Converter) devices, are routinely used in space to achieve temperatures above 170 K (e.g. the freezers aboard the International Space Station). These devices work on the same principle as the Seebeck effect, but in reverse: the creation of a temperature difference between two dissimilar metals by application of a current.

The TEC scheme is capable of cooling focal planes to 180 K starting from an ambient temperature of 300 K. TEC instruments are small, lightweight, and, being solid-state, have no vibration. TECs have the main disadvantage of having an efficiency that drops off rapidly with decreasing temperature and tending towards zero around 180 K. Traditionally, TECs are limited to cooling a small detectors; they provide high reliability with slow and low-efficiency cooling.

Examples of thermoelectric cooler implementations are: 1) The RBV (Return Beam Vidicon Camera) flown on early Landsat spacecraft (launch of LS—1 July 23, 1972); 2) GERB (Geostationary Earth Radiation Budget) flown on MSG (Meteosat Second Generation) satellites of EUMETSAT (launch of MSG-1 on Aug. 28, 2002); 3) SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals) flown on Shuttle flight STS-112, Oct. 7-18, 2002, and on STPSat-1 (launch March 9, 2006).

5) Reverse Brayton cycle cooler. Reverse/Turbo Brayton coolers have high efficiencies and are practically vibration free. Coolers consist of a rotary compressor, a rotary turbine – al-


ternator (expander), and a counterflow heat exchanger (as opposed to the regenerator found in Stirling or Pulse Tube coolers). The compressor and expander use high-speed miniature turbines on gas bearings and small machines are thus very difficult to build. They are primarily useful for low temperature experiments (less than 10 K), where a large machine is inevitable, or for large capacity devices at higher temperatures (although these requirements are quite rare). – Note: a thermodynamic concept of a combustion engine was initially developed by George R. Brayton (an engineer of Boston, MA, 1830–1892) in the 1870s. He invented the continuous ignition combustion engine that later became the basis for the turbine engine. The operation of these combustion turbines is referred to as the “Brayton-cycle” engine. Example applications: 657)

- A recent application of this class of cooler was the replacement of the old dewar for the NICMOS (Near Infrared Camera and Multi-Object Spectrometer) instrument, flown on the HST (Hubble Space Telescope) mission (installation in March 2002 on HST servicing mission SM-3B) on STS-109. Originally, NICMOS had a solid nitrogen dewar for cooling (the nitrogen depleted in Jan. 1999). The new reverse Brayton cryocooler was developed by Creare Engineering & Development of Hanover, NH, USA. The Creare instrument returned the NICMOS detectors to operational temperatures of 75 K. The NICMOS cooling system maintains the detector temperature by circulating refrigerated neon gas through existing liquid helium freeze lines via bayonet couplings. – The new cooling system technology was first tested aboard Shuttle flight STS–95 in 1998.

- This was preceded by SSRB (Single Stage Reverse Brayton in 1992, a demonstration project of the USAF Phillips Laboratory and NASA/GSFC to maintain a cooling temperature of 65 K (using a combination of centrifugal compressor, recuperative heat exchanger, expansion turbine, and thermal interfaces to the load and heat rejection devices). SSRB was also developed by Creare Engineering & Development.

6) Adsorption cooling. Adsorption (or sorption) is the physical mechanism upon which a gas can be trapped onto a material surface: when a gas is brought into contact with a solid surface, some of the molecules striking the surface will be retained for a finite period of time, resulting in a significantly higher molecular concentration at the surface than in the gas phase. Adsorption coolers are essentially JT coolers which use a thermo-chemical process to provide gas compression with no moving parts. Powdered adsorbent materials (e.g. metal hydrides), are electrically heated and cooled to pressurize, circulate, and adsorb a working fluid such as hydrogen. Efficiency is low but may be increased by the use of mixed working gases. Demonstration models have already been flown and they are expected to be useful in long-life missions where very low vibration levels are required, such as the planned Darwin mission of ESA to image the atmospheres of extra-solar planets.

7) Optical cooling. Optical cooling using fluorescence in solids and liquids is an alternate and new concept in refrigeration that represents possible applications in small cryocooler technology, in particular for infrared devices and spectrometers (O.5.4). 658) 659) The method uses anti-Stokes fluorescence to remove heat from a glass or crystal that is pumped with laser light. The basic principle of cooling using anti-Stokes fluorescence was suggested by Peter Pringsheim, Berlin, in 1929, but it was not until 1995 that the actual cooling of a solid was first demonstrated at LANL (Los Alamos National Laboratory) using Ytterbium-doped Zirconium Fluoride (Yb:ZBLAN) glass.

- A first demonstration instrument by the name of LASSOR (Los Alamos Solid-State Optical Refrigerator) was developed at LANL (Los Alamos National Laboratory) in 1995 using Yb doped Zirconium Fluoride (Yb:ZBLAN) glass.
- In Oct. 2000, NASA/LaRC awarded to BATC (Ball Aerospace & Technologies Corporation) a contract to develop an optical cryocooler (infrared focal plane demonstrator). In 2003, BATC demonstrated their first optical refrigerator. It cooled an attached load, simulating an infrared detector, to 11.8°C below its surroundings. 660)

Optical cryocooling is a feasible method for cooling focal planes and has a distinct niche in extended solid-state cooling to those temperatures that cannot be achieved efficiently (or at all) by TEC methods. Optical cryocoolers have a clear advantage over mechanical coolers in vibration (because a solid-state diode is used as the pump laser, there are no moving parts and therefore no vibration), ruggedness, EMI (Electromagnetic Interference) and magnetic field, and cooler mass. Nevertheless, they are at a disadvantage to mechanical coolers based on efficiency. Optical cryocoolers have an advantage over TECs in minimum operating temperature, magnetic field, and ruggedness. They are at a disadvantage to TECs in cooler mass, however.

8) ADR (Adiabatic Demagnetization Refrigerator) for cooling applications below 1 K. The basic principle of adiabatic demagnetization of paramagnetic salts (the removal of a magnetic field from certain materials serves to lower their temperature) was initially suggested independently by Peter J. W. Debye in 1926 and by William F. Giauque in 1927. The ADR technique was the first method developed for cooling below ~0.3 K, and has been used in laboratories on the ground for many years; it is a well-established technology reaching cooling temperatures of about 2 mK.

The ADR heat pump technology was developed at NASA/GSFC (started in 1979) for use on spaceborne instruments; it operates between liquid helium temperature (~4 K as reservoir or coolant temperature) and very low temperatures – below 0.1 K to maximize the detector sensitivity (i.e., operation near the quantum limit). ADR is a cyclic superconducting cooling system; it alternates between two states (or stages):

- In the operating state, it cools down and absorbs heat
- In the recycling state, the ADR warms up and dumps heat into a heat sink.

The refrigeration cycle of an ADR utilizes the magneto-caloric effect by exploiting the interaction between the atomic magnetic moments in a paramagnetic material (often a salt) and an externally applied magnetic field. The main components of an ADR are: a) a paramagnetic salt, and its thermal link, b) a magnet and its shielding, and c) the heat switch.

The first spaceborne ADR was realized for the high-resolution XRS (X-Ray Spectrometer) of JAXA (manufactured and integrated by Sumitomo Heavy Industries, Niihama, Japan) to cool the detectors at the focal plane to 0.065 K (or 65 mK). An ADR was chosen for space instead of a dilution refrigerator because it does not require gravity and because it is exceedingly efficient. The ADR for the X-Ray Spectrometer has an efficiency of approximately 50% of Carnot. This efficiency is necessary for spaceborne systems to allow the liquid helium dewar to operate for extended periods of time on orbit. 661)

- This XRS instrument (also called XRS-2) with ADR cooling of NASA/GSFC is flown on the Astro-E2/Suzaku mission of JAXA (launch July 10, 2005). Prior to this, the newly developed XRS experienced a launch failure on the Astro-E spacecraft of ISAS (launch Feb. 10, 2000) from the Kagoshima launch site in Japan.

- NASA is utilizing the ADR technology also on SAFIRE (Submillimeter And Far InfraRed Experiment), an instrument on the airborne mission of SOFIA (Stratospheric Observatory for Infrared Astronomy) with first flights starting in 2006.

- The Mullard Space Science Laboratory at the University College London, UK (along with EADS Astrium Ltd.), is developing a 10 mK ADR stage. This cooling system is to be flown on the XEUS mission of ESA (launch planned for 2015), a spaceborne X-ray observatory.

1.2.8.15 Uncooled infrared detectors and HTS (High-Temperature Superconductivity)

- Use of uncooled infrared detector arrays in the spectral region of TIR (Thermal Infrared) for surface imaging. The technology employs silicon micromachined microbolometer focal plane arrays. The NASA/GSFC instrument ISIR (Infrared Spectral Imaging Radiometer) demonstrated the potential of the concept on Shuttle flight STS-85 (Aug. 7-19, 1997, see J.8). 662) A bolometer is a detector type making use of the change in electrical resistance of certain materials (with small thermal capacity) when their temperature is changed. The resistance of most conductors varies with temperature, this change in resistance is measured by the bolometer. Bolometers are suitable detectors for the infrared and microwave regions. The main advantage of a bolometer detector system is the absence of a cryogenic cooler system.

The first micromachined MBAs (Microbolometer Array) were probably developed in the USA in the late 1980’s and early 1990’s under DARPA’s HIDAD (High Density Array Development) program and built by the Honeywell Sensor and System Development Center. This early MBA had about 80,000 pixels (336 x 240) with an average room-temperature sensitivity (NEAT) of less than 50 mK, measured at a 30 Hz frame rate, with f/1.0 optics and a broadband (8-14 μm) filter.

- HTS (High-Temperature Superconductivity), see also “superconductivity” in the Glossary. The characteristics/performance of superconductive electronic devices have exceptionally low loss, high speed, high dynamic range, and low noise. Superconducting materials (in hybrid components, hybrid digital circuits, semiconductors, sensors) are promising to reduce loss by several orders of magnitude at RF frequencies, increasing the sensitivity and

precision of signal discrimination in advanced electronic systems. A new detector type, based on SQUID (Superconducting Quantum Interference Device) technology, offers promising results in such applications as absolute magnetic field measurements.\(^\text{663}\)

- The first program to demonstrate the operation and survivability of simple HTS electronic components in space was initiated by NRL (Naval Research Laboratory) in 1988 within the framework of HTSSE-I (High Temperature Superconducting Space Experiment I).

- The DoD ARGOS satellite (launch Feb. 23, 1999), operated by SMC, carries HTSSE-II (High Temperature Superconducting Space Experiment II) of NRL to demonstrate the performance of superconducting (semiconductors and RF) components at cryogenic temperatures of 70-80 K (see M.3). Reductions in power by several orders of magnitude as well as signal speed increases of an order of magnitude are expected with this technology. HTSSE-I of NRL, with relatively simple HTS devices, the majority being passive components made from a single HTS film, were to be placed in orbit to investigate the durability of HTS in space. However, the DoD satellite with HTSSE-I aboard experienced a launch failure in 1993. Despite the unfortunate loss of on-orbit data from HTSSE-I, the program did conclusively demonstrate that viable and robust HTS microwave devices could be fabricated, packaged and space-qualified. - Note: The HTSSE project started at NRL in December 1988 as a long-term joint venture with other labs/industry [which in turn started CSE (Consortium on Superconducting Electronics) in 1989].

- Another HTS demonstration, namely SUPEX (Superconductivity Experiment), based on thin-film technology is flown on TechSat/Gurwin-II (launch July 10, 1998), a satellite built by the Haifa-based Technion Israel Institute of Technology. N.29

- A magnetometer based on SQUID (Superconducting Quantum Interference Device) technology is flown on Gravity Probe-B (launch April 20, 2004).

- SMILES (Superconducting Submillimeter-wave Limb Emission Sounder) of JAXA/CRL is planned to fly on ISS/JEM in 2006. The superconductive technique enables 3-D global observation of trace gases in the stratosphere in the frequency band of 640 GHz. A heterodyne receiver detects very low level signals in the submillimeter-wave band radiated from trace gases using a sensitive SIS (Superconductor-Insulator-Superconductor) mixer method to perform high-resolution spectral analysis.

- A European consortium led by SRON (Groningen, The Netherlands), is designing HIFI (Heterodyne Instrument for Far Infrared), to be flown on ESA's HSO (Herschel/Planck Space Observatory, launch 2009). HIFI takes very high-resolution spectra of astronomical objects in thousands of frequencies simultaneously. HIFI features a large telescope (> 3 m diameter), a large dewar for liquid Helium, and SIS mixers covering the frequency range of 500-1200 GHz continuously, and possibly a Hot Electron Bolometer (HEB) mixer operating at about 1.8 THz.

- SRON is also developing the ESA instrument PIRAMHYD (Passive InfraRed Atmospheric Measurements of HYDroxyl) which features an HTS transition edge bolometer to measure the signal from a spectrally isolated emission line of the OH molecule in the far infrared spectrum of wavelength 84.420 \(\mu\)m.

1.2.8.16 Observations in the FIR (Far Infrared) region, FIR detectors

The FIR region of the EMS (Electromagnetic Spectrum) is generally considered from about 30 \(\mu\)m to 1000 \(\mu\)m (equivalent to 10 - 0.3 THz in the frequency spectrum), covering by far the largest portion of the optical spectrum.\(^\text{664}\) FIR radiation exhibits rather low energy levels (much lower than UV, VIS, VNIR) corresponding to photon energies from 35 to 1 meV. FIR observations require detector cooling to liquid helium temperatures (<4 K) in order to eliminate thermal noise interference (i.e. self-emission) of the observing instru-

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\(^{664}\) Note: The FIR region is also referred to as the “sub-millimeter” region
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The FIR spectrum is of particular interest in such fields as astronomy [most galaxies are found to emit strongly in the infrared; the interstellar medium (background radiation) emits energy mostly in the FIR and microwave spectral regions; approximately one half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the FIR region], biomedical imaging, mineral detection, and Earth observation. The general topic of infrared radiation and detection is covered in O.4.3.

In general, FIR radiation (downwelling and upwelling) is being absorbed by the atmosphere, in particular by the water vapor of the Earth’s lower atmosphere (troposphere). It turns out that the spectral range between 30-300 μm is almost completely obscured by the troposphere. This makes ground-based observations in FIR simply obsolete. Early efforts in infrared astronomy included mountain-top observatories; however, with little success (Earth itself as heat source represents already a great noise problem). Hence, airborne (instruments in high-flying aircraft) or spaceborne solutions must be sought to observe in FIR.

Until the early 1980s FIR detectors have been limited to single pixels. Then, for the first infrared satellites, small manually assembled mosaics of individual photoconductor crystals have been developed. At the start of the 21st century, there is a great need for large-format FIR detector arrays. Some examples in airborne and spaceborne infrared astronomy and some EO projects are:

- A 5 x 5 element detector array of stressed and unstressed GeGa and arrays of up to 60 bolometers, cooled to liquid helium temperature (4 K), were employed onboard KAO (Kuiper Airborne Observatory), flown and operated on a modified Lockheed C-141A aircraft of NASA/ARC. It’s main payload was an infrared telescope (1 m aperture Cassegrain reflecting mirror design) for astronomy observations. KAO was flown in the time period 1974-1995 at cruising altitudes of 12 km and higher (i.e., above 85% of the Earth’s atmosphere and more than 99% of the Earth’s water vapor). KAO opened the MIR (Mid-Infrared) and FIR (Far Infrared) window to the universe.

- IRAS (InfraRed Astronomical Satellite) was an international cooperative astronomy mission of the USA (NASA), the Netherlands (NIVR), and the UK (SERC); launch of IRAS on Jan. 25, 1983 (the mission lasted for 10 months because the coolant was depleted). The IRAS mission conducted an all-sky infrared survey in the spectral range of 8-120 μm in four broadband photometric channels centered at 12, 25, 60, and 100 μm. IRAS used an infrared detector of 62 photoconductors (individually wired pixels) of the FPA, and 3 x 3 elements of Ge:Ga (40 to 110 μm).

- ISOPHOT (ISO Photo-Polarimeter) was flown on ISO (Infrared Space Observatory), an ESA space science mission (4 instruments) with a launch Nov. 19, 1995, S/C operation until May, 16, 1998 (no more coolant available). ISOPHOT infrared observations employed three single pixel detectors (Si:Ga, Si:B and Ge:Ga) covering the spectral range of 3.3-120 μm, with two FIR photometric cameras working between 60 and 240 μm (3 x 3 elements of Ge:Ga, and 2 x 2 elements of stressed Ge:Ga), and a spectrometer (two 64 element linear Si:Ga arrays, 2.5-5 μm and 6-12 μm). However, ISOPHOT observations with a grating spectrometer were not able to resolve all the spectra.

- A new generation of large-format FIR detector arrays were developed for the SIRTF (Space Infrared Telescope Facility) mission of NASA/JPL (launch Aug. 25, 2003). On Dec. 18, 2003, NASA renamed SIRTF to “Spitzer Space Telescope” to honor the late astrophysicist Lyman Spitzer Jr. (1914-1997) for outstanding accomplishments during his lifetime (as early as 1946, Spitzer proposed to place an observatory into space where it would be able to detect a wide range of wavelengths and not have to deal with the blurring effects of our atmosphere). The objectives of SIRTF are mostly in astronomy/space science, but it also of-

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fers the capability to explore and characterize aspects of the solar system. The SIRTF payload consists of a telescope (0.85 m aperture) and three cryogenically-cooled science instruments which perform imaging and spectroscopy in the 3-180 μm spectral range. MIPS (Multiband Imaging Photometer for SIRTF) is one of the three instruments providing FIR imaging with photometry and total power measurement in broad spectral bands centered at 24, 70, and 160 μm, and low-resolution spectroscopy between 50 and 95 μm. - A MIC (Multiple Instrument Chamber), cooled to < 5 K, contains the cold detectors of the three science instruments as well as the cold parts of the telescope. SIRTF employs also a lightweight optics technology (beryllium mirrors), resulting in a total telescope mass of < 50 kg. The spacecraft is shielded with a solar panel facing the sun, leaving the rest of the spacecraft facing cold space.  

- SIRTF (launch mass of 950 kg) was deployed into an Earth-trailing heliocentric orbit (drift rate of about 0.1 AU/year), providing a deep space ambient temperature environment of about 30-40 K (a cryogen-conserving orbit). Naturally, this configuration helps greatly in passively cooling the payload of the spacecraft. SIRTF is the first spacecraft employing the innovative “warm-launch” cryogenic architecture - made possible by the choice of the orbit. The term “warm launch” refers to the fact that the spacecraft was launched at room temperature, and then using the coolness of space to reach a low-temperature equilibrium after a certain period. The 360 liter tank of liquid helium is expected to provide a mission life of five years for active instrument cooling services.

- IRAC (Infrared Array Camera) is a four-channel camera that provides simultaneous 5.12 x 5.12 arcmin images at 3.6, 4.5, 5.8, and 8 μm. Each of the four detector arrays in the camera are 256 x 256 pixels in size. IRAC uses two sets of detector arrays. The two infrared channels of 5.8 and 8 μm are imaged by composite detectors made from indium and antimony (InSb). The 3.6 and 4.5 μm channels use silicon detectors that have been specially treated with arsenic.

- IRS (Infrared Spectrograph) provides both high- and low-resolution spectroscopy at midwave-infrared wavelengths (MWIR). There are four modules covering the various spectral ranges, each with a detector array of 128 x 128 pixels.
  - 5.3 - 14 μm for low-resolution imagery
  - 10 - 19.5 μm
  - 14 - 40 μm
  - 19 - 37 μm for high-resolution imagery

The shorter-wavelength silicon detectors are treated with arsenic; the longer-wavelength silicon detectors are treated with antimony.

- MIPS (Multiband Imaging Photometer for SIRTF). MIPS has three detector arrays. A 128 x 128 array for imaging at 24 μm is composed of silicon, specially treated with arsenic. A 32 x 32 element hybrid array for imaging at 70 μm, and a 2 x 20 array for imaging at 160 μm, both use germanium, treated with gallium (Ge:Ga). The 32 x 32 array consists of 8 bars of 4 x 32 elements arranged in a stacked format; it takes also spectra from 50 - 100 μm. The FOV (Field of View) varies from about 5 x 5 arcmin at the shortest wavelength to about 0.5 x 5 arcmin at the longest wavelength.

- SOFIA (Stratospheric Observatory for Infrared Astronomy) is a next-generation cooperative NASA and DLR (German Aerospace Center) airborne astronomy observatory (after KAO), using a modified Boeing 747-SP aircraft platform. The overall objective is to provide a long-term (20 years) high-resolution observation platform/capability in the infrared spectrum, in particular in FIR. First flights of SOFIA are expected to begin in 2006. DLR is providing the SOFIA telescope [Cassegrain design, 2.7 m parabolic primary mirror with 2.5 m effective aperture (lightweighted Zerodur structure) and a hyperbolic secondary mirror, FOV=8 arcmin; total instrument mass of 20,000 kg].  

667) http://sirtf.caltech.edu/about/techdev.shtml
668) http://sofia--mirror.dlr.de/Sofia/sofia.html
tral optical range of 0.3 \( \mu m \) to 1,600 \( \mu m \) (diffraction limited wavelengths \( \geq 15 \mu m \)) covering the entire optical range (0.3-1000 \( \mu m \)) + a portion in the mm-wave range. A spatial resolution of 1-3 arcsec for \( \lambda < 15 \mu m \) and \( \lambda/10 \) arcsec for \( \lambda > 15 \mu m \) is provided. SOFIA serves also as a platform for detection technology experiments. Some FIR instruments of SOFIA are:

- **CASIMIR** (Caltech Submillimeter Interstellar Medium Investigations Receiver) of the California Institute of Technology, Pasadena, CA. CASIMIR is a FIR heterodyne instrument (0.5 - 2 THz or about 140-600 \( \mu m \)) to achieve very high spectral resolutions (\( v/\Delta v = 10^6 \)) and very high detection sensitivities using SIS (Superconductor-Insulator-Superconductor) tunnel junction and HEB (Hot Electron Bolometer) mixer receiver detection technology. The goal is to cover the frequency range in seven bands, SIS mixers in four bands up to 1.2 THz, and HEB mixers in three bands covering 1.2-2.1 THz.

- **FIFILS** (Field Imaging Far-Infrared Line Spectrometer) provided by MPE Garching. FIFILS observes in the spectral range of 40-220 \( \mu m \). The instrument consists of two medium resolution liquid helium cooled grating spectrometers with common fore-optics feeding two large GeGa detector arrays (16 x 25 pixels each). Capability of simultaneous observations of an object in two spectral bands (45-110 \( \mu m \) and 110-210 \( \mu m \)), respectively.

- **SAFIRE** (Submillimeter And Far InfraRed Experiment) of NASA/GSFC. SAFIRE is an imaging Fabry-Perot bolometer array spectrometer in the spectral range of 145-655 \( \mu m \) with a spectral resolving power ranging from 5 to \( 10^4 \). The instrument uses two 6 x 32 arrays of bolometers to provide background-limited performance for critical science applications. SAFIRE specifications identify “quantum-noise limited heterodyne spectrometers” as one of four critical detector technologies needed before the goals of the SAFIRE instrument may be realized.

- The JWST (James Webb Space Telescope) of NASA (launch 2013) plans on a FIR detector array mosaic of 4096 x 4096 pixels (with a goal of 8 k x 8 k mosaic), rivaling the largest CCD arrays in the visible spectrum.

In the field of Earth observation (EO), the FIR region represents one of the richest areas for spectroscopic research and one of the most difficult areas for obtaining data (emission measurements). The FIR region contains the rotational spectra of atoms and molecules and the vibrational spectra of solids, liquids, and gases. Water vapor is the principal greenhouse gas, absorbing a significant fraction of the upwelling radiation and providing much of the downwelling longwave flux that warms the Earth’s surface (i.e., the greenhouse effect). \(^{669}\) FIR spectroscopy (or THz spectroscopy with an active FIR laser system) may be used for a wide range of climate research studies such as Earth’s energy balance (radiation budget), and measurement of trace gases in the atmosphere (environmental monitoring). Despite their fundamental importance, *spectrally resolved FIR measurements in EO have virtually not been conducted so far*, mostly due to rather expensive detector technology and the high demands on cooling. See also chapter 1.7.2 for broadband measurements of Earth’s radiation budget and the solar constant.

Some early examples of EO FIR instruments are:

- **TAFTS** (Tropospheric Airborne Fourier Transform Spectrometer), built by ICSTM (Imperial College of Science and Technology & Medicine), London, and funded by NERC, UK. \(^{670}\) TAFTS is designed to address some scientific problems connected with global warming; the objective is to provide well calibrated, high resolution radiance spectra for

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\(^{669}\) Note: Emissivity is an intrinsic property of a material, independent of sample temperature, spectrometer characteristics, and environmental conditions. It is defined as the ratio of the emittance of a sample relative to that of a blackbody at the same temperature.

\(^{670}\) http://www.sp.ph.ic.ac.uk/~jon/Tafts/

both up-welling and down-welling radiation in the upper troposphere/lower stratosphere (study of the impact of water vapor in the radiative transfer process). TAFTS is a Martin-Puplett-type FTS providing in-situ measurements in the upper troposphere in the spectral range 14-120 μm with a spectral resolution of 0.1 cm⁻¹. TAFTS was first flown in Sept. 1999, and participated in the airborne campaign EMERALD-2 (Egrett Microphysics Experiment with Radiation, Lidar and Dynamics), in Nov.-Dec. 2002. The objective was the study cirrus clouds that form as a direct result of deep convection. The detectors used by TAFTS were two pairs of photoconductors cooled to 4 K: (a) silicon BIB (Blocked Impurity Band), and (b) Ge Ga detectors.

- MLS (Microwave Limb Sounder) instrument flown on NASA’s Aura mission (launch July 15, 2004). MLS measures, among many other atmospheric constituents, also the concentration and distribution the hydroxyl radical (OH⁻) in the stratosphere, a critical component in the ozone cycle. MLS employs a 2.5 THz laser system (84 μm) to sense the hydroxyl. The CW laser source employed is of the type OPTL (Optically Pumped Terahertz Laser) using the TDS (Time Domain Spectroscopy) measurement scheme which relies on a broadband short-pulse Terahertz source. ⁶⁷²)

- FIRST (Far Infrared Spectroscopy of the Troposphere) project of NASA within IIP (Instrument Incubator Program). ⁶⁷³) The design features a nadir-viewing Michelson FTS (of GIFTS heritage) in the spectral range 10-100 μm with a spectral resolution at 0.6 cm⁻¹ (unapodized), a FOV of 100 km x 100 km, and an IFOV of 10 km. The FIRST interferometer is being designed and built by SDL (Space Dynamics Laboratory) at USU (Utah State University), Logan, UT (in partnership with NASA/LaRC and SAO). An objective of FIRST is to take advantage of state-of-the-art technologies (bilayer beam splitters, pyroelectric detectors, and high throughput FTS) to reach the thermal noise limit at ambient temperature of about 180 K in a passively cooled space environment. A successful balloon-borne technology demonstration flight was conducted in June 2005 (33 km altitude, campaign site: New Mexico). Eventually, the FIRST instrument will be flown on a spaceborne mission. ⁶⁷⁴)

- REFIR (Radiation Explorer in the Far Infrared). REFIR is a FTS (Fourier Transform Spectrometer) as part of a proposed small satellite mission of ASI (Italy) in the field of climate and global change with the objective to measure the Earth’s FIR (100-1000 wavenumber, or 10-100 μm) spectral radiance (in- and outgoing) in the context of ERB (Earth Radiation Budget) estimation. ⁶⁷⁵)

1.2.8.17 Vegetation fluorescence in passive remote sensing

The ability to observe vegetation fluorescence remotely is of great importance to the science community, because such a capability could reveal unique information about the photosynthetic activity of vegetation. ⁶⁷⁶) Unlike conventional solar induced reflectance measurements which are affected by numerous surface and atmospheric processes, fluorescence represents an observable whose process originates within plant life itself and whose complex signal is emitted by the plant’s surface. The primary regulatory mechanism of natural vegetation fluorescence is considered to occur through photosynthesis. This direct link of photosynthesis to vegetation fluorescence can serve as the prime indicator and quantifier of biomass production (also role of fluorescence in bio-chemical cycles, surface-atmosphere interactions, CO₂ flux, etc.).

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⁶⁷⁵) http://www.ifac.cnr.it/refir.htm
In 2002, an ESA-funded feasibility study, FLEX (Fluorescence Explorer), investigated the measurement aspects and challenges of the weak fluorescence signal (detectability assessment). Under natural sunlight illumination, the amount of chlorophyll fluorescence emitted by vegetation represents a very small fraction of the reflected light in the visible part of the spectrum (less than 2% in most cases). However, at certain wavelengths where the solar spectrum is attenuated (Fraunhofer lines), the fluorescence signal can be quantified (detection in very narrow spectral bands). The fluorescence emission of a leaf as derived from laboratory measurements exhibits peaks at 440, 520, 690 and 740 nm. Chlorophyll pigments exhibit red fluorescence, with a maximum at 690 and 740 nm. In addition to chlorophyll fluorescence emission, the ultraviolet part of the solar spectrum also excites a blue-green fluorescence (BGF) of plants. However, BGF is not directly linked to chlorophyll or to photosynthesis. The study also addressed the need for an integrated canopy fluorescence model (from leaf to canopy) and possible interpretation methods of the signal.

In addition, an ESA field campaign SIFLEX (Solar Induced Fluorescence Experiment) was conducted (June-July 2002) in northern Finland [tower measurements of boreal pine canopy fluorescence at different scales (needle, shoot and crown)]. For the first time, it was possible to observe the chlorophyll fluorescence signal in the natural environment over extended periods of time (passive observation methods). As a result, more realistic simulations can be made of the performance requirements of future spaceborne instruments. The results of the campaign indicate that in principle the chlorophyll fluorescence signal is detectable by a spaceborne instrument, even under low-light conditions (corrections for atmospheric effects arising from molecular and aerosol scattering may be needed, modeling of atmospheric oxygen absorption). The ability of photosynthetic activity monitoring should significantly improve estimates on CO₂ (carbon dioxide) uptake and provide a means for screening and monitoring vegetation vigor over large regions.

An important result of the various ESA study engagements is the recognition that natural fluorescence is now identified as a necessary specific observable complementary to conventional observations in the framework of land surface processes missions that must be included in the overall observation strategy.

Background: Proposals to measure plant fluorescence were already voiced in 1975 when the required detection technology (sensitivity) was not available. Of the passive fluorescence measurement techniques, there are three basic vegetation photosynthetic activity indicators:
- Oxygen absorption technique with spectral lines at 687 and at 760 nm
- PRI (Photochemical Reflectance Index) technique by using reflectances at 531 and at 570 nm
- Derivative technique of high spectral resolution reflectance in the red-edge band (680-750 nm)

So far, no operational system has been developed for remote sensing of fluorescence. Some examples of demonstration instruments or measurement concepts are:

679) Note: While active fluorescence methods (lidars) have greatly benefited from progress in optoelectronics and laser sources, they are not considered suitable for large-scale and long-range applications in remote sensing.
680) Note: In this context “uptake” refers to the ocean’s ability to take up a large fraction of the perturbation CO₂ entering the atmosphere by human activity.
- An early airborne instrument implementation was FLI (Fluorescence Line Imager), a hyperspectral sensor developed by Moniteq Ltd and Itres Ltd for the Canadian Department of Fisheries and Oceans. It was first flown in 1984, using pushbroom technology and 288 spectral bands.

- The spaceborne ocean color instruments provide already the capability of monitoring the chlorophyll and gelbstoff concentrations in the surface layer of the ocean to estimate the phytoplankton production. The spectral band set of MERIS (Medium-Resolution Imaging Spectrometer for Passive Atmospheric Sounding) on Envisat (launch March 1, 2002) already includes a band around 681.25 nm optimized for the retrieval of water chlorophyll fluorescence. However, fluorescence emission from land vegetation chlorophyll cannot be detected in the same way as for water chlorophyll, because over land the background reflectance dominates the signal, and fluorescence spectral features are masked by the dominant reflectance signatures. Another method that has been demonstrated successfully in retrieving vegetation fluorescence over land is by using the atmospheric oxygen absorption band around 760 nm, in particular with two MERIS bands at 753 nm (oxygen absorption reference) and at 760 nm (oxygen absorption R-branch). The measurements in these two bands allow to get land vegetation fluorescence provided some assumptions (same reflectance and fluorescence emission in the two spectral bands), and provided also a proper atmospheric correction of the data, or using in-scene non-fluorescent targets as reference.

- A FLEX (Fluorescence Explorer) spaceborne mission was proposed to ESA in Dec. 1998 (by a European consortium of institutions) with the objective to explore the possible use of the Fraunhofer lines in the spectrum for passive measurements of natural sunlight-induced fluorescence.

- The PMFD (Passive Multi-wavelength Fluorescence Detector) instrument was developed at LURE/CNRS, University of Paris, France. Objective: continuous measurement of chlorophyll fluorescence based on the Fraunhofer line principle, applied in the atmospheric oxygen absorption A and B bands (760 and 687 nm, respectively). PMFD and a spectroradiometer (ASD FR/FS for the upwelling radiance measurements in the range 350 - 2500 nm) were used in the ESA SIFLEX (Solar Induced Fluorescence Experiment) campaign in 2002. For the duration of the campaign, the vegetation passed from a dormant state, with very low activity, to a fully active state.

- The hyperspectral instrument CASI (Compact Airborne Spectrographic Imager) of Itres Ltd., Canada, is capable of acquiring imagery of vegetation for fluorescence retrieval. The instrument has been used in various campaigns.

- AIRFLEX (Airborne Fluorescence Experiment) campaign of ESA. The objective is to measure the fluorescence signal from an airborne platform over a variety of land cover types (information about the fluorescence signal sensitivity, spatial variability and scaling effects, fluorescence dependence on solar irradiance). The campaign will be carried out in Barrax, Spain in June 2004.

1.2.8.18 Sparse aperture imaging concepts

The requirements for high-resolution observation data, along with the constraints of minimum mass/volume (launch phase), and maximum aperture telescope/antenna size of spaceborne instruments, have eventually lead to such design concepts as “sparse aperture telescope” for optical systems and “sparse aperture array” for microwave antennas/receivers.\(^{689}\) Such systems provide improved observation capabilities in the following fields: optical imaging (visible and infrared region), radiometric sounding/imaging (visible to microwave region), and communication applications.

A sparse aperture system refers to a non-filled aperture configuration, with holes or gaps in between the individual elements (subapertures) of the system to obtain a large aperture - and to reduce mass. Conceptually, any sparse aperture is a distributed system of various cooperating elements (an array of receiving dipoles), arranged in a definite (symmetric) pattern or configuration, forming in effect a multi-aperture interferometer system. Generally, the sparse aperture concept is applicable to all wavelengths of the spectrum as well as to all concepts of interferometry, starting with a two-element interferometer (Fizeau, Michelson, etc.), a multi-aperture interferometer system, up to the highest-resolution VLBI (Very Long Baseline Interferometry) and SVLBI (Space VLBI) techniques.

Sparse-aperture interferometry concepts are currently being used (or are being planned) in remote sensing and in astronomy applications, in the spectral domains of optical interferometry and in microwave interferometry with radio/radiometry (passive) and radar (active) applications. The distinctions of optical vs microwave are primarily due to the physics involved at the different wavelength regimes (visible wavelengths result in a 10,000-fold improved spatial resolution over that available in the microwave regime).\(^{690}\)

- Optical interferometers (Michelson, etc.) employ direct detection - in which the two beams are combined using a beam-splitter with the resulting fringe sampled by a single detector. This approach results in a system whose accuracy is properly limited by the source shot noise and detector noise as opposed to the shot noise of some optical local oscillator.

- Radio and radar interferometers operate by independently detecting signals from two antennas and combining them a posteriori for indirect fringe generation. This method involves heterodyne receivers which experience shot noise from their local oscillators - about 1 photon per Hz of bandwidth. While this is acceptable at microwave wavelengths, the local shot noise grows with frequency such that it dominates the source shot noise and detector noise at visible and IR wavelengths (0.4 to 30 µm).

The sparse aperture observation concept is based on “aperture synthesis,” an interferometric technique which recombines the radiation (interference fringes) of the various subapertures - thus achieving higher resolutions. Fourier synthesis techniques play a key role in aperture synthesis analysis [the brightness distribution of the incoming target (or object) radiation is actually the Fourier Transform of the set of phase and amplitude measurements from the interferometer]. The high angular resolution of radio telescopes (in astronomy) is achieved by synthesizing a very large effective aperture from a number of small subapertures. In a simple two-element radio interferometer, the signals from an unresolved, or “point” source alternately arrive in-phase and out-of-phase as the Earth rotates and causes a change in the difference in path from the radio source to the two elements of the interferometer. - An important advantage of the aperture synthesis concept is the provision of diffraction-limited observations. A disadvantage is the reduced MTF (Modulation Transfer Function) level causing significant blurring and loss of contrast in the collected imagery.

\(^{689}\) Note: The angular resolution of an aperture (telescope or antenna) is primarily determined by the overall diameter of the aperture. The angular resolution is proportional to the diameter of the aperture and inversely proportional to the observing wavelength. The sensitivity of an aperture is determined by both the area of its aperture, and the sensitivity of the sensor.

However, image reconstruction algorithms can correct the blurring completely with a sufficiently high SNR (Signal-to-Noise) ratio.

Obviously, a distributed system can be thought of:

- As a coupled system (a monolithic structure, where all discrete elements maintain a fixed arrangement to each other) on a single spacecraft. The distances between the various subapertures represent short baselines. A telescope incorporating a sparse-aperture mirror can be folded in a compact fashion to make a small and lightweight payload, which can be placed into orbit by a relatively inexpensive launch vehicle.

- A loosely-coupled system such as a close spacecraft formation (each spacecraft with a single aperture). This arrangement permits larger sparse apertures, providing larger but only relatively stable baselines.

- Radiometry: A sparse array in the microwave region uses an array of receivers (as discrete elements) that span the imaging aperture. Typically the array is two-dimensional (Y shaped) and does not have optically focusing elements in front of the receivers. The receivers are said to be in the “pupil plane.” To form an image the detectors must record both amplitude and phase of the incoming radiation wave front. The image is formed in the electronics (typically in software) by taking spatial Fourier Transforms across the two axis of the array. A complete image can be formed as long as all of the spatial Fourier components are collected. The sparseness of the array reduces the amount of the collected radiation and reduces the SNR by the ratio of the area of the receivers to the area of the complete aperture. In a conventional sparse array the FOV is fixed and fairly large to avoid having to physically steer the entire array to view different objects of interest. The FOV of the array is determined by the antenna pattern of the individual receivers in the array.

Background: While the invention of interferometry dates back to the 19th century [Fizeau (first proposal in 1868), Michelson (first measurements in 1890), etc.], it was in the late 1940s when Australian radio astronomers realized that each interferometer pair measurement was in effect one “Fourier component” of the brightness distribution of the radio source. Further developments during the 1950s by Martin Ryle and his colleagues at Cambridge University, Cambridge, UK, involved initially the use of movable-element interferometers in the laboratory and the realization that Earth rotation provided already relative motion (of elements A and B as seen from the source), required for the sampling of interferometry observations. All experimentation was done in the microwave region of the spectrum (at wavelengths of 1 m and more) to minimize the alignment problems of instrumentation. The lack of available computer power at the time was the greatest handicap for handling the great amount of Fourier transformations. Nevertheless, radio astronomy observations began in 1964 on the “One Mile Array” at Cambridge, a microwave sparse aperture system consisting of three 18 m dishes in a line 1 mile long array. - The world’s first optical aperture synthesis telescope, COAST (Cambridge Optical Aperture Synthesis Telescope), was build in 1988 (VIS, NIR). The configuration of COAST consists of five apertures (40 cm diameter) arranged in a ‘Y’ configuration, with a maximum element separation of about 22 m. In 1974, Martin Ryle and Anthony Hewish received the Nobel Prize in Physics in recognition of their contributions to the development of the Fourier synthesis technique, also as aperture synthesis.

As of 2003, the radioastronomy community is developing concepts to build a radiotelescope with a sensitivity two orders of magnitude larger than present-day telescopes. The ground-based project is called SKA (Square Kilometer Array), referring to a sparse aperture synthesis telescope design with a receiving area > 1 km², and distributed over an area 50 to 300 km in diameter. The sparse array at each participating site would have a diameter of about

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692) http://www.cristalinks.com/telescopes4.html
300 m in order to achieve the required collecting area.

SKA is an international project and a collaboration of various institutions of the following countries: Australia, Brazil, Canada, China, France, Germany, India, Italy, The Netherlands, New Zealand, Poland, Russia, South Africa, Sweden, United Kingdom and the United States. — As of Jan. 2006, European funding (Framework 6 R&D program of the European Commission) was secured to support a 4—year SKADS (Square Kilometer Array Design Study). By the end of this decade, the design will be complete and astronomers anticipate building SKA in stages, leading to completion and full operation in 2020. 693) 694) 695)

Some examples of early sparse-aperture implementations or projects in the field of Earth observation are:

- ESTAR (Electronically Steered Thinned Array Radiometer) a passive airborne instrument developed by NASA/GSFC and the Microwave Remote Sensing Laboratory of the University of Massachusetts at Amherst (P.87). 696)
- SMOS (Soil Moisture and Ocean Salinity Mission) of ESA (launch 2007, see D.44) will demonstrate spaceborne synthetic aperture imaging radiometry with MIRAS (Microwave Imaging Radiometer using Aperture Synthesis), a Y-shaped sparse array or a “synthetic aperture radiometer.” 697)
- STAR (Synthetic Thinned Aperture Radiometry) is a microwave sounder/imager under development at NASA. The objective is to achieve a 10 km spatial resolution global soil moisture mission towards the end of the decade (LEO mission).

  **Conceptually, each SAR instrument is by definition an aperture synthesis device.** The resolution is limited by the synthetic aperture length, and so is the effective received power. Of course, a SAR instrument’s antenna is “real.”

- The ARGOS (Adaptive Reconnaissance Golay-3 Optical Satellite) project of MIT, a ground-based testbed, exploits wide-angle Fizeau interferometer technology with an emphasis on modularity in the optics and spacecraft subsystems. The objective of the ARGOS project is to demonstrate the practicality of a modular architecture for spaceborne optical systems. 698)

1.2.8.19 Astronaut-acquired photography

The space age has also provided a wealth of spaceborne photography acquired by hand-held cameras of manned missions. An online database of over 450,000 astronaut photos of Earth, dating back to the early 1960s, is maintained by NASA/JSC. This archive covers the majority of the Earth’s surface and offers imagery taken by a variety of camera configurations, including film (analog) and digital imagery, various lenses, different look angles, and changing solar illuminance. 699) 700)

Background: In the US space program, the Mercury project was the first attempt at launching a human being into space. It consisted of six manned flights in the period 1961 to 1963. Astronaut John Glenn, on the first US orbital manned flight (Feb. 20, 1962) in history, was using a conventional camera. Those amateur photographs turned out to be the first Earth

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693) http://www.astron.nl/ska/technical/
695) http://www.pparc.ac.uk/Nw/SKA.asp
700) http://eol.jsc.nasa.gov/sseop/clickmap/
observation photographs taken by an astronaut in history. Note: Some additional instrument descriptions of Shuttle EO Imaging Cameras is provided in chapter J.26.

- In subsequent Mercury flights, first experiments were conducted in hand-held photography, recording properties of Earth’s limb, observing the Earth illumination at night, and use of filters to acquire weather photographs. At about the same time, the first TIROS (Television InfraRed Observation Satellite) series meteorological satellites of NASA (unmanned spacecraft, launch of TIROS-1 on Apr. 1, 1960) were making their first attempts of gathering weather information with such instruments as TV-WA (Television Wide Angle), TV-NA (Television Narrow Angle), and a Scanning Radiometer, a five-channel instrument which measured the emitted and reflected radiation of the Earth and its atmosphere.

- The US Gemini program consisted of 12 manned (plus 2 unmanned) missions in the timeframe March 1965- Nov. 1966. Most of the hand-held photography was organized through two science experiments, a) synoptic terrain photography and b) synoptic weather photography. 701) The objective of the first experiment was to obtain high-quality pictures of significant land areas that had been previously well mapped by aerial photography and to serve as a standard for interpretation of photographs of unknown areas of Earth, the Moon, and other planets. For synoptic terrain photography, a modified Hasselblad camera was used with a mass of 0.45 kg, model 500 C (70 mm camera with black and white film and a special filter mosaic to allow each picture to be taken partly through a red and partly through a blue filter).

- The KATE-140 (Multispectral Camera) is an example of a prominent cosmonaut-operated camera system of the Soviet space program. The objectives were the provision of topographic imagery of the Earth’s surface. KATE-140 employed an objective lens with a focal length of 140 mm. The frame format of 18 cm x 18 cm could acquire photographs in the spectral range 500-700 nm (three bands) with a footprint of about 440 km x 440 km (resolution of about 50 m) from an orbital altitude of about 350 km. KATE was mostly being used as a stationary camera, porthole fixed. A further development was the KATE-200 camera with a focal length of 200 mm. The KATE model used frame film cassettes of 600 images. KATE-140 was flown on Salyut-4 (Dec. 26 1974 to Feb. 2, 1977), Salyut-6 (launch Sept. 29, 1977, crew occupation for a total of 676 days, reentry July 28, 1982) and Salyut-7 (launch Apr. 19, 1982 crew occupation for a total of 812 days, reentry 1989). 702) KATE-140 was also flown on the following manned missions: Soyuz-T-9 (launch June 27, 1983), Progress-18 (launch Oct. 20, 1983), Soyuz-T-10B (launch Feb. 8, 1984), Soyuz-T-11 (launch Apr. 3, 1984), Progress-22 (launch May, 28, 1984), Kosmos-1669 (launch July 19, 1985), and on the MIR station from 1987 onwards. 703)

- ESTER (Earth Science Toward Exploration Research). ESTER is a digital handheld camera of NASA/JSC. ESTER features a 400 mm lens (and a 160 mm and a 50 mm lens). The objective is to use ESTER onboard ISS to document global phenomena (significant events like hurricanes, plankton blooms, and volcano eruptions) in both an automated and hand-held mode in combination with WORF (Window Observational Research Facility). Since delivery of the WORF has been postponed (until 2008), ESTER is using EarthKAM hardware, an educational payload of ISS, mounted in the Destiny Laboratory. 704)

At the start of the 21st century, astronaut-acquired photography is still considered valuable complementary data to remote sensing data, in particular with regard to unexpected or unplanned event monitoring applications.

703) http://home.comcast.net/~rusaerog/aosmsf/ch5.html
704) http://spaceresearch.nasa.gov/research_projects/ros/esterop.html
1.3 Fundamental Science Limits in Space Flight and Earth Observation

All system design is subject to the fundamental limits imposed by the laws of physics, especially those formulated by Kepler, Newton, Maxwell, Airy, Nyquist and Planck.  

Background: Prior to their time, the Polish astronomer Nicolas Copernicus (1473-1543 - the name was latinized from Niclas Kopernik) hypothesized his radical new view of a heliocentric system, based on extensive observations. In 1530, Copernicus finished his theory “De Revolutionibus Orbium Coelestium” (on the Revolutions of the Celestial Bodies, the book was published in Nuremberg, Germany, in 1543), which asserted that the Earth rotated on its axis once daily and traveled around the sun once yearly. Up to the time of Copernicus, the thinkers of the western world believed in the cosmology of Aristotle and Ptolemy (Claudius Ptolemy of Alexandria, Egypt, about 150 BC) that the universe was an Earth-centered closed space bounded by spherical envelopes carrying the planets and fixed stars. Copernicus is considered the founder of the modern “Weltanschauung” (world view).

1) Kepler’s laws of planetary motion (his first two laws were announced in 1609, the third law in 1619), after Johannes Kepler (1571-1630) a German astronomer, who discovered that the Earth and planets travel about the sun in elliptical orbits. Kepler’s laws, based on extraordinarily accurate observations of the 16th century Danish astronomer Tycho Brahe (1546-1601), describe the motion of a body subject to gravitational forces - and thus describe a satellite in orbit about Earth, the sun or the moon. Kepler’s deduction of the three fundamental planetary laws (which he solved geometrically) were key elements that later enabled Isaac Newton to formulate his theory of gravitational force.

- Kepler’s 1st law: A planet orbits the sun in an ellipse with the sun at one focus
- Kepler’s 2nd law: A ray directed from the sun to a planet sweeps out equal areas in equal times
- Kepler’s 3rd law: The square of the period of a planet’s orbit is proportional to the cube of that planet’s semimajor axis; the constant of proportionality is the same for all planets.

For a satellite in Earth orbit, the time required to complete one revolution is determined primarily by its mean radial distance. LEO spacecraft with typical altitudes of 700-800 km require about 100 minutes for one orbit. Many Earth observation missions require global coverage (see also chapters 1.9 and O.10.1). The laws of orbital mechanics, in combination with the daily Earth rotation, demand a space-time trade-off: a shorter revisit interval implies less dense spatial coverage. Under such constraints, it may not be possible with only one spacecraft to achieve the simultaneity required for fine spatial coverage and short revisit intervals. In this case, a constellation may be the only solution.

2) Newton’s laws of motion (first published in the Principia in 1687), named after Isaac Newton (1642-1727), English physicist and mathematician. Newton’s three laws of motion (two of them were already discovered experimentally by Galileo Galilei) describe the response of a body to its own inertia and to forces applied from internal or external sources - relative to an inertial reference frame (Figure 18). Both sorts of forces impact all spacecraft. Examples of internally applied forces are:  
- S/C pointing by the attitude control subsystem. Observation requirements might call for a particular orientation of the S/C along its orbital path.


706) Kepler is considered a founder of modern astronomy, he formulated the famous three laws of planetary motion. They comprise a quantitative formulation of Copernicus’s theory (1530) that the planets revolve around the sun.

707) Kepler’s laws of planetary motion were first published in 1619 in his: “Harmonices Mundi Libri V,” Lincium Austriae, 1619 (Five books on the Harmony of the World)

- In addition to S/C pointing, there may be a requirement for subsystem pointing. This is for instance the case when the solar panels are rotated to keep them facing into the sun for maximum power generation.

  In general, instruments that must provide very fine angular resolution require in turn that their host S/C satisfy very stringent angular stability requirements. The unwanted reactive movements generated by these subsystems are in turn offset by reaction wheels or torque rods. - Examples of externally generated forces are:

- All S/C must be launched from Earth. Newton’s laws and the characteristics of the available propulsion system impose strict limits on the payload mass that can be lofted into Earth orbit or beyond. These limits are expressed in Newton’s second law of motion.

- The solar radiation pressure (a surface force) changes the S/C orbit over long periods of time, depending on S/C mass. The drag in LEO orbits is also a surface force. Both, radiation pressure and drag, represent non-gravitational orbit perturbations.

Newton introduced his three laws of motion in book I of his Principia (1687):

1) Every body continues in its state of rest, or of uniform motion in a right (straight) line, unless it is compelled to change that state by forces impressed upon it.

2) The change of motion is proportional to the motive force impressed and is made in the direction of the right line in which that force is impressed.

3) The every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal and directed to contrary parts.

Figure 18: Newton’s three laws of motion

- Orbital maneuvers. A S/C propulsion subsystem might change the orbital altitude.

4) Maxwell equations (publication of Treatise on Electricity and Magnetism in 1873), named after James Clerk Maxwell (1831-1879) a Scottish physicist. Maxwell’s equations describe the behavior of the electromagnetic waves as they propagate in space. Portions of the electromagnetic spectrum are used by all space missions. Observation instruments as well as the communication subsystems for the transfer of data through space must be designed within the constraints of the Maxwell equations. The first and most obvious constraint is that radio waves travel at the speed of light (c, the speed of light in vacuum, is 299,792,458 m/s). Even at this speed, light travel time imposes substantial delays on all communication between Earth and satellites. This is already quite noticeable for two-way GEO communications, it is in particular apparent for deep-space probes. A further consequence of the Maxwell equations is that all radiation gets weaker in proportion to the square of the distance between the radiation source and the observer. Hence, very distant radiation sources become very faint and therefore require much larger viewing apertures. The system design takes the signal weakening into account through the link budget of the communication system (with corresponding antenna designs and sizes). - The same physical principles as discussed above apply of course also to a satellite’s electrical power generating capability.

5) Airy diffraction (ca. 1835), named after George Biddell Airy (1801-1892), a British Astronomer Royal from 1835 to 1881. The problem: Observed imagery can never be perfect in the geometrical sense. It is either degraded by geometrical aberrations, which are a function of the lens parameters, and/or by diffraction, which is a physical optics effect. The diffrac-

709) Note: The “signal weakening” effect is due to the widening cross-sectional area of the light ray as it propagates through space - resulting of course in ever fewer photons per unit area of cross-section, hence, of measurable energy.
tion degradation is due to the wave nature of light.\footnote{Note: Early pioneers of the diffraction theory were such men as: Christian Huygens (1629-1695) of Holland, William Herschel (1738-1822) of England (born as Friedrich Wilhelm Herschel in Hannover, Germany), Thomas Young (1773-1829) of England, Joseph von Fraunhofer (1787-1826) of Germany, Dominique Arago (1786-1853) and Augustin Jean Fresnel (1788-1827) of France, and George B. Airy (1801-1892) of England.} Diffraction limits the resolution of a telescope to the size of the Airy disk. If the optics of a system is capable of producing an image that diameter or less then it is said to be \textit{diffraction limited}.

The Airy diffraction limit enforces a lower limit on the resolution (or beam width) of any device that radiates or receives electromagnetic energy. The principle applies of course also to all S/C imaging instruments (\textit{the resolution of an imaging system depends on the size of the collecting aperture}). The diffraction limit requires that the optical aperture diameter must be directly proportional to the satellite's distance from the observed surface. - The phenomenon of far-field diffraction of a light beam simply limits the distance at which a focused (resolved) image can still be taken. Due to its wave nature (delocalization), light can only be focused to a point as small as half its wavelength by traditional methods. The diffraction limit for an optical system (telescope) is defined as the sharpest possible point image obtainable by far-field beam divergence. According to Airy, the resolving power of a diffraction-limited telescope is solely dependent on its aperture.

As an illustration, the monolithic optics system on a spacecraft at GEO altitude (of about 36,000 km) must have an aperture 45 times larger than a similar instrument on a spacecraft at typical LEO altitudes (of about 800 km) to obtain the same surface resolution (example: an aperture diameter of 4 m in GEO is needed to obtain spatial resolutions of 30 m in VNIR and 300 m in FIR on Earth's surface). In addition, the GEO sensor's internal optical path length also has to grow in proportion to the aperture diameter if similar performance to the LEO instrument is to be obtained. As a consequence, instruments at GEO tend to be considerably larger than their LEO counterparts. - The launch costs of such a monolithic optics system would simply be prohibitive!

While observations from GEO offer great advantages/relationships of fixed-position, continuous-signal, continuous-coverage, and large-area coverage - the GEO missions remain rather challenging candidates for high-resolution Earth observation missions in the optical and microwave ranges due to the above mentioned diffraction limit constraints.

So far, the planned EO-3 minisatellite technology mission of NASA (launch 2008 ??, see M.11), with the optical instrument GIFTS (Geostationary Imaging Fourier Transform Spectrometer), represents the first attempt to achieve an excellent ground resolution from GEO of 1 km x 1 km in the visible range and 4 km x 4 km in the MWIR and TIR spectral regions, using an \textit{interferometric Michelson FTS optics system} of 24 cm in aperture diameter. The GIFTS observation technique conquers the adverse GEO viewing geometry by partitioning, i.e. by relatively fast accumulation of many small instantaneous target areas of about 500 km x 500 km (constant FOV of 0.81\(^\circ\) x 0.81\(^\circ\)) into large observation areas (step-and-stare scanning operation using a small mirror).

Note: Although interferometer-based FTS instruments exhibit very high spectral resolution over a broad spectral range, they tend to be large, expensive instruments (as compared for instance to a grating spectrometer architecture) with very demanding optomechanical requirements on precision and stability.

[Some remarks to the Airy diffraction limit: The defining ability of any optical imaging system is not merely a property of that system’s aperture, it is also governed by the Modulation Transfer Function (MTF), the ratio of the object contrast to the contrast of that object in the image plane. Thus, the MTF provides the response of an optical sensor as a function of object scene contrast and spatial frequency. MTF is also a measure of how accurately the actual radiance from a pixel (IFOV) is measured (a lower MTF indicates contributions from other pixels to the pixel of observation). The higher the MTF the greater the resolving power of that system. A radiometrically accurate IFOV is one for which MTF >0.95. Generally,
the MTF of a practical optical imaging system is much lower than 1. EIFOV (Effective Instantaneous Field of View) is defined as the resolution corresponding to a spatial frequency (ground resolution) for which the system MTF is 50%. Note: The value of MTF is not only reduced by the aberrations within the optical system, but also by the Earth’s atmosphere. Haze, turbulence and differential refraction will each contribute to a reduction in MTF, i.e. in the reduction of total telescope performance.

![Airy diffraction limit as a function of aperture diameter, GSD and altitude](image)

**Figure 19:** Airy diffraction limit as a function of aperture diameter, GSD and altitude

The physical diffraction limit on aperture size has deeper implications as well. The laws of physics dictate that the best (highest) angular resolution that any remote sensing system (telescope or antenna) can achieve (i.e. its diffraction limit) is proportional to \( \frac{\lambda}{D} \), where \( \lambda \) is the observing wavelength, and \( D \) is the telescope or antenna aperture diameter. The resolution with which the system can image the scene is therefore \( R \times \frac{\lambda}{D} \), where \( R \) is the range to the scene. For a satellite-based system in orbit around a planet, the range to the scene is at least a few hundred kilometers. – Hence, for any imaging device that sends or receives energy, the size of the aperture must be proportional to the wavelength it uses. The so-called optical spectrum extends from 0.01 \( \mu \)m to 1000 \( \mu \)m (or 1 mm), i.e., from the UV to the FIR region inclusively. The microwave region (radar) of the electromagnetic spectrum is generally considered from 1 mm to 1m wavelengths. In general, there are at least three orders of magnitude in wavelength between the optical and microwave instruments. Hence, the diffraction limit for active radar systems or passive microwave radiometers implies apertures in the order of a thousand times larger than their optical counterparts. For example, L-band radiometry (i.e. radiometry in the microwave region) faces the challenge of flying very large apertures to achieve a spatial resolution suitable for scientific applications.

To meet a given level of performance, an instrument’s minimum aperture size is dictated by wavelength and observable distance, it cannot be reduced by technology.\(^{711}\) Thus, even when a major SAR design goal is smallness, the SAR antenna size cannot be reduced to fit that objective. Any mission that relies on SAR to conduct science observations will continue to require a medium-sized or large S/C platform. - Future distributed (complex) apertures in

\(^{711}\) Note: An example to this challenge of distributed apertures is “two-dimensional aperture synthesis.” In microwave radiometry the concept employs an interferometric technique in which the product from antenna pairs is sampled as a function of pair spacing. Substantial reductions in the antenna aperture needed for a given spatial resolution can be achieved with this technique. However, the performance leap in resolution must be paid for with higher requirements for instrument precision sensing and stabilization.
special circumstances may to some extent circumvent this limit using the interferometric technique of aperture synthesis.

Enhanced imaging performance (finer angular resolution) can be obtained under favorable conditions. For example, a thinned array (also referred to as a sparse array or a sparse aperture consisting of many distributed but discrete subapertures) may substitute for a filled array if the viewing objective is relatively sparse. An optimal imaging concept of afocal interferometric telescopes, designed for sparsely filled arrays was first proposed by Marcel J. E. Golay in 1971 [Golay 1902-1989, a Swiss-born US information theorist (Golay codes, Golay cell, etc.); Golay used mask designs in which 3-fold symmetric spaces were searched for non-redundant array solutions]. The thinned array technique is a very promising technology to enable these very large (but lightweight) apertures in space (not requiring rotation to form an image). In this concept, the coherent product (correlation) of the signal from pairs of antennas is measured at different antenna-pair spacings (baselines). By correlating the signals received by many identical radiometer receivers each with a very small antenna (and therefore wide beamwidth), the interference pattern of the imaged scene can be measured. A key feature of a thinned array is that all the required baselines are obtained with fewer antennas than there are spacings. The angular resolution of such a thinned array, however, is governed by the Airy diffraction limit, and by the radiometric sensitivity of the array (proportional to the areas summed of all contributing subapertures). Spherical primary elements could also be used in the sparse aperture design with aberration correction by a deformable tertiary or quaternary mirror (Korsch three and four mirror aplanats).

Sparse aperture concepts (see 1.2.8.18): The use of a large aperture on a spaceborne instrument improves the remote sensing performance considerably, offering in particular increased sensitivities to sensor noise and higher spatial resolutions. This principle applies to passive as well as to active remote sensing instruments (for instance: telescopes or radiometer receivers for passive remote sensing in the optical and the microwave regions, and SAR antennas for active remote sensing in the microwave region). By their very nature, large conventional monolithic aperture structures are rather heavy (requiring stiffness and structural stability, and requiring large launch fairing diameters). These monolithic structures are expensive to build and to launch (the cost of monolithic optics increases faster than the aperture diameter squared).

The approach of “sparse aperture imaging,” on the other hand, offers a potential solution, providing the means for large distributed arrays of small (discrete) elements - at a much lower structure mass and a more compact packing volume for the launch phase. After deployment, such a distributed multi-element system (with baselines in between) represents in effect an interferometric measurement arrangement. A receiver of this type can produce images comparable to those generated by a filled aperture of the same diameter, provided that an average SNR on the order of 100 can be maintained over the entire image. Conceptually, the measurement arrangement of a sparse aperture remains the same, whether it is being applied to an aperture structure of discrete elements on a single spacecraft (with relatively small baselines), or to a close formation of several spacecraft with a single relatively small aperture to each spacecraft (and with relatively stable but considerably larger baselines).

Although the raw imagery produced by a sparse-aperture system will show significant distortions, near-diffraction-limited images can be recovered by using appropriate data processing techniques. The correction of point-spread-function distortions induced by sparse-aperture receivers is an example of an application for which Fourier deconvolution is particularly well suited.

6) Nyquist frequency (1929), after Harry Nyquist, a US physicist of Swedish descent and a pioneer in the field of communication theory (1889-1976). - The Nyquist frequency dictates

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713) Advanced Interferometric Space Telescope (AIST), URL: http://optics.nasa.gov/concept/aist.html
the minimum number of samples per second, required to transport a given amount of data over a communication channel of certain bandwidth (analog-to-digital conversion begins with sampling, or measuring the amplitude of the analog waveform at equally spaced discrete instants of time). The sample frequency is also determined by how often a point on the surface must be sampled to resolve the variations in the physical processes over time. In general, more information implies more detail but also more data. If those data have to be transferred rapidly, then the data rate must increase in proportion. The Nyquist sampling theorem in its simplest form states that a signal can be uniquely represented by periodic discrete samples whose period is no larger than 1/2 of the signal’s inverse bandwidth.

To resolve an image there is a minimum signal requirement; the number of photons that need to be collected (photon count) by an imaging system. There is an absolute minimum of two photons per ground pixel, determined, by the Nyquist criterion. However, to actually determine some type of gray scale information, and to overcome noise in the system, the actual sample size will more realistically be on the order of $10^4$ or more photons per ground pixel. Optical systems in general are limited in their ability to resolve an image by the Rayleigh criterion, and by the number of photons that can be collected (Nyquist criterion).

The Rayleigh criterion [John W. S. Rayleigh, English physicist (1842-1919) in the fields of acoustics and optics] is important in this context. It refers to the resolving power of an optical system and its consequences on aperture size. It states that the resolution of a system is directly proportional to the wavelength. Thus, with perfect optics, an imaging system working at 50 nm (EUV wavelengths) would have an order of magnitude better resolution than one working with visible light (about 500 nm wavelength). The Rayleigh criterion determines the aperture diameter of an imaging system needed to achieve a spatial resolution (i.e., minimum diameter needed to resolve an image). While the Rayleigh criterion determines the aperture size, no matter what type of optical system is used, its total area must be greater than or equal to that of a filled aperture system that will collect enough photons to resolve the image. See also the Glossary on the Rayleigh criterion.

Hence, a practicable and economical solution for a larger effective aperture can only be achieved with the introduction of interferometry and/or the use of phased arrays. Phased arrays get around the beamwidth limit (i.e., Rayleigh criterion) by using several small apertures (linked together) to achieve the same result as one large aperture. Phased arrays synthesize larger apertures from an array of elements.

7) Planck’s radiation law, named after Max Planck (1858-1947), a German physicist who originated quantum theory. In 1900, Planck formulated an equation to explain the spectral energy distribution of thermal radiation from a perfect absorber (blackbody) and showed that the formulation required a discontinuous process of emission or absorption involving discrete quantities of energy. Planck’s radiation law relates the energy of radiation to its frequency ($E = h \times \nu$). The energy $E$ of each quantum, or of each photon, equals Planck’s constant $h$ multiplied by its radiation frequency $\nu$.

Within the electromagnetic spectrum the spectral radiance (i.e., energy per unit time, area, solid angle, and wavelength) varies considerably and with it the ability to detect (measure) radiation. In general, photons are considerably more energetic at shorter wavelengths than at longer wavelengths.

All instrument observation techniques based on radiation measurements (there are indeed many instruments in this category) are constrained to Planck’s radiation law. Chapter O.4.4 provides some information as to the radiation detection limits in the various spectral ranges. To illustrate the spectral energy distribution, let us consider three imaging instruments on the same spacecraft, all looking into the same footprint, with each instrument observing incoming radiation in a different spectral range, namely:

- The VIS range (0.4 - 0.7 $\mu$m) with photon energy levels of 3.1 - 1.8 eV
- The FIR range (30 - 1000 $\mu$m) with photon energy levels of 35 - 1 meV
- The MW range (1 mm - 1 m) with photon energy levels of 1 meV - 1 μeV

The photon energy levels for each spectral range decrease practically by three orders of magnitude from VIS to FIR and again from FIR to MW. This vast photonic energy range of $10^6$ puts in particular great demands on the detector technology in the microwave range to measure such minute energy levels and to discriminate between signal differences.
1.4 Spacecraft Systems

A bouquet of topics is presented in this chapter of spacecraft systems, from system design issues to operations and inflatable structures. At the start of the 21st century considerable change can again be expected in all aspects of space systems due to the introduction of still further innovations. In particular, spacecraft component technologies are becoming important for future mission/observation capabilities. All these changes will introduce more functional flexibility, leading also to more system complexity.

1.4.1 Spacecraft platform stabilization concepts

Spacecraft stabilization is a prerequisite for any observation from space. There are a number of techniques in use to stabilize and orient a spacecraft (also referred to as momentum stabilization). The orbital motion of a spacecraft experiences various disturbance forces that, if they do not act on the center of mass, produce a torque applied to the vehicle. Principal external sources of disturbance on a spacecraft are: a) aerodynamic torque, b) gravity-gradient torque, c) solar radiation pressure torque, d) magnetic torque, e) other disturbance torques. In addition, there may be internal torques of consequence in the control of attitude of the spacecraft, resulting from the exchange of momentum between internal mobile elements. Typical internal torques are generated by the movement of antennas, solar panels, pointing instruments, etc. In addition to the stabilization problem, there may be an independent direction requirement, generally a problem of active control, in which the space vehicle or a part of the equipment of the space vehicle must point into a specific direction (spacecraft body pointing). In general, there are two broad classes of stabilization concepts in use: (see also chapter 1.8.2)

1) Passive attitude control techniques: These take advantage of basic physical principles and of forces that are produced spontaneously to design the space vehicle, reinforcing the effect of a force while reducing other. An advantage of the passive control is the capacity to achieve a very long life of the satellite, not limited by onboard consumable or, possibly, even by the wear and mobile pieces breaks. The typical disadvantages of the passive control are the relatively poor total accuracy and response something inflexible to changing conditions. Some passive techniques employed are:

- Spin stabilization
- Gravity-gradient stabilization
- Aerodynamic stabilization
- Solar pressure stabilization (solar sail)
- Permanent magnet

2) Active attitude control techniques: The underlying concept of active attitude control is cyclic in nature, involving the continuous sensing of the attitude and comparison of the actual attitude to the required attitude. A corrective actuation is provided in the case of a prescribed deviation. Actuation\(^{714}\) may be provided by each the following devices or combinations thereof: reaction wheels, momentum wheels, control moment gyroscopes, magnetic torquers, thrusters, etc. Obviously, consumables are being required for the maintenance of the actuation process. Some consumables, like electric power, are replenishable while others (fuel) are finite. Some sensor options are: magnetometer, gyro, star tracker, horizon and sun sensors. In general, active attitude control techniques are providing improved pointing accuracies and response times over the passive attitude techniques.

The following list represents some examples of platform stabilization concepts:

- Single spin stabilized spacecraft: Early spacecraft relied heavily on pure spin stabilization for gyroscopic stiffness. In such a system, inertial orientation is provided by the spin of

\(^{714}\) Note: An actuator is a device able to modify the orientation of a spacecraft.
the entire spacecraft (generally about its axis of maximum moment of inertia or “major axis”). A nutation damper is used to damp the nutation (precession still exists). In such a configuration, the sensor collection is limited to scanning by the spin motion. This method continues to be used on many of today’s satellites. Examples: The world’s first weather satellite, TIROS-1 (launch April 1, 1960) and the follow-up TIROS and ESSA series S/C (up to ESSA-9, launch Feb. 26, 1969) were all spin-stabilized. Also, the advanced Vela satellite series of USAF (launch of Vela-7 on April 28, 1967; six S/C, Vela-7 to -12 were launched from 1967 to 1970) and SAS-1 (launch Dec. 12, 1970]) followed the single-spin concept. 715)

- Dual-spin stabilization systems were quickly recognized as a superior stabilization concept for satellites (two bodies rotating at different rates about a common axis). The dual-spin concept was developed by Vernon Landon at RCA and Anthony Iorillo at Hughes. 716) 717) The term “dual-spin” was coined by Peter Likins in 1967. 718) With a dual-spin satellite the payload (i.e. the antenna, sensors) is despun while the other portion of the spacecraft spins to provide gyroscopic stability (the system requires torquers such as thrusters or magnets for momentum control and nutation dampers for stability). In general a dual-spin satellite features a relatively fast-spinning rotor and a slowly spinning platform. The despun platform portion allows an Earth-pointing payload. – Following is a short history of early dual-spin configurations: 719)

- The OSO-1 (Orbiting Solar Observatory-1) of NASA, launched on March 7, 1962, demonstrated the dual-spin concept successfully by spinning about its principle axis. The objective of the LEO spacecraft was to study ultraviolet, X-ray and gamma radiation from the sun. OSO-1 was followed by six more OSO S/C launched between 1962 and 1975, all of the same dual-spin design. 720) 721) 722)

- Communication satellites introduced the concept in the late 1960s. The TACSAT-1 (Tactical Communication Satellite-1, launch Feb. 9, 1969) of DoD, built by Hughes Aircraft Company, was the first minor-axis dual-spin-stabilized S/C by the Hughes-developed “Gyrostat” system.

- The first EO (Earth Observation) missions using the dual-spin Earth-pointing concept were METEOSAT-1 of ESA (launch Nov. 23, 1977) and MAGSAT of APL/NASA/USGS with a launch on Oct. 30, 1979.

- The Galileo spacecraft of NASA/JPL (launch Oct. 18, 1989) is the first dual-spin interplanetary satellite implementation. A spinning section rotates at 3 rpm, and a despun section is counter-rotated to provide a fixed orientation for cameras and other remote sensors.

- Gravity-gradient stabilization (a passive technique): The concept employs the change in gravity with altitude to create a torque when the principal axes are not aligned with the orbital reference frame. Long booms with an end mass are usually extended to create the torque. The concept is simple and reliable, but pointing accuracies are poor, generally in the order of < 5°. - The gravity-gradient boom technique, particularly suitable for microsatellites, was first introduced by the LEO Transit navigation satellite series of the US Navy (starting with the launch of Transit-5A-3 on June 16, 1963), followed by other missions: the

715) Note: The Vela (meaning “watchman” in Spanish) spacecraft series of DoD was designed to monitor worldwide compliance with the 1963 nuclear test ban treaty. Vela-1 was launched Oct. 17, 1963; Vela-6 was launched July 20, 1965
722) http://www.nasm.si.edu/research/dsh/artifacts/SS---OSO1.htm
GGSE (Gravity Gradient Stabilization Experiment) satellite series of DoD started on Jan. 11, 1964 with GGSE-1, GGSE-4 and -5 were launched May 31, 1967 along with Timation-1 (NRL, launch May 31, 1967); ATS-2 (Application Technology Satellite-2), a NASA GEO satellite prior to GOES, launch April 6, 1967. GGTS-1 (Gravity Gradient Test Satellite-1 with a mass of 47 kg) of the USAF was launched June 16, 1966 from Cape Canaveral. The UoSAT microsatellite series of SSTL, UK (launch of UoSAT-1 on Oct. 6, 1981) is using the gravity-gradient concept (in LEO) extensively. The DODGE S/C (launch July 1, 1967, see M.8) was the first to study a number of advanced biaxial and triaxial gravity-gradient stabilization techniques at near-synchronous altitudes.

**Gravity-gradient boom.** A deployable extension of a spacecraft (a rod fixed to the S/C with a small mass at its other end) intended to give the spacecraft elongated mass properties to contribute to gravity-gradient stability (the concept was first successfully demonstrated by JHU/APL on the Transit 5A-3 satellite with a launch on June 16, 1963). The principle: The attractive force $F_1$ of mass 1 (satellite) about the common center of mass exceeds the attractive force $F_2$ of mass 2. Hence, a torque arises to align the satellite to the vertical. - An elongated dumbbell-shaped spacecraft is the most gravity gradient stable configuration with the long axis oriented vertically in orbit, i.e. (usually) the smaller mass is always pointing toward the center of the Earth. The gravity-gradient torque, small even for LEO S/C, decreases with the cube of the orbital radius. In GEO, gravity-gradient stabilization can barely be achieved.

- Magnetic field stabilization: The first passive magnetic field stabilization system of a satellite was introduced at JHU/APL on the US Navy’s Transit-1A (launch Sept. 17, 1959), Transit-1B (Apr. 13, 1960, see H.6) and DME-A (Direct Measurement Explorer - A) with a launch on Nov. 29, 1965. The principle of operation: If three mutually orthogonal electromagnets are placed in a S/C, a magnetic dipole $M$ can be created in any direction. The satellite can determine the Earth’s magnetic field $\mathbf{H}$ by means of a vector magnetometer. By activating the electromagnets appropriately in response to the magnetometer measurements, a torque $\mathbf{T} = \mathbf{M} \times \mathbf{H}$ in any direction can be obtained. This torque can be used for S/C attitude control (including spin/despin). Essentially, the satellite acts like the rotor of an electric motor, with the Earth’s magnetic field being the stator. The method has been used many times since (see also Table 92). Examples:

  a) The ESRO satellites ESRO-1/Aurora (launch Oct. 3, 1968) and ESRO-1/Boreas (launch Oct. 1, 1969) as well as the German Azur-1 (launch Nov. 11, 1969).
  b) The Magion-1, -2, and -3 subsatellites of the Czech Republic (launch of Magion-1 on Oct. 24, 1978) all employed the technique of magnetic field stabilization (the Magion-4 and -5 S/C were spin-stabilized). The Magion S/C were part of the USSR mission ACTIVE (K.2);
  c) The AMSAT OSCAR (Orbiting Satellites Carrying Amateur Radio) microsatellite series [OSCAR 5 (launch Jan. 23, 1970), 16, 17, 18, 19, 26, and 30, for example] employ magnetic field stabilization with its SAPPorre ACS (Attitude Control Subsystem);
  d) the Munin nanosatellite of IRF (Sweden, launch Nov. 21, 2000).

- Momentum-bias S/C. 723) 724) Over the years, spin stabilization systems gradually gave way to momentum-bias spacecraft employing internal momentum [a momentum wheel is a flywheel designed to operate at non-zero (i.e. “biased”) angular momentum and providing

723) Note: A reaction wheel is a flywheel designed to operate at zero bias - i.e. nominally non-rotating. Like a momentum wheel, the reaction wheel is also used for storage and transfer of angular momentum. The term “momentum dumping” refers to the despinning of a reaction wheel.

momentum storage capacity about its rotation axis] or reaction wheels. In concept gyroscopic stiffness is provided by a rapidly spinning momentum wheel rather than the satellite bus itself. The momentum wheel provides control about the spin (pitch) axis; in addition, a combination of nutation damper, magnetic torquing, or propellant provide control about the roll and yaw axis. The advantages of such a system are: better pointing accuracy, better power efficiency due to the despun solar arrays. The momentum-bias approach with magnetic torquers is the dominant ACS (Attitude Control Subsystem) solution in LEO S/C.

- **Three-axis stabilization:** In this concept all three axes of a S/C are independently controlled either by reaction wheels (RW), or by thrusters, or by CMGs (Control Moment Gyros). The advantages are: good pointing accuracy, maneuverability and adaptability to changing mission requirements. Usually, RWs or CMGs are used for control and propellant (sometimes magnetic torquing) is used for momentum dumping. The three-axis stabilization concept offers better size and space options, in particular with the mounting of deployable solar panels. Solar arrays may be large and inertially pointed, i.e. independently steered, to maintain normal incidence to the sun, thus optimizing power generation. However, full active control is required. Early examples of three-axis stabilization are:
  - **Discoverer-2** (launch Apr. 13, 1959), a US military reconnaissance satellite, was the first satellite to be stabilized in orbit in all three axes, to be maneuvered on command from Earth.  
  - The **Nimbus-1** satellite (launch Aug. 28, 1964) was the first civil three-axis stabilized spacecraft (followed by the Nimbus series).
  - The **Improved TIROS Operational Satellite**, ITOS-1 (launch Dec. 11, 1970, the NOAA-1 satellite that followed it (launch Dec. 11, 1970), and all follow-up satellites of the series) featured also three-axis stabilization. The three-axis control concept is still the most applied stabilization method in space flight.

- **Yaw spinner:** A yaw spinner is a three-axis controlled satellite. The payload/sensor is spun about the yaw axis to provide Earth scanning. A counterspun momentum wheel is used to cancel the angular momentum of the spinning sensor. Reaction wheels are normally used for attitude control. The advantages are: precision pointing and good maneuverability.

### 1.4.2 Spacecraft/Component Design Topics

Early satellites featured custom designs (in shape, size, etc.) to suit the requirements of a particular mission. It meant continued change for the S/C builders to incorporate general support functions over and over again along with specific mission instruments. The availability of a standard S/C bus (for a particular observation capability) was practically unknown until the end of the 1970s. The Magsat mission (launch Oct. 1978), a dual-spin satellite, demonstrated to NASA in particular the usefulness of a general-purpose bus for science applications. The bus could support a variety of bolt-on experiments. The concept has been used extensively ever since. - Integration of flight hardware and subsystems has become an important aspect of modular design. Introduction of such items/concepts as: GaAs solar cells, light-weight composite materials, multi-purpose platforms. Satellite design lives have improved considerably they are now approaching seven to ten years (depending on applications), mini- and microsatellites. In the 1990s, onboard processing is becoming a service introduction.

Spacecraft design (for Earth observation) has experienced interesting trends. Early space-age satellites were small due to the limitations of launch capabilities. The current classes of microsatellites (10 - 100 kg) and minisatellites (100 - 500 kg) are a fitting description for these early space-age satellites (only with regard to mass). As the space age progressed into the 1970s and 1980s, the capabilities of launch vehicles increased constantly. Hence, satel-

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725) http://www.losangeles.af.mil/SMC/HO/7%20chapter%20v%20%20satellite%20systems.pdf
lites became much larger and much more complex. In parallel, electronics became much more dense, many subsystems could be combined into a single instrument on a satellite. The new complexity, along with its demands for reliability and quality assurance, had to be managed, generating bureaucracy and large organizations. As a consequence, overall creativity suffered considerably while costs increased rapidly. It meant a reduction in launches with longer in-between periods. Large projects like ISS, EOS, and Envisat encountered planning (and re-planning) phases alone that came close to a decade. For the experimenter, it meant a reduction in flight opportunities for observations as well as a reduction in technology advances.

A rethinking of the situation started with the re-invention of microsatellites in the late 1970s. SSTL [Surrey Satellite Technology Ltd (University of Surrey, UK)] was such a pioneer of microsatellite design, including a modular and flexible platform (MicroBus), instruments, looking for new concepts in functionality, services, and cost reductions. Miniaturization techniques of solid-state electronics, sensors, optics, actuators (i.e. miniature mechanisms), etc., are important enabling factors in microsatellite design. Short development times from project approval to S/C launch were the result. This new approach seems to gain momentum, everywhere. There is also a realization that small-project financing can easier find support in tight budgets, this applies to government sponsorship of research projects as well as to the commercial sector. Calculated risks are being taken again. Many organizations are ‘re-organizing’ to improve the conditions for innovation and creativity. The future seems to have room for microsatellites as well as for larger-class satellites, depending on applications.

The early microsatellites of the 1980s were simple S/C, they were for instance built without a propulsion system, due to the cost and complexity of such a system. Attitude control was typically performed using magnetic torquers and gravity stabilization, at a later time reaction or momentum wheels were introduced. Also, propulsion for attitude control using tiny thrusters could be implemented using cold pressurized gas. However, for orbit changes, such a cold gas system remained simply too inefficient. Small satellite projects have also small budgets. Thus, by their very nature, they depend on launch opportunities as secondary payloads which are offered by larger satellites. As a consequence, a microsatellite project has only the choice of taking the same orbit of the main satellite payload.

In the late 1990s the miniaturization technology is considered viable for integration of electric propulsion systems onto small satellites - to obtain orbit maneuverability. Examples: STRV-1a (launch June 17, 1994) a microsatellite of DERA (S/C mass of 52 kg), made flight tests of the xenon gas flow control system, developed for the UK-10 IPS (Ion Propulsion System), with associated solenoid valves, orifices, and valve actuating electronics (M.41.1.1). Deep Space 1 (launch Oct. 24, 1998) a minisatellite of NASA/JPL with a mass of 490 kg, carried IPS (Ion Propulsion System) to demonstrate deep space propulsion. UoSAT-12, a minisatellite of SSTL (launch April 12, 1999, S/C mass of 325 kg) carries an electric propulsion system, a 100 W resistojet, which uses nitrous oxide as its working fluid.

At the start of the 21st century, the spectrum of microsatellite services is by all means as impressive as that of their bigger brother satellites, but at considerably reduced costs. Overall, microsatellites experienced an impressive evolution from flying gadgets to real and advanced service providers. In fact, microsatellites make it possible to open up new fields of services previously considered too expensive (in particular technological missions are in this category). As a consequence, the space agencies as well as the military establishments of the world are re-evaluating their programs, in favor of smaller systems, to offer a solution for ever tighter budgets. 726) 727)

• S/C instrument mounting. A cartwheel mounting configuration was realized in TIROS-9 (launch Jan. 22, 1965). For the first time, the two TV-WA cameras were mounted into the sidewalls of the S/C cylinder, 180° opposite to each other. This cartwheel concept allowed each camera to observe the same ground target during each cycle of rotation. Prior to this time, instruments were generally mounted axially into spin-stabilized S/C.

• In the late 1990s, an evolving micro-technology is permitting the design of single-board spacecraft, referred to as “nanosatellites” (1 kg < mass ≤ 10 kg) and “picosatellites” (mass ≤ 1 kg). In such single-board designs, there is no physical separation between platform and payload. Naturally, the capabilities and performance of these tiny pioneering monsters are still very limited and “inferior” to those of their bigger brothers, the micro- and minisatellites (because they have less pointing accuracy, less power, less communication capability, etc. - than the larger micro- and minisatellites). However, the main advantages of nano- and picosatellites are their very low cost and the speed of designing/building a satellite practically from off-the-shelf components; these are indeed strong arguments, even for a limited set of objectives that can be achieved. In particular, such applications as technology demonstrations are favored within the class of nano- and picosatellites (an example is the introduction of such concepts as spacecraft constellations (networks or clusters) for distributed Earth observations or for communication purposes in LEO orbits). The satellite classification of the Glossary (table 810), is simply repeated here for better reference to the reader.

<table>
<thead>
<tr>
<th>Satellite Class</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large satellite (observatory, etc.)</td>
<td>&gt; 1000 kg</td>
</tr>
<tr>
<td>Minisatellite</td>
<td>100 – 1000 kg</td>
</tr>
<tr>
<td>Microsatellite</td>
<td>10 – 100 kg</td>
</tr>
<tr>
<td>Nanosatellite</td>
<td>1 – 10 kg</td>
</tr>
<tr>
<td>Picosatellite</td>
<td>0.1 – 1 kg</td>
</tr>
<tr>
<td>Femtosatellite</td>
<td>1 – 10 g</td>
</tr>
</tbody>
</table>

Table 40: Satellite classification by mass criterion

In most nanosatellite designs to date, the primary attitude sensor has been a magnetometer which measures the amplitude and direction of the magnetic field vector relative to the spacecraft coordinate system. This measurement is then compared with that of a model of the geomagnetic field for the specific orbital location and the attitude between the spacecraft axes and the inertial reference frame is evaluated.

• The first university-developed microsatellites were designed at Surrey University, Surrey, UK, namely UoSat-1 (launch Oct. 6, 1981) and UoSat-2 (launch March 1, 1984). This was followed later on by the high-performance UoSat series of SSTL. NUSAT-1 (Northern Utah Satellite) was developed and built as a senior class project at Weber State University, Ogden, Utah. NUSAT was deployed from a modified GAS (Get Away Specials) canister on Shuttle flight STS-51B (Spacelab-3 mission, April 29 - May 6, 1985). The 54 kg microsatellite orbited for 20 months (reentry in Dec. 1986). NUSAT-1 was designed to study high-altitude radar field patterns for FAA (Federal Aviation Agency). During the 1990s, satellite and payload development projects have become the program of choice for challenging (multi-year) training courses in quite a few engineering departments at universities throughout the world (see Part N).

• CubeSats - a first attempt to standardize the bus structure and deployment of picosatellites for low-cost experiments and applications (see N.34), in particular for student-built satellites at universities. CubeSat is the name given a cube-shaped picosatellite design of 10 cm side

length and a mass of \( \leq 1 \) kg. The CubeSat idea, concept and program began in 1999 at SSDL (Space Systems Development Laboratory) of Stanford University under the leadership of Robert J. Twiggs. The overall objective of the CubeSat program is to provide an effective framework (including specifications and guidelines) for the design, construction and launch of picosatellites. All CubeSats feature a standard form factor and share launches by using standard launch tubes, referred to as P-PODs (Poly Picosatellite Orbital Deployers), provided by the Stanford/CalPoly CubeSat program.  

- The first CubeSat mission, involving half a dozen picosatellites as secondary payloads, took place on June 30, 2003 on a Rockot KS vehicle of Eurockot from Plesetsk, Russia. The CubeSat S/C are: XI (University of Tokyo), CUTE-I (Tokyo Institute of Technology), CanX-1 of UTIAS/SFL (University of Toronto Institute for Aerospace Studies/Space Flight Laboratory), AAUSat (Aalborg University of Denmark), DTUSat (Technical University of Denmark), QuakeSat (Stanford University, Stanford, CA).

- The second multiple spacecraft launch, involving 3 CubeSats (UWE-1, XI-V, and nCube-2), was released/deployed from SSETI—Express, a microsatellite of European students, and itself a secondary payload on a multiple S/C mission. The launch of this S/C mission took place on Oct. 27, 2005 (Cosmos-3M launch vehicle of AKO Polyot from the Plesetsk Cosmodrome, Russia) involving the following S/C: TopSat of QinetiQ (UK), and China-DMC+4 (Beijing-1) of SSTL (UK) as primary payloads. – The other secondary payloads on this multi–satellite flight were: SSETI Express (European Students), Mozhayets 5 (Russia), Sinah-1 (Iran), and Rubin-5 (OHB, Bremen, Germany).

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Nanosatellite</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 3, 1997</td>
<td>Sputnik-II, built by French students from the l’Aeroclub of France and staff from the Russian Aeronautical Federation</td>
<td>A S/C of only 3 kg deployed from the MIR space station (with VHF-FM beacon transmitter)</td>
</tr>
<tr>
<td>July 7, 1998</td>
<td>TUBSAT-N and -N1 of TU Berlin, Germany</td>
<td>A dual underwater/space launch of data collection satellites</td>
</tr>
<tr>
<td>Jan. 27, 2000</td>
<td>ASU-Sat-1 (Arizona State University)</td>
<td>S/C mass of 5.9 kg (launch on JAWSAT)</td>
</tr>
<tr>
<td>June 28, 2000</td>
<td>SNAP-1 of SSTL (UK) and an academic team of Surrey University</td>
<td>S/C mass of 6.5 kg. SNAP-1 was deployed from the Nadezhda mother ship.</td>
</tr>
<tr>
<td>Sept. 26, 2000</td>
<td>UniSat-1 of University of Rome, Italy</td>
<td>S/C mass of 12 kg (educational program)</td>
</tr>
<tr>
<td>Nov. 21, 2000</td>
<td>Munin of IRF Sweden (S/C mass of 6 kg)</td>
<td>Space science and space weather activity,</td>
</tr>
<tr>
<td>Dec. 20, 2002</td>
<td>UniSat-2 of University of Rome</td>
<td>S/C mass of 10 kg (educational program)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Picosatellite</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 27, 2000</td>
<td>All picosats were ejected from OPAL of Stanford University (as mother ship) StenSat, of amateur enthusiasts Artemis, of Santa Clara University PICOSAT1.0, a tethered 2 S/C system from the Aerospace Corporation</td>
<td>No ground communication with StenSat No ground communication with Artemis Communication established with ground and in crosslink</td>
</tr>
<tr>
<td>July 19, 2000</td>
<td>PICOSAT1.1, a tethered system from the Aerospace Corporation was launched and flown on MightySat II.1 (as mother ship)</td>
<td>Each PICOSAT has a mass of 0.275 kg. The system was ejected successfully from MightySat II.1 13 months after launch.</td>
</tr>
<tr>
<td>Dec. 6, 2002</td>
<td>Release of MEPSI (MEMS-based PICOSAT Inspector), 2 tethered picosats of AFRL from STS-113</td>
<td>Each picosat has a mass of about 1 kg. Demonstration of a launch system and communication with ground station.</td>
</tr>
</tbody>
</table>

Table 41: Chronology of early nanosatellite and picosatellite launches

- On July 26, 2006, a launch of multiple smallsats on a Dnepr–1 launch vehicle from Baikonur, Kazakhstan (launch provider: ISC Kosmotras), ended in a total launch failure after about 2 minutes of flight. The following CubeSats were on this flight: ION (University of

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730) Note: Stanford University and California Polytechnic State University in San Luis Obispo, CA (referred to as Cal-Poly) have combined efforts to develop a means of launching small standard picosatellites called CubeSats.

Illinois), Sacred (University of Arizona), KUTESat (Kansas University), ICEcube-1, -2 (Cornell University), Rincon (University of Arizona), SEEDS (Nihon University), HAU-Sat-1 (Hankuk Aviation University), nCube-1 (Norsk Romsenter), Merope (Montana St. University), AeroCube-1 (The Aerospace Corporation), PolySat-1, -2 (CalPoly), and Voyager (University of Hawaii);

Additional smallsats on the flight were: Belka (RKK Energia) 250 kg, the first remote sensing satellite of Belarus, Baumanets (NPO Mash) 80 kg, UniSat—4 (University of Rome, Italy) 12 kg, and PicPot (University of Torino, Italy) 3 kg. This launch failure represented a great setback and disappointment to all involved, in particular to the members of the 14 CubeSat projects. All the work and effort of years from many student satellite teams from around the world was lost in a single instant. The launch failure was due to a malfunctioning hydraulic drive unit in a combustion chamber on the booster’s first stage. — Unfortunately, occasional launch failures are simply part of spaceflight — in spite of careful launch preparations. 732)

- On April 17, 2007, seven CubeSats were launched on a Dnepr vehicle from Baikonur, Kazakhstan. These were: PolySat—3 and PolySat—4 of CalPoly; AeroCube—2 of The Aerospace Corporation; CSTB—1 of the Boeing Company; CAPE—1 of the University of Louisiana; MAST of Stanford and TUI; and Libertad—1 of the University of Sergio Arboleda, Columbia.

Most existing lightsats (or “litesats”), in particular nanosatellites, feature one of two types of primary bus structures: 1) a load-bearing shell structure, or 2) a stack of component trays with stiffeners. The designs use either a sandwich construction, stiffened plates, or thin-walled trays (also referred to as cast design). The materials chosen are either fiber-reinforced composites or aluminum as primary structures. Sandwich structures are usually composed of two face sheets bonded to a core. 733) The most common core type material is aluminum honeycomb, constructed of bonded strips of aluminum foil which are expanded to create hexagonal cells. Both metals and fiber-reinforced composites can be used in honeycomb panels. At the beginning of the 21st century, the sandwich design approach seems to be the most efficient S/C structure design technique, offering compact and modular choices with minimal mass. On the other hand, the cast structure design approach seems to be particularly suitable for mass production of nanosatellites that are needed for larger constellations. The cast design is based on different modules attached to the main structure. Some advantages of the cast or tray structure are: modular design, flexibility, each assembly can be handled independently, minimum assembly time, less number of parts.

- The SNAP-1 nanosatellite mission of SSTL (Surrey, UK) is a prime example of miniaturization, offering in parallel a great variety of functional capability within a total S/C mass of 6.5 kg (see D.52.17). SNAP-1 was developed with a VHF uplink (9.6 kbit/s), S-band downlink (38.4 or 76.8 kbit/s), a StrongARM onboard computer (4 MB EDAC memory), a CAN bus for data handling, three-axis attitude determination and control, a GPS receiver (SRG-05), a power subsystem (4W/9W average/peak, 6-cell NiCd battery), a CMOS camera that served as its primary payload, and a microthruster of 30 μN with a Δv capacity of 3 m/s (the micro-propulsion system had the size of a pencil). During in-orbit deployment, SNAP-1 demonstrated immediate functionality by completing a 60 second imaging sequence of its own deployment, commencing two seconds upon separation from the deployer platform.

- Standard spacecraft buses (as listed in Table 42) 734) come in all shapes and sizes. Again, standards with a “common bus” design approach are important to lower manufacturing costs. The weather satellites of NASA in LEO and GEO were the first to adopt a

734) http://rsdo.gsfc.nasa.gov/
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A common design (TIROS series), followed by the commercial communication satellites in GEO (since the 1970s). This is due to the commonality of mission requirements and orbit geometry. In 1997, NASA introduced an online spacecraft catalog to apply the COTS (Commercial Off-The-Shelf) concept approach also to its science missions. RSDO (Rapid Spacecraft Development Office) at NASA/GSFC.

<table>
<thead>
<tr>
<th>Organization</th>
<th>S/C Bus</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>TIROS/POES series spacecraft (built by LMMS)</td>
<td>TIROS-1 (launch Apr. 1, 1960)</td>
</tr>
<tr>
<td></td>
<td>Nimbus series spacecraft (built by GE Astro Space)</td>
<td>Nimbus-1 launch Aug. 28, 1964</td>
</tr>
<tr>
<td></td>
<td>Landsat series spacecraft (built by LMMS)</td>
<td>Landsat-1 launch July 23, 1972</td>
</tr>
<tr>
<td></td>
<td>GOES D-H series spacecraft (built by Boeing)</td>
<td>GOES-4 to 7, launches 1980-1987</td>
</tr>
<tr>
<td></td>
<td>GOES I-M series spacecraft (built by SS/L)</td>
<td>GOES-8 to 12, launches 1994-2001</td>
</tr>
<tr>
<td></td>
<td>GOES N-O series spacecraft (BSS, 601 platform)</td>
<td>GOES-N (launch May 24, 2006)</td>
</tr>
<tr>
<td></td>
<td>GOES-R next generation</td>
<td>GOES-R, launches in 2014-2029</td>
</tr>
<tr>
<td></td>
<td>MMS (Multimission Modular Satellite), Fairchild</td>
<td>SMM, launch Feb. 14, 1980</td>
</tr>
<tr>
<td></td>
<td>SMEX (Small Explorer Program) S/C bus</td>
<td>Landsat-4 (launch July 16, 1982)</td>
</tr>
<tr>
<td></td>
<td>SMEX-Lite</td>
<td>Landsat-5 (launch March 1, 1984)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAMPEX, launch July 3, 1992</td>
</tr>
<tr>
<td>DoD</td>
<td>DMSP weather series spacecraft (built by LMMS)</td>
<td>Block-4A series started in 1965</td>
</tr>
<tr>
<td></td>
<td>More than 30 DMSP S/C have been launched so far</td>
<td>Block-5D series started in 2003</td>
</tr>
<tr>
<td>ESA</td>
<td>Meteosat series (built by Alcatel)</td>
<td>Meteosat-1 launch Nov. 23, 1977</td>
</tr>
<tr>
<td></td>
<td>PPF (Polar Platform) bus, based on an enlarged version of the SPOT Mk2 bus</td>
<td>Envisat, launch Mar. 1, 2002</td>
</tr>
<tr>
<td></td>
<td>PROBA (mini-bus (Verhaert))</td>
<td>PROBA (launch Oct. 22, 2001)</td>
</tr>
<tr>
<td>CNES</td>
<td>Spot Mk1; Mk2; and Mk3 bus; Proteus (Alcatel Space), mass of 100-500 kg</td>
<td>SPOT-1-3, ERS-1/2, SPOT-4/5</td>
</tr>
<tr>
<td>Alcatel</td>
<td>Spacebus-3000 (Alcatel Space), mass of 2000-3400 kg, power 5-7 kW, 3-40 transponders, 15 year life</td>
<td>Jason-1/2, CALIPSO, SMOS, CoRoT,</td>
</tr>
<tr>
<td></td>
<td>Spacebus-4000 provides Hall-effect thrusters for north-south stationkeeping (NSSK)</td>
<td>Telecommunications (Sirius-2, Eutelsat W, Atlantic Bird-2, etc.)</td>
</tr>
<tr>
<td>SSTL (UK)</td>
<td>MicroBus since UoSAT-3 and -4 (launch Jan. 22, 1990); MiniBus since UoSAT-12</td>
<td>UoSAT-1, launch Oct. 6, 1981</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UoSAT-12, launch Apr. 21, 1999</td>
</tr>
<tr>
<td>LMMS</td>
<td>LM900 (Lockheed Martin Missile &amp; Space)</td>
<td>Ikronos-1, l. Apr. 27, 1999 (failure)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ikronos-2, launch Sept. 24, 1999</td>
</tr>
<tr>
<td>Astro, Inc.</td>
<td>SA-200 HP (Spectrum Astro-200 High Performance)</td>
<td>DS1 (launch Oct. 24, 1998)</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td>Coriolis (launch Jan. 6, 2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swift (launch Nov. 20, 2004)</td>
</tr>
<tr>
<td>OSC</td>
<td>MicroStar platform (payloads up to 68 kg), mission life between 3-5 years</td>
<td>OrbView-1 (Microlab), Apr. 3, 1995</td>
</tr>
<tr>
<td>(Orbital</td>
<td>LeoStar (payloads up to 360 kg)</td>
<td>QuikTOMS (failure of Taurus launcher Sept. 21, 2001)</td>
</tr>
<tr>
<td>Space</td>
<td>LeoStar-2 (payloads up to 210 kg)</td>
<td>TSX-5 (Jun. 6, 2000), Orbvew-3 (Jun. 26, 2003), 5 STEP missions</td>
</tr>
<tr>
<td>Corporation)</td>
<td></td>
<td>OrbView-4, SORCE (Jan. 25, 2003)</td>
</tr>
<tr>
<td>Astrium</td>
<td>1) Flexbus (minisatellite bus); S/C mass of 100-1000 kg, power of 150-1000 W average</td>
<td>CHAMP, launch July 15, 2000</td>
</tr>
<tr>
<td>GmbH</td>
<td>2) MiniFlex bus, S/C mass of 80-250 kg</td>
<td>GRACE, launch Mar. 17, 2002</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
<td>Nilesat, AsiaStar, Ameristar, etc.</td>
</tr>
<tr>
<td>EADS Astrium</td>
<td>Eurostar 2000; S/C mass of 1200-1900 kg, GEO LEOSTAR-200 and -500 bus for LEO orbits</td>
<td>ROCSat-2 (launch May 20, 2004)</td>
</tr>
<tr>
<td>SAS France</td>
<td>Eurostar 3000; S/C mass of 4000-6000 kg, GEO</td>
<td>Pleiades of CNES (launch 2009)</td>
</tr>
<tr>
<td>EADS Astrium</td>
<td>AstroBus (successor of Flexbus and LEOSTAR due to industrial merger)</td>
<td>W3A of Eutelsat (launch Mar. 16, 2004)</td>
</tr>
<tr>
<td></td>
<td>AstroSat-100, a microsat bus of Myriade heritage</td>
<td>is first in this series</td>
</tr>
<tr>
<td></td>
<td>AstroSat-500, a minisat bus</td>
<td>TerraSAR-X (launch June 15, 2007)</td>
</tr>
<tr>
<td></td>
<td>AstroSat-1000,</td>
<td>AIsat-2 (launch 2008)</td>
</tr>
<tr>
<td>TRW</td>
<td>T-300 bus series (graphite epoxy bus). The bus provides a low-jitter, precision-pointing and long-term perspective</td>
<td>GeoLITE (T-310), launch May 18,01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aqua (T-330), launch May 4, 2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aura (T-330), launch July 15, 2004</td>
</tr>
</tbody>
</table>
### Table 42: Introduction of some spacecraft bus/platform designs

<table>
<thead>
<tr>
<th>Organization</th>
<th>S/C Bus</th>
<th>Mission</th>
</tr>
</thead>
</table>
| **ASI**          | 1) PRIMA (Reconfigurable Italian Platform for Multiple Applications) of Alenia Aerospazio. Support of payload masses up to 1000 kg  
                  2) MITA (Minisatellite for Advanced Technology) of Carlo Gavazzi Space, | RADARSAT-2, launch in 2007  
                  COSMO/SkyMed (1: June 8, 2007)  
                  MITA S/C launch Jul. 15, 2000  
                  AGILE (launch Apr. 23, 2007) |
| Stanford University | SQUIRT (Satellite Quick Research Testbed)                              | ORION, planned launch in 2001                                           |
| **CNES**         | Myriade microsatellite bus for missions of <120 kg, built by Latécoère of Toulouse, mission life of 3 years | DEMETER (launch Jun. 29, 2004)  
                  PARASOL (launch Dec. 18, 2004)  
                  Picard (launch 2009), and Microscope (launch in 2010) |
| **BATC Boulder, CO** | BCP (Ball Commercial Platform) 2000 bus; average power supply of 730 W | QuikSCAT (launch Jun. 19, 1999)  
                  QuickBird-2 (launch Oct. 18, 2001)  
                  ICESat (launch Jan. 13, 2003)  
                  CloudSat (launch Apr. 28, 2006)  
                  NPP (launch 2009) |
| **SSC Sweden**   | Astrid-microbus; mass of 10-100 kg,                                      | Astrid-1 (launch Jan. 24, 1995)  
                  Astrid-2 (launch Dec. 10, 1998) |
| **DERA/QinetiQ, UK** | STRV (Space Technology Research Vehicle) microbus,                     | STRV-1a/b (launch Jun. 17, 1994)  
                  STRV-1c/d (launch Nov. 16, 2000) |
| **EADS+ Thales Alenia Space** | AlphaBus a new generation European multi-purpose bus for large communication satellites (15-20 kW, 5.5-8 tons); the AlphaBus program is supported by ESA and CNES | AlphaSat of Inmarsat is the S/C using the AlphaBus proto-flight platform (launch 2011) |
| **SSTL, Surrey, UK** | MicroSat-70 bus Utilized for missions between 50-70 kg total mass     | UoSat-3/-4 (launch Jan. 22, 1990)  
                  UoSat-5 (launch July 17, 1991)  
                  S89/T,KitSat-1 (1. Aug. 10, 1992)  
                  KitSat-2, PoSat-1, HealthSat-2 (1. Sept. 26, 1993)  
                  CERISE (launch July 7, 1995)  
                  FASat (launch Aug, 31, 1995)  
                  Clementine (launch Dec. 3, 1999)  
                  PICOSat (launch Jan. 27, 2000)  
                  Tsinghua-1 (launch June 28, 2000)  
                  TiungSat-1 (launch Sept. 26, 2000) |
| **SSTL, Surrey, UK** | MicroSat-100 bus (enhanced microsatellite bus) Utilized for missions between 70-130 kg total mass | AISat-1 (launch Nov. 28, 2002)  
                  BilSat-1, NigeriaSat-1, UK-DMC (launch Sept. 27, 2003) |
| **SSTL, Surrey, UK** | MicroSat-150 bus (enhanced microsatellite bus) | TopSat (launch Oct. 27, 2005)  
                  Beijing-1 (launch Oct. 27, 2005)  
                  CFESat (launch March 9, 2007)  
                  RapidEye (launch 2007)  
                  DMC+2.5 (launch 2008) |
| **SSTL, Surrey, UK** | MiniSat-400 bus Utilized for missions up to 400 kg total mass | UoSat-12 (launch April 21, 1999) |
| **SSTL, Surrey, UK** | GMP (Geo Minisatellite Platform) bus (400-500 kg), deployable solar arrays, up to 1 kW power, and up to 110 kg payload mass. Utilized for GEO (and MEO) missions | GIOVE–A (launch Dec. 28 2005),  
                  EarthSHINE (UK, 2009) |
| **SpaceDev**     | MMB＝100 (Modular Microsat Bus), up to 100 kg                            |                                                                         |
| **CAST, Beijing built by DFH** (a spin-off company of CAST) | CAST968 (China Academy of Space Technology) minisatellite bus (payload capacity of 200-300 kg) | SJ–5 (launch May 10, 1999)  
                  HY-1A (launch May 15, 2002)  
                  DSP (launches in 2003 and 2004)  
                  HY-1B (launch (April 11, 2007) |
| **CAST, Beijing built by DFH** (a spin-off company of CAST) | CAST2000, second generation minisatellite bus for payload capacity of 200–400 kg | TS-2 (launch Nov. 18, 2004)  
                  HJ-1 Constellation (launch 2007/8) |
| **CAST, Beijing built by DFH** (a spin-off company of CAST) | CAST minibus for payloads of 50–120 kg                              |                                                                         |
| **CAST, Beijing built by DFH** (a spin-off company of CAST) | DFH–3, a 2nd generation bus for communication satellites in GEO | DFH-3 FM1 (launch Nov. 29, 1994)  
                  DFH-3 ChinaSat-22 (launch Jan. 26, 2000)  
                  DFH-3 bus for Chang’e lunar mission in 2007 |
A very special AstroBus configuration is the so-called Snapdragon, a deployable bus of EADS Astrium Ltd., Portsmouth, UK, developed under ESA contract. The design of Snapdragon resulted from the requirement to fly rather large structures, like an L-band SAR antenna, and to accommodate this payload structure elegantly into the available space of a launch vehicle fairing (the smaller the launch vehicle, the lower the launch cost). In Snapdragon, the accommodation problem was approached from the payload’s point of view. It resulted in a series of “diametric” SAR accommodations, meaning that the SAR antenna is stowed (two hinged halves) across the diameter of the launcher fairing. The basic Snapdragon configuration features two similar structural assemblies to either side of the diameter of the launcher payload fairing. A single central deployment mechanism is placed at the foldline between the two halves of the spacecraft, with the rotation axis in the separation plane of the launcher-satellite interface. A series of HRMs (Hold-down and Release Mechanism) up each side of the S/C ensures structural integrity during launch. Thus, the Snapdragon concept represents essentially a re-packaging of existing hardware into a new structure. Several design variations make the Snapdragon concept very attractive for a number of potential applications with a range of options (not only for large structures) in Earth observation as well as in communication payloads. For instance, the Snapdragon concept is capable to support other missions than SAR. It can carry a large optical telescope simultaneously with radar, multi-frequency radars; and when fitted with fixed arrays and a control-moment gyro it can be very agile having a deployed S/C stiffness > 10 Hz. Snapdragon configurations may also be used for large communication antennas as well as antenna farms. A hinge removal provides the option of flying two similar spacecraft.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Mission</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPAS-1 (Shuttle Pallet Satellite)</td>
<td>STS-7, June 18-24, 1983</td>
<td>MOMS-01 imaging instrument of DLR (MOMS-01 and SPAS-1 built by MBB, Munich)</td>
</tr>
<tr>
<td>LDEF (Long Duration Exposure Facility)</td>
<td>STS-41-C, Apr. 6, 1984</td>
<td>NASA/LaRC free-flying S/C. Retrieval of LDEF on STS-32, Jan. 12, 1990</td>
</tr>
<tr>
<td>SPAS-II</td>
<td>STS-39, Apr. 28 - May 6, ’91</td>
<td>DoD payload</td>
</tr>
<tr>
<td>SPARTAN-201-1</td>
<td>STS-56, Apr. 8-17, 1993</td>
<td>Solar physics mission</td>
</tr>
<tr>
<td>ORFEUS-SPAS-1</td>
<td>STS-51, Sept. 12-22, 1993</td>
<td>ORFEUS-1 is a DARA/NASA science mission</td>
</tr>
<tr>
<td>SPARTAN-201-2</td>
<td>STS-64, Sept. 9-20, 1994</td>
<td>Solar physics mission coordinated with Ulysses south polar pass</td>
</tr>
<tr>
<td>CRISTA-SPAS-1</td>
<td>STS-66, Nov. 3-14, 1994</td>
<td>Joint flight of CRISTA-1 and ATLAS-3 mission</td>
</tr>
<tr>
<td>SPARTAN-204</td>
<td>STS-63, Feb. 3-11, 1995</td>
<td>Solar physics mission coordinated with Ulysses north polar pass</td>
</tr>
<tr>
<td>SPARTAN-201-3</td>
<td>STS-69, Sept. 7-18, 1995</td>
<td>Solar physics mission coordinated with Ulysses north polar pass</td>
</tr>
<tr>
<td>SPARTAN-206</td>
<td>STS-72, Jan. 11-20, 1996</td>
<td>Also retrieval of SFU (Space Flyer Unit)</td>
</tr>
<tr>
<td>SPARTAN-207</td>
<td>STS-77, May 19-29, 1996</td>
<td>Inflatable Antenna Experiment (IAE)</td>
</tr>
<tr>
<td>ORFEUS-SPAS-2</td>
<td>STS-80, Nov. 19, Dec. 7, 96</td>
<td>ORFEUS-2 is a DARA/NASA science mission</td>
</tr>
<tr>
<td>CRISTA-SPAS-2</td>
<td>STS-85, Aug. 7-19, 1997</td>
<td>Reflight of CRISTA-1 mission</td>
</tr>
<tr>
<td>SPARTAN-201-4</td>
<td>STS-87, Nov. 19-Dec. 7, 97</td>
<td>Solar physics mission coordinated with SOHO</td>
</tr>
<tr>
<td>SPARTAN-201-5</td>
<td>STS-95, Oct. 29 Nov., 98</td>
<td>Solar physics mission coordinated with SOHO</td>
</tr>
</tbody>
</table>

Table 43: Chronology of retrievable free-flyer structures on Shuttle missions

- Reusable space platforms. Flown on Shuttle flights as free-flyer structures for experiments/payloads with special requirements, and offering a number of service functions for

operational autonomy. SPAS-1 (Shuttle Pallet Satellite) on STS-7 initiated the free-flyer scenario.

- Large-diameter antenna deployment mechanism for GEO communication satellites. The new technology features a springback antenna design, developed by Hughes Space & Communications Company, now BSS (Boeing Satellite Systems) of El Segundo, CA. The springback design employs flexible graphite mesh antenna reflectors. The unique design not only provides a lightweight antenna, it also takes advantage of normally unused space in the top of the rocket fairing - instead of being folded against the spacecraft body for launch as conventional antennas are.

- The communication satellite MSAT-1 (Mobile Satellite System) of TMI Communications & Company Ltd. of Ottawa and of AMSC (American Mobile Satellite Corporation), with an antenna pair of 6.8 m by 5.25 m (elliptical shape), was the first spacecraft to demonstrate this technology (launch of MSAT-1 on Apr. 20, 1996).

- The TDRS-H, -I, and -J spacecraft of NASA with a pair of 4.8 m diameter flexible mesh antennas employ the same technology (since 1983). The reflectors fold up for launch, then spring back into their original cupped circular shape on orbit. The springback antennas are equipped with a mechanism to allow for on-orbit contour adjustments. It’s a cheaper, lighter (mass of 20 kg), better design and costs 1/10 as much as a conventional large antenna. TDRS-H was launched June 30, 2000; TDRS-I was launched March 8, 2002. Note: The successful demonstration of the springback antenna technology was so convincing to NASA to cause a switch in the TDRS (Tracking and Data Relay Satellite System) spacecraft series contract award from TRW to BSS.

- In March 2004, a 12 m diameter furlable mesh antenna (lightweight deployable reflector) with a mass of only 85 kg was successfully deployed in space on Japan’s MBSAT (Mobile Broadcasting Corporation Satellite). 736) The communication satellite in GEO, built by SS/L (1300 S/C bus), was launched on March 13, 2004 from Cape Canaveral, FLA. The reflector, referred to as AstroMesh™ reflector and developed by Northrop Grumman’s Astro Aerospace unit in Carpinteria, CA, is a very large aperture antenna of its kind. AstroMesh reflectors, which come in 6 m and 12 m designs, are made of a graphite composite tube truss structure that unfolds from a cylindrical stowed shape. The Thuraya-1 communication satellite of UAE (United Arab Emirates), built by BSS and launched in Oct. 2000, features also a 12 m AstroMesh antenna in L-band. 737)

  MBSAT enables MBCO (Mobile Broadcasting Corp. of Japan) and SKT (SK Telecom of Korea) to provide pioneering digital multimedia broadcasting information services such as high CD-quality audio, MPEG-4 video and data to mobile users throughout Japan and Korea who are equipped with receivers in cars, ships, trains, handheld terminals, cellular phones and home portables. The AstroMesh reflector is a key component of the MBSAT’s antenna systems, reflecting S-band radio frequency energy and focusing it into a pattern on the ground. – Obviously, the same large-aperture technology concept (with accurate surfaces and shape) may also be used in future EO missions in support of L-band radiometry, featuring for instance an array of MMIC (Microwave Monolithic Integrated Circuit) receivers in a push-broom configuration. 738)

- In the USA, new procurement strategies were introduced in the late 1990s with the projects GFO (GEOSAT Follow-On), NPOESS (National Polar-orbiting Operational Environmental Satellite System), LDCM (Landsat Data Continuity Mission), GOES-R, etc. The approach for these projects specifies performance objectives and goals, and requires a data specification of the parameters in the end products (their quality and quantity), rather

than a traditional system (i.e., satellite and payload) specification. In this concept, the design of the system is left to the contractor (fostering of creativity and reduction of costs).

- **MFS (Multifunctional Structures)** technology reduces spaceborne electronics size and mass with improved packing techniques. In the mid-1990s, an MFS development program initiative was launched by AFRL (Air Force Research Laboratory) and by BMDO (Ballistic Missile Defense Office) to reduce spacecraft mass and volume (to reduce launch costs). Lockheed Martin Astronautics Corp. (LMA) of Denver, CO, was given a contract to provide an innovative and enabling MFS design approach (eliminating “black boxes”, lots of cabling, harness, bulky connectors, etc.) by integrating spacecraft electronics, structural, and thermal control functions into a single structure. The MFS concept involved embedding passive—electronic components within the actual volume of composite materials, new approaches to attaching active—electronic components directly to mechanical surfaces, using surface areas for mounting sensors and transducers. This new packaging technology development reduced spacecraft mass and volume considerably.

The first MFS technology demonstration was flown on the STEX (Space Technology Experiment) mission of NRO (launch Oct. 3, 1998). Other missions followed like: DS1 (Deep Space 1, launch Oct. 24, 1998) of NASA, EO–1 (Earth Observing, launch Nov. 21, 2000) of NASA, and the STRV–1d (Space Technology Research Vehicle – 1d, launch Nov. 16, 2000) mission of DERA, UK. MFS is now a proven and accepted technology used in virtually all space missions.739) 740)

1.4.2.1 Introduction of COTS parts in spacecraft

Introduction of COTS (Commercial Off-The-Shelf) and PEMs (Plastic Encapsulated Microcircuits) electronic products as well as software products into spacecraft subsystems. For instance, in 1979 a group of radio amateurs and academics at the University of Surrey designed and built a 50 kg satellite using COTS microprocessors. With this the concept of the modern microsatellite was born. UoSAT-1 was launched Oct. 6, 1981 pioneering the way for a highly successful series of microsatellites. Since then SSTL (Surrey Satellite Technology Ltd) and the University of Surrey (Surrey, UK) has pioneered the use of COTS products like the commercial GPS technology for spaceborne applications. The PoSAT-1 mission, launched Sept. 26, 1993, was the first microsatellite to make use of a commercial GPS receiver in orbit (Trimble TANS-II receiver). COTS products are normally part of technology-class (and university) missions with emphasis on technology demonstrations, and not on the provision of long-duration support services. At the start of the 21st century, an ever increasing proportion of COTS and PEM products are being integrated into all types of spacecraft, including some military service (communications) missions.

Examples of EO missions: a) Jason-1 (launch Dec. 7, 2001) employs as much as possible electronic parts of commercial or military standard as opposed to the usual space standard; b) the GRACE twin S/C mission of 1.4.5NASA/DLR (launch March 17, 2002) contains about 80% of COTS products. About 5-6 years ago, a similar mission would have used only about 10% of COTS products. The demand of cheaper and affordable missions is the main reason for COTS products in S/C. Space-qualified products are extremely expensive due to the relatively small electronics space market and the long waiting periods for test opportunities (space products account only about 0.5% of the semiconductor market).741) 742)

740) http://www.afrlhorizons.com/0001/t.html#Dec00
COTS hardware products are generally not specifically radiation-hardened, or they may lack stiffness for the launch phase, or they do not provide a suitable temperature range for proper operation in a hostile space environment. The performance of COTS products with regard to processing power, etc., is generally always superior to space-qualified products, due to the availability to most recent developments in the electronics field. However, when reliability and long-term provision of service is the decisive mission criteria, then the space-qualified option might turn out to be the best choice. The amount of risk a mission can take on and the available budget dictate generally the percentage of COTS parts.

- Comparison of two computer systems on a spacecraft with regard to radiation hardness performance. The ARGOS (Advanced Research and Global Observation Satellite) mission of DoD (launch Feb. 23, 1999, see M.3) provides the first direct on-orbit comparison of a modern radiation hardened 32 bit processor (RH3000 of Harris) with a similar COTS processor (IDT-3081, a single chip implementation of the MIPS RISC architecture). An ECC (Error Correction Code) software technique was implemented with the IDT-3081 processor for autonomously correcting errant bit patterns for mass storage and communication devices. The investigation was motivated by the continuing need for higher capability computers for spaceflight use than can be met with currently available radiation hardened components. The comparison test was conducted within the USA (Unconventional Stellar Aspect) experiment of NRL and ASCAT (Advanced Space Computing and Autonomy Testbed), both part of the ARGOS payload. Both systems featured a package, referred to as SIHFT (Software-Implemented Hardware Fault Tolerance), providing corrections for radiation-induced SEUs (Single Event Upset) and for the purpose of performance analysis. The comparison test demonstrated that even though the RH3000 board uses radiation-hardened technology, the test applications showed a small non-vanishing number of errors occurring over time. The memory test collected 7 errors over 543 days of actual run time, resulting in an error rate of $3.1 \times 10^{-9}$ errors/bit-day. While this low rate reflects the memory technology in use, it is higher than the $< 1 \times 10^{-10}$ rate expected for the board. 743) 744)

During the same time period the various IDT-3081 tests of the COTS board produced a total of more than 2000 SEUs detected and more than 50 task exceptions and reboots. The overall error rate is $6.4 \times 10^{-7}$ errors/bit-day. The performance of the IDT-3081 demonstrates that it is possible to increase the reliability of a COTS system operating in the space environment. This is illustrated by the improvement in the reliability provided by the ECC routines. The error detection and correction software techniques are not able to correct all errors on the IDT-3081 board, resulting in more crashes than the RH3000 board experienced.

- MDS-1 (Mission Demonstration Satellite-1, referred to as Tsubasa) of JAXA (formerly NASA) in GTO (Geosynchronous Transfer Orbit) with a launch Feb. 4, 2002. The objectives were to verify the use of commercial parts in orbit (COTS components), to verify minimization technology for components, and to collect space environment data (e.g., radiation on equipment, etc.). 745) One of the onboard COTS devices was SSR (Solid State Recorder) of NEC Toshiba Space Systems Ltd., a high-density semiconductor device (32 Gbit capacity for mission data, 64 Mbit DRAM, EDAC, etc.). An analysis was performed after one year of spacecraft operations on a number of parameters, including SEU (Single Event Upsets) and TID (Total Ionizing Dose). The SSR operational performance was trouble-free (no minor/major failure on stack memory module of SSR). EDAC performance was

confirmed (all SEU bit errors were corrected). Operations of MDS-1 were terminated on Sept. 27, 2003 by JAXA.

- **SERVIS-1** (Space Environment Reliability Verification Integrated System-1) is a Japanese mission (launch Oct. 30, 2003) with the objective to develop technologies for the use of COTS parts under space environment conditions (establishment of COTS evaluation guidelines and equipment design guidelines to utilize COTS). The goal is to find solutions for cheaper spacecraft design and development. The SERVIS program of METI (formerly MITI) started in 1999 and is project until 2007. It includes two technology verification spacecraft with launches in 2003 and 2005.

It should be understood, however, that new and more capable onboard components can only be developed and introduced (cost-effectively) by using commercial standards in an open architecture environment, all of which are COTS products. This approach is for instance being taken by the selection of new onboard data bus systems (see 1.4.5). New bus examples are: CAN (Controller Area Network); FireWire (IEEE 1394a-2000), and SpaceWire (IEEE 1355-1995). See 1.4.5.

### 1.4.2.2 Satellite structure vibration/jitter damping

The operation of cryocoolers, needed for the cooling of detectors in the infrared region (to lower the thermal noise threshold), as well as attitude actuators (momentum wheels, power thrusters, etc.) introduce unwanted micro-vibrations into the satellite structure which in turn degrade the quality of instrument measurements. Examples of experiments involving vibration damping are:

- The STRV-1b satellite of DERA (launch June 17, 1994, see M.41.1.2) is flying CVSE (Cryocooler Vibration Suppression Experiment), provided by BMDO and JPL, to demonstrate a new vibration suppression design by employing piezoelectric actuators.

- The NASA/JPL CSE (Cryo System Experiment) demonstrated vibration suppression on Shuttle flight STS-63 (Feb. 3-11, 1995) in the launch phase and on-orbit by using the Hughes-built ISSC (Improved Standard Spacecraft Cryocooler) Stirling cooler and an experimental diode oxygen heat pipe.

- The TSX-5 mission of AFRL (launch June 6, 2000) carries VISS (Vibration, Isolation, Suppression and Steering System), a self-contained precision vibration control device designed to provide an ultra-quiet environment for sensitive optical sensors, laser transmitters, and other detection and measurement devices (M.48).

- SAMS-II (Space Acceleration Measurement System II) of NASA/GRC was delivered to ISS by STS-100 (Apr. 19- May 1, 2001). The objective is to detect the vibration environment present while the space station is in operation (crew and equipment). SAMS-II has a distributed architecture with multiple locations throughout the US Laboratory Module Destiny. SAMS-II uses small remote triaxial sensor systems that are placed directly next to experiments in various locations throughout the module. MAMS-II (Microgravity Acceleration Measurement System) is complementary to SAMS-II measuring accelerations caused by aerodynamic drag and by ISS roll movements (MAMS-II was also delivered on STS-100).

- SUITE (Satellite Ultraquiet Isolation Technology Experiment), a hybrid vibration isolation system of AFRL is flown on PICOSat (launch Sept. 30, 2001), a microsatellite of the USAF Space Test Program (STP). SUITE employs piezoelectric rather than electromagnetic actuators. The active portion of the system reduces vibration transmission at low frequencies and the passive portion attenuates high frequency inputs.

746) [http://www.usef.or.jp/english/f3_project/servis/f3_servis.html](http://www.usef.or.jp/english/f3_project/servis/f3_servis.html)
- ARIS (Active Rack Isolation System) of NASA/MSFC/JSC, developed by the Boeing Co., Seattle, WA. ARIS was installed in EXPRESS (EXpedite the PRocessing of Experiments to the Space Station) Rack No. 2, a standardized payload rack on ISS. Objective: monitoring of on-orbit vibration reduction during a variety of station activities, including crew sleep/wake periods, operation of SSRMS (Space Station Remote Manipulator System), etc. - the goal is to attenuate external vibration disturbances at selected payload locations. ARIS uses a combination of sensors and actuators to achieve vibration damping. Among these are accelerometer assemblies that measure vibration disturbances and send data to the ARIS electronic unit; pushrods that apply force against the framework of ISS; and a microgravity rack barrier that prevents accidental disturbance of the active ARIS rack. - ARIS-ICE (ARIS-ISS Characterization Experiment) is a separate payload created to characterize the on-orbit performance of ARIS. ARIS-ICE works in concert with SAMS-II and MAMS-II to characterize the range of vibrations onboard the Station.

ARIS was flown to ISS on STS-100 (Apr. 19-May 1, 2001) and set up during the week of May 25, 2001. ARIS-ICE was activated on June 12, 2001. The ARIS system became “operational” on ISS in April 2002. ICE was returned to Earth on STS 111 (June 5 - 15, 2002). A prototype of the ARIS system was already tested during the Shuttle STS-79 mission (Sept. 16-26, 1996) during which the Shuttle docked with the Russian space station MIR.

- The JAXA spacecraft OICETS (Optical Inter-orbit Communications Engineering Test Satellite) with a launch on Aug. 23, 2005 is carrying MVE (Micro-Vibration Measurement Equipment) to sense the vibration environment of the spacecraft.

- Control-Structure Interaction (CSI) in space vehicles. Structural vibration (jitter) and structural dynamics issues are the cause of many difficulties in spaceborne structures. CSI occurs when control detrimentally interacts with flexibility in the system. The space programs of the USA and Russia have a history of problems related to CSI, which have ranged from degrading spacecraft performance to causing catastrophic loss of the system.  The US MACE program (long-term collaboration effort of AFRL and NASA) explores CSI as a means for controlling rather than avoiding flexibility in space systems (in particular with regard to ISS), thereby penetrating this artificial performance barrier. The MACE (Middeck Active Control Experiment) program and its predecessor, MODE (Middeck 0-Gravity Dynamics Experiment), were designed to investigate the modeling and control issues related to high-precision pointing and vibration control of future space systems.

- MODE (Middeck 0-Gravity Dynamics Experiment), of the DoD STP program developed by MIT/SSL (Space Systems Laboratory); the MODE experiments were conducted on three Shuttle flights [STS-40 (Jun. 5-14, 1991), STS-48 (Sept. 12-18, 1991), and STS-62 (Mar. 4-18, 1994), respectively]. The objectives of MODE were to study suspension and gravity influences on the structural dynamics of a modular truss system by comparing the measured response in ground and orbital tests and to quantify the suspension and gravity induced perturbations using analytical models of the suspension and nonlinear effects (characterize fluid slosh, Space Station structure behavior, and crew motion dynamics in zero gravity).

- MACE (Middeck Active Control Experiment) flown on Shuttle (STS-67, March 2-18, 1995) for AFRL (developed by MIT). MACE consisted of three components: a multibody platform, experiment support module, and the handheld terminal. MACE, on STS-67, reduced vibration up to 19 dB and achieved a 25 Hz bandwidth of control (using a 50 Hz bandwidth disturbance).

- MACE-II (Middeck Active Control Experiment) is a follow-up experiment to the original MACE flight (MACE-II is sponsored and managed by AFRL and supported by two

748) http://www1.msfc.nasa.gov/NEWSROOM/background/facts/aris.html
749) http://ssl.mit.edu/programs/flight/mode.html
science teams, led by MIT and by the University of Michigan). The overall objective is use adaptive control algorithms for precision structural control. MACE-II is a significant step toward spacecraft autonomy; it consists of a hardware/software package that independently learns to control motion-dampening technologies and suppress unwanted vibrations. The first on-orbit demonstration of MACE-II took place on ISS (MACE-II was carried on STS-106 (Atlantis, Sept. 8 - 20, 2000) to ISS.

The MACE-II unit was returned to Earth on STS-105 Aug. 10-22, 2001), successfully completing all its experiment objectives while on Station (adaptive vibration control). MACE II relies on algorithms that enable it to adapt to changing conditions and correct problems without using a ground controller to exchange messages with the space shuttle. This technology, known as frequency domain expert control, is an advancement beyond MACE I, which was able to test and fix gained controls but unable to adapt to unforeseen changes or detect faults and failures in the hardware and technology. The MACE-II is a device of 1.5 m in length that floats free in a pressurized compartment. The unit has gimbals at each end and reaction wheels in the middle. One gimbal creates vibrations, which are detected and countered through complex computer algorithms, keeping the other end steady. Most important, these algorithms can modify themselves or “adapt” when they sense changes in the characteristics of the system - without human intervention.

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Note: The essence of MACE-II is that it creates the necessary control instructions “on the fly” to counteract unwanted disturbances without any input from a human being. These vibration control algorithms use embedded sensors and actuators to identify and counteract movement, all without requiring extensive modeling or ground testing. The algorithms can also adapt to changes in a structure caused by temperature fluctuations, moving parts, or the normal degradation of mechanical subsystems. Such autonomy is precisely the requirement aerospace engineers have in mind for spacecraft of the future.

1.4.3 Spacecraft power generation - solar cells, batteries, etc.

Electrical power is the prime resource for the provision of all spacecraft operations. Practically all spacecraft use the sun as a source of electrical power produced by solar arrays. Photovoltaic (PV) solar cells are the prime devices of conventional long-term electrical power provision for all Earth-orbiting satellites in LEO, GEO, HEO, MEO, etc. They convert solar radiation into electricity directly at the atomic level (by transforming photon energy into electrical energy). Their principle of operation is the same as that for photodiode light detectors. The solar energy, arriving at the top of the atmosphere, amounts to about 1.3-1.4 kW/m². This energy can be tapped by direct conversion into electricity through the use of solar cells.

Background: The energy supply from the sun is truly enormous; on average the Earth’s surface receives about $1.2 \times 10^{17}$ W of solar flux (representing only the tiny fraction of the sun’s energy that can be intercepted by the Earth). It amounts to a specific flux of about 1366 W/m² (generally accepted value) at the top of the atmosphere (or for a S/C in LEO). This means that in less than one hour enough energy is supplied to the Earth to satisfy the entire energy demand of the human population over an entire year. Indeed, it is the energy of sunlight, assimilated by biological organisms over millions of years, that has made possible the industrial growth as we know it today. Most of the other renewable means of power generation also depend on the sun as the primary source: hydroelectric, wind and wave power all have the same origin.

Historically, solar energy generation dates back to 1839, when Alexandre Edmond Becquerel, a French physicist (1820-1891), first observed the phenomenon of the photoelectric effect while experimenting with an electrolytic cell containing two metal electrodes exposed to sunlight (see Glossary). The photoelectric effect or better, the “photovoltaic effect,” is the basic physical process through which a PV cell converts sunlight into electricity. In 1904, Albert Einstein published his paper on the photoelectric effect (or the release of electrons from metal when light shines on it), in 1921 he received the Nobel Prize for this theory of the photoelectric effect.

However, the process of producing electric current in a solid material using sunlight wasn’t truly understood until the arrival of semiconductor technology in the 1940s. The space age, in particular, has played an important role in the development of photovoltaics - requesting ever increased power to accommodate its science instrumentation, housekeeping, communication, and attitude subsystems. Over the years, the main effort has been to increase the conversion efficiency of silicon-based semiconductor technology; another important aspect was to extend their life times (improved radiation hardness response), the end-of-life (EOL) power generation capability per unit mass (W/kg). Photovoltaic power generation is reliable, it involves no moving parts, the operation and maintenance costs are very low. The operation of a photovoltaic system is silent creating no pollution. Photovoltaic systems are modular and can be quickly installed.

The following list represents some development stations in the history of PV technology related to the topic of space applications (naturally, there are many other fields of PV applications today, including many government programs, in many countries, to foster the use of alternative energies):

- In 1883, the American inventor Charles Fritts was probably the first to build a solar cell. He used junctions formed by coating selenium (a semiconductor) with an extremely thin layer of gold - exposed to sunlight. He achieved an energy conversion efficiency of < 1%.

- In 1927, the first solar cells were made from copper and copper oxide.

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752) http://www.soton.ac.uk/~solar/intro/intro.htm
753) http://www.pvpower.com/pvhistory.html
- In the 1930s, both the selenium cell and the copper oxide cell were being employed in light-sensitive devices, such as photometers, for use in photography. They also had conversion efficiencies of < 1%.


- In 1954, G. L. Pearson, Daryl M. Chapin, and Calvin S. Fuller of the AT&T Bell Telephone Laboratories, Murray Hill, NJ, were the first to demonstrate a crystalline silicon photovoltaic (PV) cell with an efficiency of about 4% (a few months later of 6%). A patent, “Solar Energy Converting Apparatus,” was submitted in March 1954 (and officially issued in 1957). This was the first practical silicon cell available.

- In 1957 (at the start of the space age), the Hoffman Electronics Corp. (of El Monte, CA, and Evanston, IL) achieved 8% efficiency on its PV cells. In 1960, 14% efficiency was obtained by the same company. Crystalline silicon was the original materials technology used by the PV industry.

- March 17, 1958, successful launch of Vanguard-1 with the first PV-powered solar cell system in space. The solar cell was the backup power system of this S/C (< 1 W, approx. 100 cm², powering a 5 mW backup transmitter) and was used to power its radio, referred to as “Minitrack transmitter” which operated at frequencies of 108.0 and 108.3 MHz (VHF). Vanguard-1 was a small satellite, a magnesium sphere of 16.3 cm in diameter, < 2 kg mass; it contained two power systems for the two Minitrack transmitters: 1) a short-life battery as prime (seven mercury cell batteries in a hermetically sealed container), and 2) the solar cell system as backup consisting of six clusters of 16 silicon solar cells each. The solar cells were mounted on the surface of the sphere. Solar power, it turned out, functioned perfectly and kept Minitrack on the air for more than six years (until 1965). The battery-powered prime transmitter gave up after the short battery life of a few days. The PV technology has been developing ever since. The solar cells were manufactured by the Bell Laboratories, the solar cell technology was introduced/managed on Vanguard by SRDL (Signal Research and Development Laboratory), Fort Monmouth, NJ (of the US Army Signal Corps). The Vanguard project, the first US satellite program, was managed by the US Navy, the S/C was built at NRL (Naval Research Laboratory), Washington DC. The orbit of Vanguard-1 was elliptical at about 750 km x 3900 km, inclination of 34.2º. The orbital life of Vanguard-1 is estimated to be 240 years.

Background: The first artificial satellite, Sputnik-1, carried a chemical battery (a silver-zinc accumulator - which accounted for some 38% of the spacecraft’s total mass of 83.6 kg) that provided just one watt of power. Since then, the sophistication of spacecraft has increased power demands by many orders of magnitude. Moreover, the lifespan of spacecraft power systems is a determinant of the lifespan of the spacecraft. Sputnik-1 lasted just three weeks; the International Space Station (ISS), with replaceable batteries and long-lived solar arrays, is designed to last decades.

- May 15, 1958, launch of Sputnik-3 from Baikonur. The satellite carried the first Russian-developed solar power PV cell system (according to Ref. 755). Further cell details are not available. Sputnik-3 had a mass of 1,327 kg, its orbit was elliptical (217 km x 1,864 km), inclination of 65.2º. Sputnik-3 was a geophysical laboratory, performing experiments on the Earth’s magnetic field, radiation belt, and ionosphere. Data was transmitted until Apr. 6, 1960.

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755) http://www.infoage.org/tac-zig23.html
- OSCAR-1, the first Amateur radio satellite (launch Dec. 12, 1961), carried a small battery-powered pack only. The S/C transmitted continuously the Morse code identifier to amateur receivers on Earth until its battery ran down.

- The Apollo-11 mission (launch July 16, 1969) placed the first solar panel on the moon. Apollo-11 was the first US lunar landing mission with Neil A. Armstrong, Michael Collins and Edwin E. Aldrin.

- In 1976, the amorphous silicon (a-Si) cell was developed by David Carlson and Christopher Wronski at the RCA Laboratories, Princeton, NJ.

- In the late 1970’s, the photovoltaic industry attracted the interest of large energy companies and government agencies. With their investment of capital, a tremendous acceleration in module development took place.

- In 1977, Hideki Shirakawa, Alan J. Heeger, Alan G. MacDiarmid and co-workers at the University of Pennsylvania demonstrated that halogen-doped polyacetylene had a conductivity $10^9$ times greater than the undoped material (at the time, plastics were considered nonconductors). Since their discovery (all three received the Nobel Prize in Chemistry in 2000), conducting polymers have found applications in electronic components, also in solar cells. 757)

- In the early 1980s, the Boeing Co. (Seattle, WA) pioneered a new kind of thin-film PV cell technology based on copper indium diselenide (CuInSe$_2$), later simply referred to as CIS (even when gallium and sulfur are added). The CIS compound displayed some very attractive qualities: sunlight absorption was the strongest of any PV material (absorbing over 90% of available light within 0.2 microns), and the capability of producing high-efficiency cells. In 1981, a CIS conversion efficiency of 10% was obtained. The CIS thin-film solar cell technology is vapor-deposited on a flexible substrate which is substantially lighter than cells bonded to a rigid panel.

- In the 1980s, silicon cells offered EOL efficiencies ranging from 13-16%, while the costlier GaAs cells delivered efficiencies of 16-19%.

- June 1986. ARCO Solar of Camarillo, CA, released the G-4000 - the world’s first commercial thin-film “power module.” Note: As of 1990, Siemens AG of Germany bought ARCO Solar from the Atlantic Richfield Company. The new company is called Siemens Solar Industries (the world’s largest producer of PV cells).

- In the 1990s the silicon cell efficiency improved to 17-18%. 758) 759) Still better cells were made from GaAs (Gallium Arsenide) and GaAs/Ge with efficiencies of 19-21%. Silicon (Si), Gallium Arsenide on Germanium (GaAs/Ge), and multijunction solar cells are technologies that involve crystal growth on a fragile wafer. The CIS thin-film efficiency reached 17.7% in 1996.

Also in the 1990s, the first polymer photocells were produced. Polymer PV cells are cheaper and easier to make than inorganic cells; they permit the fabrication of flexible photodetector arrays (fabrication process identical to that of LEDs).

- In Jan. 1994, a joint US/Russian program MCSA (MIR Cooperative Solar Array) was created between NASA/LeRC and RKK Energia with the objective to construct and test a jointly made solar array. 760) On Nov. 12 1995, the MCSA was launched on Shuttle Atlantis (STS-74) and installed on MIR, supporting experiments conducted on MIR by visiting NASA astronauts during the Phase I Shuttle/MIR program. Successful MCSA operation

759) “NREL World Record Thin-Film Cell Efficiency,” URL: www.nrel.gov/ncpv/pdfs/tf_nrel2.pdf
760) http://space—power.grc.nasa.gov/ppo/projects/mcsa/index.html
also served as early validated of the ISS solar arrays. In-orbit measurements made by the MIR crew of the MCSA's electrical output were used to validate predictions made with a NASA solar array electrical performance computer model. The MCSA consisted of 42 hinged panels with two PPMs (Photovoltaic Panel Module) to each panel. Size: 18 m x 2.7 m; mass = 476 kg; power = 6 kW at 29-33 V. There are 6,720 solar silicon cells in the entire solar array. A PPM is a collection of 80 large-area silicon solar cells in a 5 cell x 16 cell matrix (PPM size: 0.44 m x 1.30 m, average power = 88.5 W, mass = 0.75 kg without frame).

- In 1997, AEC-Able Engineering Co., of Goleta, CA (in cooperation with Entech Inc. and Spectrolab Inc., the program was sponsored by BMD0 and NASA/GRC), developed and introduced a new variant of solar cells, referred to as SCARLET (Solar Concentrator Array with Refractive Linear Element Technology).\(^{761}\) The method employs curved, glass-composite optics to concentrate the solar energy on a strip of photovoltaic cells (use of cylindrical silicone Fresnel lenses to concentrate sunlight onto GaInP\(_2\)/GaAs/Ge cells). Efficiencies of 22% were obtained. Some inherent benefits of concentrator arrays are: a) high array efficiency, b) protection from space radiation effects, and c) minimized plasma interactions. - A disadvantage of this technique is that the solar panels have to be pointed and stabilized (e.g., articulated toward the sun) for maximum output. SCARLET-II is flown on Deep Space 1 (launch Oct. 24, 1998), it uses dual-junction solar cells.

Note: Key components of concentrator arrays were already successfully tested in space on an USAF experiment called PASP-plus (Photovoltaic Array Space Power-Plus Diagnostics) that was launched on APEX (Advanced Power Experiment) Aug. 3, 1994. PASP-plus flew a panel of mini-dome concentrators and proved that their performance was steady and that degradation was much less than with planar arrays. SCARLET was developed and qualified for flight on NASA's METEOR-1 (Multiple Experiment Transporter to Earth Orbit and Return) spacecraft. However, a launch failure occurred on the first Conestoga 1620 launch from Wallops Island (Oct. 23, 1995).

- DS1 (Deep Space 1, launch Oct. 24, 1998) of NASA is the first S/C to rely exclusively on refractive concentrator arrays, it is among the first to use only multi-bandgap cells. The first dual-junction cells were introduced in 1997 (Spectrolab of Hughes Electronics Corporation and HSC, who built PAS-5) with an efficiency of about 21%. Spectrolab Inc. produced also triple-junction solar cells in 1998 (efficiency of 27%). Spectrolab HQ is in Sylmar, CA (near Los Angeles).

- Nov. 1998. Early versions of the FTFPV (Flexible Thin-Film Photovoltaic) blanket modules, developed by United Solar Power Corp. (United Solar) of Troy, MI (Uni-Solar as of 2000), were installed and tested on the MIR space station for a period of 19 months (with Energia support).\(^{762}\)\(^{763}\) Cells based on FTFPV technology are low-cost because they can be grown on just about any surface, whereas conventional solar cells are produced on crystal wafers. The solar modules are the subject of a new joint development and testing program between United Solar, Kvant GNPP, the leading Russian enterprise in space PV technology, RSC Energia (Energia), the operator/manager of the MIR Space Station, and Sovlux, a Russian-American joint venture owned by United Solar, Kvant of Moscow and the Russian Ministry of Atomic Energy.

- 2002. Hybrid solar cells in a semiconductor-polymer photovoltaic device were demonstrated by researches at LBL (Lawrence Berkeley Laboratory) of UCB. The new generation of solar cells combines nanotechnology with plastic electronics. Ever since the discovery in 1977 of conducting plastics (polymers which feature conjugated double chemical

761) Note: Solar concentrators reflect radiation so as to expose the cells to more radiation, together with multijunction devices that capture a larger slice of the spectrum (UV, VNIR, and IR). Efficiencies of about 30% and more are expected to be achieved in the early years of the next decade.


bonds, that enable electrons to move through them), there has been interest in using these materials in the fabrication of solar cells. Plastic solar cells can be made in bulk quantities for a few cents each. So far, the conversion efficiency of the Berkeley hybrid cells was only 1.5% at AM1.5 (which corresponds to a sun-zenith angle of 48°). See Glossary for Air-mass definition.

- AFRL (Air Force Research Laboratory) at Kirtland AFB, NM, is funding a program called LFSA (Lightweight Flexible Solar Array) to demonstrate key array technologies on four space flights.

  - The first space opportunity 764) consisted of a successful flight experiment of a Shape Memory Alloy (SMA) deployment hinge experiment that was demonstrated on Shuttle flight STS-93, July 23-28, 1999 (hinges are the primary mechanism used to deploy solar arrays that are folded at launch). The hinge operations for the experiment were reported by the crew as nominal (six SMA hinges were tested).

  - The second flight opportunity consisted of a sub-scale two-panel solar array that was demonstrated on NASA's Earth Observing-1 (EO-1) spacecraft (launch Nov. 21, 2000). The new solar array technology is referred to as LFSA (Lightweight Flexible Solar Array) experiment, sponsored by AFRL, managed by GSFC, and built by Lockheed-Martin Astrotech, Denver, CO). EO-1 has two solar panels, the wide-wing-like extension employs conventional PV technology with GeAs/Ge cells, and an experimental LFSA panel on the underside of the S/C. LFSA consists of very lightweight composite, window frame-like structures that contain the thin-film CIS solar cells (with polyimide substrate), and SMA (Shape Memory Alloy) technology for the hinge and deployment systems (shape memory alloys are novel materials that have the ability to return to a predetermined shape when heated). The LFSA solar cell modules are 10 cm x 10 cm in size, each module consist of 15 monolithically-interconnected cells in series. 765) 766) 767) The AM0 (Air-Mass-Zero) module efficiency achieved for this size was about 2%. The hinges were deployed by means of heaters powered by the S/C bus (28 V). SMAs undergo a reversible crystalline phase transformation that is the basis of the “shape memory effect.” - The deployment demonstration turned out to be successful. The new alloys offer a “shockless” solar array deployment technique, a much safer method than conventional solar array systems that use explosives for deployment. In addition, LFSA aboard EO-1 offered an unprecedented specific power-to-weight ratio of 100 W/kg, compared to the 40 W/Kg supplied by conventional solar arrays on satellites today.

  - Another demonstration of LFSA technology is planned for the Encounter spacecraft (a commercially funded mission), being developed by Team Encounter LLC of Houston, TX. 768) 769) 770) The LFSA array will be the primary power source for the Encounter sailcraft, called Earthview, for a secondary launch in 2005 on Ariane-V. The S/C bus of Earthview is being built by Microsat Systems of Littleton, CO, the inflatable boom and solar sail (400 m² sail area) are being developed by L’Garde of Tustin, CA, and the High Definition TV Camera will be built by Ecliptic Enterprises Corp. of Pasadena, CA. NASA and NOAA have considerable interest in the Earthview mission and its technology providing some assistance to Team Encounter.

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766) http://www.vs.afrl.af.mil/News/00---03.html
769) http://www.teamencounter.com/starship/mission_2.asp
Global solar energy production. About 90 MW of photovoltaic power modules were produced worldwide in 1996 (for Earth-bound applications such as solar roof installations), the figure was 135 MW for 1997 and 360 MW for 2001. Of the global demand for solar photovoltaics (PV), approximately 30% is accounted for by Japan, 20% by European countries and less than 10% by the USA. All indications are that direct conversion of light into electricity, or photovoltaics, is becoming accepted as an important form of power generation in the future. Still, at this stage photovoltaics remains the costliest among the renewable energy sources. – Note: As of 2007, 55% of the PV capacity worldwide is installed in Germany. The main reason for Germany’s leading position in PV energy is the Renewable Energies Act. The law requires power companies to buy electricity from the owners of PV installations at a set price. 771)

Conventional solar arrays of the late 1990s provide power/mass ratios of <40 W/kg. Silicon solar cells are made using either single crystal wafers, polycrystalline wafers, or thin films. Amorphous silicon, one of the thin-film technologies, is made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH₄). Since single PV cells have a working voltage of about 0.5 V, they are usually connected together in series (positive to negative) to provide larger voltages.

At the start of the 21st century, the state of the art in solar array technology provides specific power levels of 45-80 W/kg and packing efficiencies of about 8 kgW/m³. These systems represent a power generation cost of approximately $1000-2000/W. Some examples of large power installations in space are:

- ISS (International Space Station). The STS-97 assembly flight of Endeavour (Nov. 30 - Dec. 11, 2000) brought the P6 Integrated Truss Segment to ISS. The P6 consists of two identical PVAs (Photovoltaic Array Assembly), each of which is made up of an SAA (Solar Array Assembly) and a SAW (Solar Array Wing). The two SAWs have a power generation capability of about 64 kW each. The ISS electrical bus system uses 120 V of DC power.
- EnviSat of ESA (launch March 1, 2002), the EO (Earth Observation) satellite with a record mass of 8140 kg, provides an onboard electrical power of 6.5 kW (EOL).
- The commercial platform HS-702 of BSS (Boeing Satellite Systems) provides power levels of 10-15 kW. The first communications satellite with this platform is Galaxy-11 of PanAmSat Corp., launched Dec. 21, 1999. HS-702 bus has a design life of 15 years.
- A successor communications satellite on the HS-702 platform, Galaxy-IIIC (launch June 15, 2002 into GEO) of PanAmSat Corp., provides a power level of 15 kW (EOL). The solar power array consists of 2 wings each with six panels of improved triple-junction gallium arsenide (ITJ GaAs) solar cells of Spectrolab with a minimum average efficiency of 26.5%, and a battery pack of NiH cells at 328 Ah capacity. Galaxy-IIIC is the highest capacity S/C in orbit at the start of its service life.
- The Astra-1K (launch Nov. 25, 2002) commercial communications satellite of SES Societe Europeenne des Satellites) Luxembourg, built by ASI (Alcatel Space Industries) of France, provides 13 kW of solar power (S/C mass of 5250 kg, wingspan of 36 m). The S/C is outfitted with 10 reflector antennas and 52 active active Ku-band transponders to provide coverage for Europe. Note: A launch failure occurred due an upper stage malfunction (Proton K/DM3 launch vehicle from Baikonur) leaving Astra-1K in a useless orbit.
- The TFSC (Thin-Film Solar Cell) technology 772) 773) 774) offers large reductions in power cost and in weight over traditional cells. However, due to their relatively low efficiency the needed thin-film arrays turn out to be quite large. At the start of the 21st century the

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771) [http://www.solardaily.com/reports/Germany_L eading_The_International_PV_Market_999.html](http://www.solardaily.com/reports/Germany_Leading_The_International_PV_Market_999.html)
US military (AFRL) is developing a new PowerSail (PS) program to meet the power requirements of future missions (Space Based Radar, Space Based Lidar, etc.). The goal of the PS initiative is to develop a scalable solar power generation array technology with performance levels of up to 100 kW; the specific power increases with the new technology are estimated to be 3-5 times higher than conventional systems, there is also a reduction in packing volume and cost. The PS concept replaces the thin polyimide blanket with an FTFPV (Flexible Thin-Film Photovoltaic) solar cell blanket; the technology is also referred to as FITS (Foldable Integrated Thin-Film Stiffened) array.

An FTFPV blanket consists of a thin-layer deposition of amorphous or polycrystalline semiconductors onto a lightweight polymer or steel substrate. This configuration permits the FTFPV structure to be pointed (directed into the sun) and to be used in a similar fashion as the Kapton sail. Four key technologies are targeted to support this program: large deployable/inflatable structures, FTFPV blankets, advanced GNC (Guidance Navigation and Control), and electric propulsion. The PowerSail flight demonstration is based on a 50 kg system package and is expected to be flown in the time frame of 2007.

<table>
<thead>
<tr>
<th>PV solar cell type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline silicon (c-Si)</td>
<td>C-Si is the leading commercial material for photovoltaic cells, and is used in several forms: single-crystalline or monocrystalline silicon, multicrystalline or polycrystalline silicon, ribbon and sheet silicon and thin-layer silicon.</td>
</tr>
<tr>
<td>Thin-film photovoltaic cells</td>
<td>They use layers of semiconductor materials only a few micrometers thick, attached to an inexpensive backing such as glass, flexible plastic, or stainless steel. Semiconductor materials for use in thin films include amorphous silicon (a-Si), copper indium diselenide (CIS), and cadmium telluride (CdTe). Amorphous silicon has no crystal structure and is gradually degraded by exposure to light. Because the quantity of semiconductor material required for thin films is far smaller than for traditional PV cells, the cost of thin film manufacturing is far less than for crystalline silicon solar cells.</td>
</tr>
<tr>
<td>Group-II-IV technologies</td>
<td>They are based on Group III and V elements in the Periodic Table. The PV technologies display very high conversion efficiencies under either normal sunlight. Single-crystal cells of this type are usually made of gallium arsenide (GaAs). Gallium arsenide can be alloyed with elements such as indium, phosphorus, and aluminum to create semiconductors that respond to different energies of sunlight.</td>
</tr>
<tr>
<td>Multijunction devices</td>
<td>Multijunction devices stack individual solar cells on top of each other to maximize the capture and conversion of solar energy. The top layer (or junction) captures the highest-energy light and passes the rest on to be absorbed by the lower layers. Much of the work in this area uses gallium arsenide and its alloys, as well as using amorphous silicon, copper indium diselenide, and gallium indium phosphide. Although two-junction cells have been built, most research is focusing on three-junction (thyristor) and four-junction devices, using materials such as germanium (Ge) to capture the lowest-energy light in the lowest layer.</td>
</tr>
</tbody>
</table>

Table 44: Overview of photovoltaic (PV) solar cell technologies

The FTFPV blanket technology shows great potential for use in future space solar array designs. This is due to it’s increased specific power (W/kg), lower cost and enhanced radiation-resistance compared to conventional single-crystal solar cell technologies such as silicon and gallium arsenide multijunction cells. The high specific power of FTFPV blankets derive from the deposition of ultra-thin (<10 μm) layers of semiconductor absorber material on flexible thin (25-75 μm) polymer or steel substrate blankets. The semiconductor layers are typically deposited onto large polymer or steel sheets using low-cost evaporation, sputtering, or plasma-enhanced techniques. The leading FTFT candidates under development are amorphous silicon (a-Si) and polycrystalline copper indium gallium diselenide (CIGS) and it’s alloys. Current solar-to-electric conversion efficiencies are about 8-9% (AM0, 774) K. Zweibel, “Thin Films: Past, Present, Future,” http://www.nrel.gov/ncpv/documents/thinfilm.html
space spectrum) for large area (500 - 1000 cm²) a-Si and 6-8% (20 cm²) for CIGS on stainless steel. The goal is 10-12% by 2002. 

- Combing energy generation and communication functions into one structure: SOLANT (Solar Antenna Concept), an ESA-funded project in the time frame Oct. 1998 to March 2000 (the follow-up project “ASOLANT” started in June 2000). SOLANT refers to a new antenna design which combines the functions of solar cells (energy) and printed antenna patches (communication) into one structure. The idea is to use thin-film solar panels, which generally occupy large surface areas of a satellite structure, for antenna mounts or prints, provided the system is in itself compatible. Printed antennas, commonly used in microwave communications, are naturally suited for this combination, in particular when their radiating patches can be isolated from the feed circuits. Amorphous silicon (a-Si) solar cell technology has been found to be suitable for realizing the solar antennas.

The SOLANT concept was demonstrated in the MITA platform (MITA S/C launch Jul. 15, 2000) of ASI, Italy, using the combination of specially designed slot antennas with high efficiency GaAs solar cells. The entire antenna is composed of a low-gain half-omni directional antenna and of a 2 cm x 2 cm element high-gain array. The low-gain antenna has a bandwidth allowing the coverage of the uplink and downlink bands (2025 MHz-2290 MHz) based on the low-gain antenna.

<table>
<thead>
<tr>
<th>System/Technology</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin GaAS/Ge solar cells</td>
<td>Mass saving, flown on many S/C such as UoSats series (since UoSats-5, launch: July 17, 1991)</td>
</tr>
<tr>
<td>Multijunction solar cells</td>
<td>MightySat-I (launch of STS-88, Dec. 4, 98) uses InP (Indium Phosphide) dual-junction solar cells;</td>
</tr>
<tr>
<td></td>
<td>STEX (launch Oct. 3, 1998) uses dual-junction solar cells</td>
</tr>
<tr>
<td></td>
<td>PAS-5 (launch July 30, 1997) is the first commercial S/C to use dual-junction GaAs solar cells</td>
</tr>
<tr>
<td></td>
<td>STARSHINE-3 (launch Sept. 31, 2001) uses triple-junction cells, namely GaInP/GaAs/Ge cells of Emcore Corporation (experiment)</td>
</tr>
<tr>
<td>Concentrators for solar cells</td>
<td>DSI (launch Oct. 24, 1998) employs refractive concentrator arrays (SCARLET-II) in combination with cylindrical lenses and dual-junction GaInP2/GaAs/Ge solar cells</td>
</tr>
<tr>
<td>Lightweight solar arrays</td>
<td>Cells on flexible Kapton substrate and inflatable Torus solar array.</td>
</tr>
<tr>
<td></td>
<td>LFSAs (Lightweight Flexible Solar Array) is a technology demonstration on EO-1 (launch Nov. 21, 2000)</td>
</tr>
<tr>
<td>Micromachined blue-red reflective cover glasses</td>
<td>Increase of solar cell efficiency</td>
</tr>
</tbody>
</table>

Table 45: Emerging solar cell technologies at the start of the 21st century

- The Rosetta deep space mission of ESA (launch March 2, 2004) represents a rather special case of solar cell technology use. At its destination in 2014 [rendezvous with Comet 67P/Churyumov-Gerasimenko, (discovered in 1969), followed by an orbital period around the tiny comet of 4 km diameter, etc.], the spacecraft is at a distance of about 675 million km from Earth, corresponding to 4.5 AU, a distance as far out as Jupiter. In Earth orbit, Rosetta

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is the most powerful S/C that ESA ever built, at 12 kW of installed solar power generation provided by two solar arrays, each of 14 m length and each of 32 m² in area. But at the deep space distance of Comet 67P/Churyumov-Gerasimenko, the total solar power available is only 400 W. — Rosetta is the first deep space mission ever to rely entirely on solar power generation beyond the main asteroid belt (with sunlight levels of only 3-4% as those in LEO) — without the use of RTG (Radioisotope Thermoelectric Generator) technology (as is being done by all other deep space satellites). 781) 782) 783)

1.4.3.1 Electric power subsystem (EPS) on spacecraft

- An EPS of a conventional spacecraft normally consists of the following elements: a solar array for power generation, a power conditioning electronics unit providing a regulated or unregulated bus voltage, and a battery for energy provision to all required satellite functions during eclipse phases of the orbit. The EPS mass is generally dominated by the solar array and battery mass portions (the electronics unit represents the smallest portion of the mass).

- JHU/APL offers an innovative architecture in EPS design for small spacecraft systems (micro and nanosatellites). The patented system is called IPS (Integrated Power Source). IPS includes highly integrated electronics technologies as well as the integration of functions (normally implemented in separate elements) which combines energy storage (a matrix of LI battery cells), solar array electronics (dual-junction solar cells), and processor-based charge control electronics into a single structural element. 784)

- A new stand-alone power/storage package, named IMPS (Integrated Microelectronic Power Supply), was also developed at NASA/GRC. It provides the capability of power generation and power storage for microelectronic applications - by combing a thin-film photovoltaic array with a thin-filmlithium-ion battery. The first version of IMPS is being flown on STARSHINE-3 (launch Sept. 30, 2001, reentry Jan. 21, 2003; see N.25.3).

Satellites with large power demands normally employ sun tracking with the solar array (also referred to as “sun articulation”) to maximize their power generation capability. This requires usually a drive mechanism (gimbals, control, etc.) to adjust the array(s), generally normal to the sun direction, during the spacecraft’s orbit, for peak power generation results. There are still cases left in satellite operations when the power subsystem of a S/C can’t meet the power demands of its payload. This situation occurs usually with satellites carrying an active payload (SAR and/or lidar instruments) in addition to a passive payload (example: ERS-1/2). These cases are operationally handled with the introduction of a “duty cycle,” representing the fraction of the orbital period, in which a power-hungry instrument can be operated. Hopefully, these observational limitations may soon become a relict of the past with the introduction of power-efficient instrumentation as well as with more efficient power generation capabilities.

- Satellite batteries. Batteries have been in use for spaceflight applications since the flight of Sputnik-1. Since that time, batteries have matured from non-rechargeable one-use power systems to rechargeable multi-use backup power systems. In the early years of space-flight, relatively short flight times encouraged the use of batteries as a primary source of power. As the mission durations grew longer, solar and nuclear energy took as the primary sources. This development sparked the need for batteries as secondary power sources - for operations support during ecliptic orbit phases as well as for support during peak power de-

782) http://www.esa.int/export/SPECIALS/Rosetta/ESAS7F7708D_1.html
mand periods. Batteries, therefore, remain an essential component of spaceflight. Some essential characteristics of a battery are: required power, mission lifetime, system mass, and cost. Non-rechargeable primary batteries are still being used today on short demonstration flights of nanosatellites and picosatellites. Example: The PICOSAT1.0 mission of the USAF (launch Jan. 27, 2000, see N.18.3), flown on OPAL and deployed as a separate S/C, employed only batteries to test low-power communications.

A battery consists of several subunits called cells. Early batteries on satellites were silver-zinc (AgZn) non-rechargeable (primary) batteries. These provided the best compromise among several characteristics such as lifetime, energy density, and mass. Later, in the early 1960s, rechargeable AgZn batteries were used for the first time on the Ranger missions. The rechargeable Nickel Cadmium (NiCd) batteries were introduced in the mid-1970s, they remained the battery standard for most missions practically up to the start of the 21st century. A disadvantage of the NiCd battery is the memory effect that causes them to lose their capacity for full recharging if they are discharged repeatedly. The effect was first noticed in aerospace applications.

![Figure 20: Overview of EPS elements in a spacecraft](image)

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Time frame of introduction</th>
<th>Energy density (Energy/unit mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgZn (Silver Zinc)</td>
<td>Since the 1950s (first as non-rechargeable battery). The cell is reliable and inexpensive.</td>
<td>50-100 Wh/kg</td>
</tr>
<tr>
<td>NiCd (Nickel Cadmium)</td>
<td>Since the mid-1960s (and the 1970s).</td>
<td>20-30 Wh/kg</td>
</tr>
<tr>
<td>NiH₂ (Nickel Hydrogen)</td>
<td>In the early 1980s. Improved energy density and cycle lifetime</td>
<td>36-40 Wh/kg</td>
</tr>
<tr>
<td>NiH₂ (Nickel Hydrogen)</td>
<td>At the end of the 1990s</td>
<td>45-50 Wh/kg</td>
</tr>
<tr>
<td>Li-ion (Lithium-Ion)</td>
<td>Introduction at turn of the 21st century. STRV-1d of QinetiQ (launch Nov. 16, 2000) uses a Li-ion battery. PROBA of ESA (launch Oct. 22, 2001) uses a 36-cell Li-ion battery of 9 Ah capacity.</td>
<td>60-120 Wh/kg (potential up to 170 Wh/kg)</td>
</tr>
<tr>
<td>SPE (Solid Polymer Electrolyte) fuel cell</td>
<td>Introduction on PICOSat (launch Sept. 30, 2001). SPE is a fully regenerative fuel cell</td>
<td>20-90 Wh/kg</td>
</tr>
<tr>
<td>Fuel cell (alkaline)</td>
<td>Rechargeable fuel cells is the emerging technology of the 21st century. So far the Shuttle Orbiter uses fuel cells to generate electricity through the combination of oxygen and hydrogen (about 7 kW at 28 V).</td>
<td>about 90 Wh/kg</td>
</tr>
</tbody>
</table>

Table 46: Overview of the rechargeable battery evolution for spacecraft

Higher efficiency Nickel Hydrogen (NiH₂) cells were first introduced on the NTS-2 (Navigation Technology Satellite-2) with a launch on June 23, 1977 (NiH₂ batteries have the ad-

785) “Spacecraft Power Generation,” a document prepared by graduate students at The University of Texas at Austin, Department of Aerospace Engineering and Engineering Mechanics, 1992, www.tsgc.utexas.edu/archive/subsystems/power.pdf
786) http://www.mssl.ucl.ac.uk/~pdt/lectures/3C64/strand1/powergen/powergen.html
vantage of a high number of charge-discharge cycles; the NiH$_2$ battery was developed by Comsat).\textsuperscript{787} NTS-2 is considered the first NAVSTAR GPS satellite series, built by the NRL (Naval Research Laboratory), Washington, DC, to provide near-instantaneous navigation and time—synchronization service on a worldwide, continuous basis. There are several designs of NiH$_2$ batteries available: Individual pressure vessel (IPV), Single Pressure vessel (SPV) and dependent pressure vessel (DPV). The performance varies according to the design used, ranging from 50—75 Wh/kg.

The Lithium-Ion (Li-ion) battery still holds greater promises in efficiency at the turn of the 21st century. Li-ion batteries are already common devices in such appliances as cell phones and laptop computers. They have no memory effect and do not use poisonous metals, such as lead, mercury or cadmium.

- The orbit of ISS (International Space Station)\textsuperscript{788} is such that it spends 36 minutes of each orbital period (92 minutes) in eclipse of the sun. During the shadow phase, ISS relies on banks of NiH$_2$ rechargeable batteries to provide a continuous power source. Each battery consists of 38 cells in series. The batteries, which are recharged during the sunlit phase of each orbit, have a design life of > five years. A total of 110 kW of solar power is available for all uses, 46 kW of continuous electric power is left for research work (experiments). Excess electric storage energy of the ISS power system is being dissipated using liquid ammonia radiators.

![Figure 21: Battery technology development trends (image credit: EADS Astrium SAS)\textsuperscript{789}](image)

1.4.3.2 Fuel cell power systems on spacecraft

A fuel cell converts directly the chemical energy of reactants (a fuel and an oxidant) into low-voltage electricity, via electrochemical reactions. A fuel cell (FC) is thus similar to a conventional chemical battery. The main difference is that in the ordinary battery, the “fuel” is the built-in expendable electrode (representing a fixed amount energy). When this electrode is depleted, the battery is either “dead” or requires recharging in order to restore

\textsuperscript{788} http://www.cosmiverse.com/space11140101.html
the chemical state of the electrode. A fuel cell is an electro-chemical converter only, using an external fuel supply. Hydrogen has become the fuel of choice in space applications (due to its high energy density when stored as a cryogenic liquid). Energy is released when two hydrogen molecules (\(2\text{H}_2\)) exothermally combine with an oxygen molecule (\(\text{O}_2\)). The fuel is oxidized electrochemically at the anode, i.e., it loses electrons, to produce positively-charged intermediates or protons, \(\text{H}^+\), in the case of hydrogen fuel. At the cathode, oxygen is reduced, accepting electrons to make oxide anions, \(\text{O}_2^-\).

In the late 1950s about 200 research contracts were funded by the US space program to come up with a solution to generate electricity for space missions. The answer was fuel cells. Fuel cells were introduced in the US space program in the 1960s when NASA selected them as the power source for the Gemini (acid type FC) and Apollo (alkaline type FC) programs. All Orbiter power (7 kW average, 12 kW peak) of the Space Shuttle missions comes from its three fuel cell stacks (alkaline type) developed by United Technologies Corporation.

In a regenerative fuel cell (RFC) system, the water by-product is broken down into hydrogen and oxygen through electrolysis and reused in the fuel cell. Basic fuel cell types are:

- Alkaline (or Alkali) electrolyte fuel cells (AFC). AFCs operate on compressed hydrogen and oxygen and generally use a solution of potassium hydroxide in water as their electrolyte. Operating temperatures inside alkaline cells are around 150\(^\circ\) to 200\(^\circ\) C. In these cells, hydroxyl ions (\(\text{OH}^-\)) migrate from the cathode to the anode. At the anode, hydrogen gas reacts with the \(\text{OH}^-\) ions to produce water and release electrons. AFCs operate with efficiencies of up to 70\%, and like other fuel cells, create little pollution. Because they produce potable water in addition to electricity, they have been a logical choice for spacecraft. AFCs are suitable for short mission support. Aqueous alkaline electrolyte systems have a low activation energy for the cell reactions. They therefore have high power output even at below ambient temperatures. This type of fuel cell, however, is not suited for use as a truly regenerative cell (i.e., without an electrolyzer) due to material problems. The alkaline fuel cell system with a separate electrolyzer appears to be best for shorter missions (<5000 hours).

AFCs, with a performance of 1.5 kW, were developed by Pratt & Whitney and used in NASA’s Apollo missions from 1968-1972. - AFC history: Francis T. Bacon (1904-1992), UK, began experimenting with alkaline electrolytes in the 1930s; he developed the first successful AFC device in 1932.

- SPE (Solid Polymer Electrolyte) fuel cells are fully regenerative and suitable for longer missions. They use Nafion\textsuperscript{TM} -type plastics (produced by DuPont), known as ionomer, or its family of compounds [SPE compounds are derivatives of poly(ethylene oxide) or PEO]. General Electric worked on the development of the SPE fuel cell technology (trademark name SPFC) from 1960-1984 and applied it during the Gemini and BioSatellite space programs (BioSatellite-I launch in Dec. 1966; BioSatellite-II launch Sept. 7, 1967), when it was referred to as the IEM (Ion Exchange Membrane) fuel cell. In the period 1962-1965, the IEM (1 kW fuel cells) of GE were used for seven flights in the Gemini Earth-orbiting program. The SPE technology is also referred to as the PEM (Polymer Electrolyte Membrane) technology.

In the early 21st century, SPE is considered to be the forerunner of the PEMFC (Polymer Electrolyte Membrane Fuel Cell).

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790) Note: The fuel cell principle was discovered in 1839 by William R. Grove (1811-1896), an English lawyer turned physicist. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen. It took another 120 years until fuel cells were considered for space applications. The fuel cell technology turns out to be two to three times more efficient than an internal combustion engine in converting fuel to power.


PEM fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet (proton conductive solid polymer technology). \textsuperscript{793} \textsuperscript{794} They work by passing a fuel, such as hydrogen, across the membrane, which is only permeable to protons. The hydrogen’s electron must go around the membrane, generating the electrical current. On the other side of the membrane, the hydrogen bonds with atmospheric oxygen, so the only byproduct is water. The solid electrolyte in PEMs reduces corrosion and management problems.

Since the 1990s, the PEMFC technology is under consideration by the automobile industry around the world as an alternative to the internal combustion engine. \textsuperscript{795} NASA considers to replace the current alkaline fuel cells of the Space Shuttle with a PEMFC system. A recent demonstration of the PEM technology in space was realized with PBEX (Polymer Battery Experiment), developed at JHU/APL and flown on PICO\textsc{sat} of the USAF (launch Sept. 30 2001, see M.28) STP (Space Technology Program). In PBEX, both electrodes and the electrolyte are made of polymers. The objective is to validate the charging and discharging characteristics of polymer batteries in the space environment. PBEX has a mass of 0.4 kg.

- SOFC (Solid Oxide Fuel Cell), a high operating temperature device. An SOFC uses a hard ceramic electrolyte instead of a liquid and operates at temperatures up to 1,000\textdegree C. The semi-permeable ceramics has the ability to conduct an electric current by the passage of oxygen ions through the crystal lattice at sufficiently high temperatures. The electrolyte material mostly used is zirconium oxide and calcium oxide. SOFCs are fully reversible with a potential to provide specific a energy of > 1kW/kg. Emil Baur and H. Preis of Switzerland experimented with solid oxide electrolytes in the late 1930s, using such materials as zirconium, yttrium, cerium, lanthanum, and tungsten.

At the start of the 21st century, fuel cell power generation is an emerging and enabling technology with potentials in many fields with characteristics of high energy-conversion efficiency and extremely low environmental emissions. The current spaceborne applications are dwarfed by the multitude of fuel cell uses in Earth-based applications, providing an ever increasing functional autonomy, in particular in support of mobile services. The fuel cell market promises also inroads into the distributed-power-generation technology. \textsuperscript{796}

\subsection*{1.4.3.3 RTG (Radioisotope Thermoelectric Generator)}

The RTG technology represents an alternate power source to solar radiation energy. Radioisotope power systems convert the heat energy of decaying radioactive material into electricity (use of Plutonium-238). Unlike a nuclear reactor, an RTG uses decay that is not accelerated by controlled chain reaction, so the power density is limited, but so is shielding weight.

The RTG power conversion method employs the thermoelectric effect, where a pair of electrodes, typically SiGe held at different temperatures, develop a potential difference due to the Seebeck effect. This can drive a current and hence generate power. Efficiency is low, typically around 4-5\%. Note: RTG is also referred to as REP (Radioisotope Electric Propulsion) in the literature.

\textit{The major advantage of RTGs is the availability of a constant power source — whatever the distance to the sun. Hence, RTGs are being used in environments (in particular in deep space missions) where the solar radiation becomes ineffective for a spacecraft power subsystem, namely at vast distances from the sun.}

\textsuperscript{793} http://www.technologyreview.com/articles/wo_leo041901.asp
The early US space program used RTG systems in Earth orbit for demonstration purposes of alternate power systems. Thus, the first RTG nuclear power generator, referred to as SNAP (Systems Nuclear Auxiliary Power). — SNAP-3A was flown on the US Navy’s navigation S/C Transit-4A (launch June 29, 1961 from Cape Canaveral on a Thor Ablestar vehicle) in Earth orbit (see H.6). The RTG on Transit-4A generated electricity from thermoelectric junctions in the RTG module. Further Transit S/C were flown with RTG systems. The Nimbus-3 research weather satellite (launch Apr. 14, 1969) of NASA in LEO used an RTG system called SNAP-19B or IRHS (Intact Reentry Heat Source). The LES [Lincoln (Laboratory) Experimental Satellite] communication S/C of DoD used the first RTG demonstration called MHW (Multihundred Watt) in an inclined GSO (Geosynchronous Orbit), launch of LES-8/9 March 15, 1976.\(^{797}\)\(^{798}\)\(^{799}\)\(^{800}\)


The RTGs, all <500 W, provided a specific power of about 3-8 W/kg. RTGs were also used in the Apollo program missions to power and heat systems and sensors on the lunar surface; they were deactivated after the astronauts departed the moon. LANL (Los Alamos National Laboratory) developed the MHW (Multihundred Watt) RTG system for the Voyager missions. In MHW, 24 heat sources were contained within a RTG; heat was converted to electrical power by 312 silicon-germanium thermoelectric couples. Each RTG provided about 157 W at BOL. LANL also developed the GPHS (General Purpose Heat Source) RTG for the Galileo, Ulysses, and Cassini missions. The GPHS RTG system contains 572 SiGe thermoelectric couples inside a thermoelectric converter, generating of 285 W (BOL). There are 18 GPHS modules to the RTG. A GPHS-RTG has a mass of 54kg.

Note: The US has flown one space nuclear fission reactor (SNAP-10A) on the experimental DoD spacecraft SNAPSHOT (launch Apr. 3, 1965).\(^{804}\) It provided 500 W of electrical power. SNAP-10A was a liquid-metal-cooled nuclear reactor with thermoelectric conversion. The SNAP—10A operated for 43 days.

Of course, the energy generated by an RTG could also be used for electric propulsion, referred to as NEP (Nuclear Electric Propulsion) or REP (Radioisotope Electric Propulsion), to speed up a mission’s cruise phase. The NEP technology, or the use of nuclear reactors to

\(^{797}\) J. Dassoulas, R. L. McNutt, Jr., “RTGs on Transit,” STAIF (Space Technology & Applications International Forum) 2007, Feb. 11–15, 2007, Albuquerque, NM, USA

\(^{798}\) http://www.doc-md.gov/moundinfo/rtg2.htm

\(^{799}\) http://nuclear.gov/space/ spacepw.html


\(^{801}\) The Galileo spacecraft ended its mission with a final intended plunge into Jupiter’s atmosphere on Sept. 21, 2003


\(^{803}\) Note: After over 30 years of operation, it appears that Pioneer-10 has sent its last signal to Earth. Pioneer’s last, very weak signal was received on Jan. 23, 2003. The last time a Pioneer 10 contact returned telemetry data was on April 27, 2002. Launched in March 1972, Pioneer-10 was the first spacecraft to travel to an outer planet, providing data and images of Jupiter.

generate heat, which is converted into electrical power for high-performance electric thrusters, can add significant benefits to space missions:
- NEP will enable much faster and more frequent planetary investigations with greater science capabilities “anywhere, all the time” mission design
- NEP enables a revolutionary change in approach to outer solar system exploration
- Drive spacecraft directly to the planets in ways not possible today, and perform complex orbital maneuvers once there
- Provide ample electrical power to operate advanced scientific instruments and transmit the resulting data to Earth at a very high bit rate.

Project Prometheus (formerly known as Nuclear Systems Initiative) is a NASA and DOE program initiative (start in 2002) to develop a next-generation long-term on-orbit propulsion system technology. The objective is to define and to develop an improved performance ARPS (Advanced Radioisotope Power System) for the support of future deep space science missions (starting launches beyond 2012) for solar system exploration. In the past, the availability of sufficient electrical power has always been a very limiting and critical design factor in deep-space missions, in particular for power-hungry active instrument applications like SAR observations of planets. Such SAR missions require the support of high communication links in addition to the power for the SAR instrument.  

Note: Project Prometheus was officially discontinued in October 2005. In August 2005, NASA re-evaluated its priorities in light of available funding and established “Return to Flight”, the International Space Station, and the Crew Exploration Vehicle as the highest priority tasks for the Agency. Consequently, the Prometheus Project was directed to not proceed into Phase B.

Background: Past/current sample deep-space radar missions with RTG power implementations are: NASA's Magellan orbiter to Venus (launch of Magellan on STS-30, May 4, 1989, arrival at Venus in Aug, 1990, the mission lasted for 4 years) employed a SAR instrument to be able to observe the surface of Venus through a dense cloud layer [a lot of SAR data collected by Magellan had to be discarded onboard because of the lack of a sufficiently high-rate downlink communication to Earth], NASA's Cassini probe, to reach Saturn in July 2004 after a nearly seven-year journey, is also equipped with a SAR instrument. Cassini will use it to map Titan, Saturn’s largest and most mysteries moon. The objective of NASA's Mars Reconnaissance Orbiter (planned launch in 2005) is to penetrate the surface of the planet to search for water. Again, this requires a SAR instrument, called SHARAD (Shallow Subsurface Radar), to obtain high-resolution data to surface depths up to 1 km.

In the overall Prometheus program, there are two basic types of technologies under consideration: 1) radioisotope-based systems (managed by NASA), and 2) nuclear fission-based systems (managed by DOE). The new ARPS technology focus is on two technologies:

- a) MMRTG (Multi-Mission Radioisotope Thermoelectric Generator)
- b) SRG (Stirling Radioisotope Generator).

NASA/GRC and its industrial partners are working on the definition of SRG. The efficiency of the new SRG system, referred to as ASC (Advanced Stirling Convertor), is expected to

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808) http://spacescience.nasa.gov/missions/prometheus.htm
810) http://spacescience.nasa.gov/missions/prometheus.htm
be four times higher than that of the conventional RTG technology.\textsuperscript{812)} The design requirements call for an operational life of $> 10^5$ hr (11.4 years) with an energy provision of $> 100$ W DC to the S/C. The Stirling convertor consists of two free-piston Stirling engines coupled to a linear alternator (two engines are needed to suppress vibration), all of which is contained in a hermetically sealed pressure vessel (first use of a dynamic power conversion technology for space application). Due to the reduced envelope and lighter mass of the ASC compared to the previous Stirling convertor, the specific power of the flight generator is projected to increase from 3.5 $\text{W/kg}$ to 7 $\text{W/kg}$, along with a 25% reduction in generator length. As of 2007, tests are being planned and conducted on the ASC prototype to demonstrate the capability for long life, high reliability, and flight qualification needed for use in future missions.

In June 2003, DOE awarded the MMRTG system design, development, test and integration contract to a team led by the Boeing Company’s Rocketdyne Propulsion and Power Division. Top level requirements for the MMRTG design have been established. The heat source for the MMRTG design will consist of eight (8) enhanced GPHS (General Purpose Heat Source) modules. These modules are similar to those used in the GPHS – RTG that powered the Galileo, Ulysses, and Cassini spacecraft. At the beginning of the mission, the MMRTG is designed to generate a minimum of 110 W of power at 28 volts DC, and to have a design life of at least 14 years.\textsuperscript{813)}

A first candidate in the nuclear fission-based scenario, a technology with considerably improved power generation capability, is NASA’s proposed JIMO (Jupiter Icy Moons Orbiter) demonstration mission to observe three planet-sized moons of Jupiter — Callisto, Ganymede and Europa — which may harbor vast oceans beneath their icy surfaces (planned launch of JIMO in 2015 time frame). The JIMO mission also may raise the capability for deep space exploration to a revolutionary new level by pioneering such features as: a) the use of electric propulsion powered by a nuclear fission reactor, b) use of much higher data rates ($> 10$ Mbit/s) from deep space, c) more power availability for science instruments, etc.\textsuperscript{814)}

- SDS (Solar Dynamic System), proposed systems so far used for power demands in the 20-100 kW range). The difference between solar photovoltaic (PV) and solar dynamic power generation is the power conversion technique. A PV system converts the radiative energy directly into electric energy. On the other hand, an SDS employs solar radiation to heat a working fluid to drive a heat engine which is used to generate electricity. The advantage of SDS over PV systems is that dynamic systems in general have a higher thermal efficiency and can be used for higher power levels. An SDS is made up of four elements: the collector/concentrator, receiver, radiator, thermal storage material, and the heat engine.

1.4.3.4 NPS (Nuclear Power System) in Soviet/Russian space program

In the early 1960s, the former USSR initiated a thermal—electric energy conversion program that received the name ROMASHKA (the program was based on nuclear fission reactors to generate onboard electricity). The ROMASHKA reactor—converter was designed and developed at KIAE (Kurchatov Institute of Atomic Energy) in cooperation with other institutes. The ground testing of the ROMASHKA converter-reactor was conducted with the reactor integrated and operated with a pulsed plasma thruster — for the first time in


\textsuperscript{813)} F. Ritz, C. E. Peterson, “Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Program Overview,” Proceedings of the IEEE Aerospace Conference, Big Sky, MT, March 6-13, 2004

\textsuperscript{814)} http://ossim.hq.nasa.gov/jimo/
Earth Observation History on Technology Introduction

1964. ROMASHKA generated electric power of 0.5 kW, thermal power of 28 kW, use of 49 kg of U235, and had a total mass of 450 kg. 815)

- Concurrently, the so-called BUK (Space Nuclear Thermoelectric System) propulsion concept was developed (at the Institute of Physics and Power Engineering, as well as at other institutes in the USSR) around a fast reactor and an out-of-core thermoelectric converter. The BUK NPS used 37 fuel rods in the core and a liquid metal cooling system. A lifetime of 4400 hours of operating time was demonstrated. BUK provided electric power of up to 3 kW, thermal power of 100 kW, use of 30 kg of U235, total instrument mass of 900 kg.

- In the period 1967-1988, the USSR launched as many as 36 low-power BUK reactors on the so-called RORSAT (Radars Ocean Reconnaissance Satellite) series into LEO (Low Earth Orbit). Note: the RORSAT S/C were part of the Cosmos series. The first RORSAT mission was launched Dec. 27, 1967. Two RORSAT satellites with nuclear-powered generators caused worldwide alerts during their breakup and reentries to Earth in 1978 (Cosmos—954) and in early 1983, respectively. 816) 817)

- In parallel, efforts were initiated in Russia to develop SNPS (Space Nuclear Power Systems) based on in-core thermionic energy converters. Two thermionic system designs were used. The development of the SNPS technology led to first system power tests in 1970 and 1973, using a multi-cell TFE (Thermionic Fuel Cell) system design. In 1987, two experimental TOPAZ NPS units were flight-tested as part of the Plasma-A experimental spacecraft (Cosmos—1818 and Cosmos—1867), and demonstrated the lifetime of the SNPS of 142 days during the first test, and 342 days during the second test. – Note: Launch of the Plasma—A spacecraft on flight Cosmos—1818, Feb. 1, 1987 from Baikonur on a Tsyklon—2 vehicle. Launch of the Plasma—B spacecraft on flight Cosmos—1867, July 10, 1987 from Baikonur. The TOPAZ system provided electric power of up to 5 kW, thermal power of 150 kW, use of 11.5 kg of U235, total instrument mass of 980 kg.

- The TOPAZ-2 project development (referred to as ENISEY in the USSR, and developed by the Krasnoyarsk Design Bureau of Applied Mechanics) employed the thermionic SNPS design based on single-cell TFES. The TOPAZ-2 system consisted of the following main subsystems: the reactor subsystem, the radiation shield, the primary coolant loop, the cesium supply system, the gas systems, the thermal cover, the primary power system structure, and the instrumentation and control subsystem. – Full cycle ground tests were conducted confirming an operational lifetime of 1.5 years (post flight analysis predicted a lifetime of at least 3 years). Two full-scale system unit ground tests were conducted and completed in 1988 – but project funding cuts stopped all further system work and prevented any flight tests.

- In 1991 (at the end of the Cold War), a cooperative Russian-American space research program was started with the objective to perform demonstration tests with the TOPAZ-2 SNPS units. Two systems without fuel were delivered to the USA under a contract between INTERTEK (International Energy Technologies) of Moscow and ISP (International Scientific Products) of San Jose, CA, for ground tests (the systems were electrically heated). The first stage of the TOPAZ program culminated in power tests of two SNPS experimental units (V-71 and Ya-21U) and tests of single-cell TFES performed in 1992–1993 by a team of specialists from Russia, USA, UK, and France (international inspection!!) at electrically heated test facilities newly built at the University of New Mexico, Albuquerque, NM. The successful tests of the TOPAZ-2 units resulted in plans for flight tests, using a spacecraft

816) R. Hagen, “Nuclear Powered Space Missions - Past and Future,” http://www.globenet.free—online.co.uk/ianus/npms2.htm
called NEPSTP (Nuclear Electric Propulsion Program). This resulted in a transfer of 4 more TOPAZ-2 units to the USA. Although the NEPSTP flight tests were never realized, the TOPAZ program remains an outstanding example of cooperation between Russia and USA.  

- Also, so-called RHUs (Radioisotope Heater Units) were used in the Soviet/Russian space program. The moon mission Luna-17 (launch Nov. 10, 1970) and Luna-20 (launch Feb. 14, 1973) used Polonium-210 isotopic heat sources to keep the Lunokhod rovers warm during the lunar nights. The MIR Space Station in LEO (1986-2001) used an RHU onboard (controlled reentry into the Pacific Ocean on March 23, 2001).

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1.4.4 SPS (Solar Power Satellites): PowerSats

Background: At the start of the 21st century the primary world power consumption is at a level of about 12 TW (12 x 10^{12} W); the share of electric power generation amounts to about 1.7 TW, while the fossil fuel (oil, gas, coal, nuclear - all non-renewable energies) portion of energy is at a level of > 10 TW. It means that about 85% of the primary world power is fossil-fueled with significant CO2 emissions into the atmosphere. Obviously, regenerative solutions must be taken into account and installed with higher priority. Significant terrestrial energy options are: solar, wind, hydro, biomass, geothermal (the last one being not strictly regenerative but practically inexhaustible). In addition, power from space may also contribute to the global power supply.Major questions are: Is the “import” of solar energy from space an alternative to its terrestrial use? Is it technically and economically feasible and safe? How does it compete with other terrestrial regenerative alternatives? What could be a reasonable and affordable solution to the energy problem (e.g. a mix of several different options)?

The solar irradiation power (the solar energy, arriving at the top of the atmosphere, amounts to about 1.368 kW/m² - or about 1 kW/m² arriving on Earth’s surface) is Earth’s prime renewable energy source capable to meet the world’s growing energy needs. When multiplying the above specific solar flux with the Earth’s cross-section (disk projection), leads to a global incoming solar power of 1.7 x 10^5 TW at the top of the atmosphere, or about 1.3 x 10^5 TW on the ground. Indeed a great reservoir of renewable energy!

The considerable advances in the field of photovoltaic technologies over the past decades lead logically to consideration of continuous solar power generation from space. Considerable experience is available from large ground-based solar power installations to plan for future space-based generation concepts. Most proposed space designs are based on photovoltaic energy collection/conversion to electricity and wireless (microwave or laser-based concepts) power transmission to Earth, using large high-power antennas - directly or via orbital redirectors - to Earth-based receivers or rectennas (= antennas + electric rectifiers).

The major motivation for pursuing SPS concepts is that in space the sun’s irradiation can be utilized more efficiently than on Earth. A spacecraft in GEO is not eclipsed by the Earth but is in sunlight continuously, 24 hours a day, due to its high orbit of about 36,000 km altitude. The only exceptions are several days around the seasonal equinoxes, March 21 and September 22, when the satellite will be eclipsed briefly around midnight, for up to an hour and 12 minutes. This virtually permanent available power source from GEO implies a factor of almost 5 in favor of an orbital SPS (1366 W/m² average) compared to the best ground solar power plants (300 W/m² average at best due to the atmosphere, weather conditions, day-night cycle, etc.). A disadvantage in GEO is of course the requirement of fairly large antenna structures (S/C and ground) to transmit the power to Earth. Also, due to safety considerations, only a restricted flux can be allowed on ground for the microwave power transmission.

Studies: Many assessment studies have been made on the topic in the past decades (in fact since the 1960s) looking at new concepts and the feasibility of space-based solar power -- orbiting satellites, so-called “PowerSats,” in GEO (optimal location with nearly continuous irradiation by the sun) that would serve as high-tech space dams, generating power for Earth-bound and space-based applications. However, so far, the considerable economic in-

823) Note: A spacecraft in GEO is not eclipsed by the Earth but is in sunlight continuously, 24 hours a day, due to its high orbit of 36,000 km. The only exceptions are several days around the seasonal equinoxes, March 21 and September 22, when the satellite will be eclipsed briefly around midnight, for up to an hour and 12 minutes. A disadvantage in GEO is the requirement of large antenna systems (S/C and ground) to transmit the power to Earth.
vestment into the development of such a space solar power generation plant is the main bar-
rier that has kept governments away from potential resource commitments into the future. 824) 825)

The past and current SPS concepts are all on a study level. Still, on a long-term perspective,
solar power systems from space may eventually turn out to be a promising energy option for
the 21st century. On a global and long-term scale, there are three major parameters that
have to be considered in connection with the energy system for the 21st century and beyond.
The main projections of the IEA (International Energy Agency) for 2030 are as follows: 826)

1) According to current projections and past experience, the global energy need will con-
tinue to rise in close connection with the increasing world population

2) The availability and use of energy is closely connected to living standards and develop-
ment levels in the world. Currently, the average primary energy consumption per capita
worldwide is about 17,000 kWh/year. It is more than 5 times higher in North America
(100,000 kWh/year) but only 4 and 10 kWh/year for the worldwide most numerous and
fasted increasing populations, in Africa and Southeast Asia, respectively.

3) A significant part of the global emission of greenhouse gases (GHG) stems from the
production of electricity (40%) and from transport (21%). Despite the continuous de-
crease of carbon intensity over the last 30 years, the decrease has not been and will
probably not be sufficient to stabilize or reduce the total CO₂ emissions due to the
stronger increase of the total power consumption. The IEA estimates that worldwide
carbon dioxide (CO₂) emissions will rise to 38 billion tons per year from currently 16
billion tons (increase of 70%).

**System concepts:** The overall analysis of solar power generation from space considers two
main categories of applications:

1) **Space-to-Earth energy generation systems,** i.e. classic SPS (Solar Power Satellite) con-
cepts.

2) **Space-to-Space energy generation systems** (for space exploration and utilization).

For the space-to-Earth category, the classic application of SPS concepts was first suggested
in 1968 by Peter E. Glaser, a Czech-American of Arthur D. Little (consulting company).
The basic SPS design requires: 827)

- a) Very large and light-weight structures in space to collect the solar energy efficiently
(solar cells, concentrators or other)
- b) A power transmission system to the ground (based on wireless power transmission)
including the conversion of electrical energy and the generation of the transmission beam.
Both laser and microwave transmission systems have been considered.
- c) A power receiver system on the ground — closely linked to the laser or microwave
technology.

The following items deal with SPS concept studies (energy generation in space) as well as
with energy transmission from space to Earth.

- A NASA/DOE concept of **SSP** (Space Solar Power) was already extensively developed

International Conference on Solar Power from Space. SPS’04, ” June 30 – July 2, 2004, Granada, Spain
in the 1977-1980 system study. The overall SSP study goal was to define a reference system and to determine if a space-based solar collection system can produce power for customers on Earth at competitive rates. The purpose of the reference system was also to serve as a basis for evaluating the SPS (Solar Power Satellite) concept for environmental and societal impacts and as an alternative energy source. The power output of one derived SPS reference system (a space structure of 10 km x 5 km x 0.5 km in size and 50,000,000 kg of mass) is 8 GW, the ground rectenna (~10 km diameter) output is 5 GW.

However, negative assessments of the state-of-technology and plans for nearer-term development by the US Congress and NRC (National Research Council) resulted in a termination of SSP activities in the early 1980s.

- Japanese interest in Space Solar Power followed closely in 1981 by the establishment of ISAS (Institute of Space and Astronautical Science) at the University of Tokyo (ISAS became part of JAXA as of Oct. 2003). Japan recognized the enormous cost and technical difficulty of building the NASA/DOE system and decided to concentrate on the development of a ground receiving system, which led to an offshore, floating rectenna design.

- In the 1995-1997 “Fresh-Look” study, NASA considered a number of innovative concepts and technologies aimed at reducing the required upfront investment. In this so-called ‘Sun Tower’ concept, NASA employs inflatable, gossamer-like structures for the realization of concentrators which direct the solar radiation onto PV receivers. The Sun Tower, with dimensions of 15 km x 0.2 km x 0.1 km, and a total mass of about 1,000,000 kg, would be in sun-synchronous low Earth orbit (LEO). About 100 inflatable concentrators would be mounted on a central truss structure, and a 5.8 GHz antenna would transmit the power to the surface (ground output of several hundred MWe).

- In 1999-2000, NASA started another initiative called SERT (SSP Exploratory Research and Technology) due to significant progress in space technology (e.g. lightweight structures, PV, etc.). The objective in SERT was to conduct preliminary strategic technology research and development to enable large SSP systems and WPT (Wireless Power Transmission) systems for future missions. The designs of the SERT study were the so-called POP (Perpendicular-to-Orbit Plane) configuration and the ISC (Integrated Symmetric Concentrator) configuration. The latter is a modified sandwich concept, in which the photovoltaic array is moved from the back of the two photovoltaic arrays and placed at the focus of the concentrator array.

The following enabling technologies are considered challenging and of great importance to all involved:

- WPT methods. Transmission of energy using microwave or laser concepts. The WPT concept has been demonstrated by various research groups in many locations over many

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828) DOE 1978 “Satellite power system (SPS) concept development and evaluation program (CDEP) Reference System Report,” DOE/ER-0025, October 1978
833) http://spacesolarpower.nasa.gov/objectives_goals.html
834) http://www.permanent.com/p--sps--ps.htm
years. There is a need for high-power generators (magnetrons, klystrons) and large space antennas with excellent mechanical properties and exact and safe phase steering. There is also a need for light-weight, high-efficiency, and high-power IR lasers (current laser efficiencies are generally < 5%; however, there are already some diode lasers available with efficiencies of about 30%).

- Intelligent robotics to permit the assembly, inspection and maintenance of large structures in space
- Improved PMAD (Power Management, Distribution and Control) techniques with special emphasis on mass reduction
- Availability of energy conversion levels from solar cells of 170 W/kg specific power and better
- Availability of cheaper and re-usable space transportation (heavy-lift launch vehicles).

The attractiveness of SPS is strongly dependent on future launch costs.

Some background on WPT (Wireless Power Transmission). In 1873 Maxwell predicted that power could be transmitted from one point to another in free space. WPT dates back to the early work of Heinrich Rudolf Hertz (1857-1894, German physicist), who demonstrated electromagnetic wave propagation in free space in 1888 using a parabolic reflector. The idea of radio power transmission was first conceived and experimented on in 1899 by Nikola Tesla (1856-1843, Austro-Hungarian/American inventor and scientist).

On 28 Oct. 1964, William C. Brown (1916-1999), an American wireless power transmission pioneer, demonstrated publicly a wireless microwave power transmission experiment to a tethered helicopter at the Spencer Laboratory of the Raytheon Company, sponsored by the USAF. In 1975, a JPL demonstration took place where beamed microwave power (30 kW) was transmitted over a distance of 1.54 km using a transmitting antenna and a microwave receiver referred to as "rectenna" (a rectenna absorbs the microwave beam and simultaneously converts it to DC power). In 1987, Canadian researchers flew a microwave-powered aircraft and concluded that a microwave beam could power it indefinitely. The University of Kyoto, Japan, (cooperation with CRL and Texas A&M University) conducted several experiments demonstrating MPT (Microwave Power Transmission) technology: 838) 839) 840)

- The MINIX (Microwave Ionosphere Nonlinear Interaction eXperiment) rocket experiment was carried out in 1983. The objectives were to verify MPT in space and to investigate the nonlinear plasma effects caused by the microwave energy beam through the space plasma as well as the counter effects onto the microwave beam.
- ISY-METS (International Space Year - Microwave Energy Transmission in Space) rocket experiment carried out on Feb. 18, 1993. ISY-METS also demonstrated that one spacecraft could supply power to another in space using wireless power transmission. 842) 843)
- SPS 2000 (Solar Power Satellite 2000) is a Japanese WPT study project. The objective is to demonstrate energy delivery from space to Earth. 844) The design calls for a gravity stabilized satellite capable of delivering 10 MW of electricity from a circular 1100 km east-to-west equatorial orbit. The phased array antenna will be capable of steering ±30° along the orbital path (E-W) and ±16.7° perpendicular to the orbital path (N-S).

840) Note: The MPT technology is also known under the term “microwave power beaming.” The technology of power beaming is still in the research state, in spite of all the experiments conducted.
841) http://engineer.tamu.edu/tees/csp/wireless/homepage.htm
842) http://www.kurasc.kyoto-u.ac.jp/plasma-group/sp-s-e.html
843) http://www.kurasc.kyoto-u.ac.jp/plasma-group/spss/mets-e.html
Initial design studies have been completed and a scale model mock-up of the satellite has been made.

In 2001, a study was provided by the US NRC (National Research Council), entitled: “Laying the Foundation for Space Solar Power: An Assessment of NASA’s Space Solar Power Investment Strategy.” In this study, NASA’s SERT was evaluated in the context of the “plan’s likely effectiveness to meet the objectives of the program.” The outcome: There is considerable interest in solar energy generation by all parties involved (institutional, governmental, industry, and academia).  

A first small-scale demonstration of SSP, in the order of 100 kW from GEO, may become a reality in the time frame 2010. Many experts expect large-scale SSP to become technically achievable by about 2020. In the long run, SSP may indeed represent an alternative or at least a needed supplementary energy source to conventional power generation, thus contributing to resource conservation on Earth.

Japan’s METI (Ministry of Economy, Trade and Industry), the former MITI (Ministry of International Trade and Industry), has plans in 2002 to launch a solar power station by 2040. JAXA considers to launch a power satellite demonstration by 2010 and a practical version of a space-based solar-power generation system as early as 2020. In 1992, Japan demonstrated the flight of a small model airplane powered by microwaves beamed up from the ground. – In 2006, JAXA/ISAS is proposing a tethered SPS configuration (without a concentrator) in GEO as a practicable solution.  

- An ESA study of 1998-1999 under the lead of DLR came up with a new concept for SPS called “European Sail Tower SPS,” whose design was inspired by the Sun Tower concept of NASA, and the use of innovative solar sail technologies. The dimensions of such a Sail Tower in GEO are 15 km x 0.35 km x 0.05 km (except for the antenna which is 1 km in diameter), the total mass is about 2,000,000 kg. The structure consists of a 15 km long central tether with 120 power generating sun-tracking “sail modules” attached in pairs. Deployable carbon fiber booms (CFRP) spread Kapton film segments coated with thin-film solar cells (TFSC), each sail of 150 m x 150 m in size and a mass of 1100 kg (including all add-ons).  

- In 2002, ESA created the “European Network on Solar Power Satellites,” a framework to focus all research activities on SPS (Solar Power Satellite) technology, following an ESA study initiative on advanced SPS concepts.

Prohibitive launch costs, limited launcher capabilities, enormous launch mass requirements as well as large frontend investments are among the most prominent reasons - why most proposed WPT systems rely on microwave power transmission instead of laser power transmission (laser

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845) http://books.nap.edu/books/0309075971/html/12.html#pagetop
The following sample calculation, (stated by Leopold Summerer et al. in Ref. 854), gives an overview of the dimensions involved: A GEO laser-based SPS system, using PV solar arrays (GaInP/GaAs/Ge with concentrators operating at 32% efficiency and a mass of 1.6 kg/m²), employing an advanced GaAs laser diode transmission system emitting to the ground at 840-890 nm wavelength with an assumed 70% generation efficiency and only 0.02 kg/W for the laser system --- lead to a satellite mass of about 384,000,000 kg to deliver 5 GWe to a ground-based PV receiver system (such a gigantic mass is appalling). This configuration, although optimistic, would still be about six times more massive than the 5 GW Sail Tower option using microwave power transmission. Important progress remains to be done in laser generation specific mass kg/kW and efficiency to profit from its advantages.  

- NASA conducted already a series of studies testing the environmental impact of microwave energy transmissions from space to ground on plant life, using a tower-mounted microwave transmitter in the experimental setup. An experiment was done that exposed alfalfa to continuous microwave energy at 2.45 GHz with intensities of 0.5-1.2 mW/cm².857 A tray of growing plants was illuminated with microwaves while control plants were grown behind a microwave-opaque shield. Statistical analysis indicated no difference in chlorophyll content of the leaves between the control and test plant populations throughout the test period. A set of further experiments will be performed to test if the offspring from plants grown under microwave radiation at 2.45 and 5.8 GHz, the F1 generation, will show any deleterious characteristics as a result the parent plants being exposed to microwave radiation. This experiment will be important for understanding the generational effects of microwave exposure.

1.4.5 Spacecraft Avionics and Onboard Data Handling (bus systems)

The early history of spaceflight (all of spaceflight, not only Earth observation) has seen a lot of project-developed (i.e. custom-built, and/or proprietary) “electronic interconnect solutions” (using lots of wiring and cables) with regard to onboard data management systems (interprocessor communication and control functions for the onboard subsystems, the payload instruments, and RF communications), and flight control functions. This was mainly due to the lack of available standards, the multitude of subsystems to be integrated, each with a wide spectrum of operational requirements, performance needs, interfaces on many levels, protocols, data transmissions, distributions and data recordings to be handled (in all directions, various types of data, etc.), and with a fast-changing and evolving field of (often non-compatible) computer technology.

It took a while, even within each space agency, to get a certain “degree of structure and modularity” with standardized building blocks and interface connectivity into the avionics system architecture of satellites along with the general functional service spectrum and procedures. The ever increasing functional demands by the operational side of the spacecraft as well as the science side of the project were probably the main drivers for all these developments. Interface standards are the key to maximizing the benefits of modular systems (decrease of complexity, reduction in integration time and costs, and increase the reuse of a system). Standard interfaces are the technical specifications that ensure interoperability between different products or modules. Standard interfaces enable the independent development of modules and complementary products and services (including flight systems, test/validation systems, simulators, etc.).

In the 1960s and 1970s there was also a great interest among space agencies in international cooperative activities. This gradually led to requirements in cross-support between the respective communications and space data systems of the agencies. The absence of standards led to many costly interface conversions, all were handled by the introduction of so-called “black boxes” to establish compatibility.

Conventionally, space segments are separated into two main functional classes, namely the platform and the payload subsystems and/or instruments. 858)

- Conventional tasks of the platform are: maintaining communication with the ground segment, guiding the satellite on the appropriate trajectory, controlling the attitude and performing an overall management of the parts constituting the system. If some autonomy is required the platform has to make decisions with respect to particular situations.

- The payload, being intimately related to the objective of the mission, often consists of multiple instruments, very different in terms of generated data rate and from a command and control viewpoint. In the past, because of technological limits, all data were transmitted to the ground segment where the selection, elaboration and analyses were performed. At the start of the 21st century, payload systems requirements are becoming more and more demanding in order to comply with the project needs to elaborate (select, compress, format, encrypt, etc.) data in real-time or near real-time onboard and only downlink the useful part of the information. Moreover, payload systems are endowed with a certain level of autonomy and are asked to be reconfigurable, reliable and robust. In other words, they frequently drive advances in space data systems.

Some common onboard interface and data-system standards:

The first onboard data buses on the scene were the MIL-STD-1553 (Military Standard-1553) bus of DoD/USAF and the OBDH (On-Board Data Handling) bus of ESA, permitting a frequent system reuse and functional resource sharing. These two buses are based

on well proven technology, commonly used between spacecraft components. Conventional interfaces between spacecraft components are usually provided by **point-to-point** connections (such as RS-422/23), or a master-slave bus architecture (MIL-STD-1553, -1553B, or OBDH). These point-to-point configurations have proven to be extremely limited in flexibility and expendability. In spite of the wide use of MIL-STD-1553 and OBDH, the prevailing situation at the start of the 21st century is that there are still too many different (customized) interface types and “standards” around to interconnect onboard components and subsystems. Note: In this context the reader should also consult chapter O.13.

In contrast to conventional -1553 and OBDH bus systems, newer standardized onboard network architecture concepts (candidates are: CAN, SpaceWire, TCP/IP, FireWire, Ethernet, etc.) employ routers which take care of delivering packets to the appropriate address without processor supervision. 859)

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<th>Bus designation</th>
<th>Main Characterization</th>
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</thead>
</table>
| MIL_STD-1553B (its optical derivative is MIL-STD-1773) | - Introduced by USAF in 1973 (1773B released in 1978)  
- Used in thousands of military and commercial aircraft and in many spacecraft  
- Multi-drop bus (master-slave architecture)  
- Mainly for control / configuration purposes  
- The raw data rate is 1 Mbit/s  
- The 1553B is transformer-coupled and dual-redundant, providing a level of failure protection  
- For point-to-point connections that do not require the complexity of a 1553/1773 connection, a synchronous serial connection such as RS-422/23 with a bit rate around 1 Mbit/s is typically used. |
| OBDH (On-Board Data Handling) data bus | - ESA standard onboard data bus (was defined the mid-1970s)  
- First onboard introduction on Giotto (launch July 2, 1985)  
- Multi-drop bus (master-slave architecture)  
- Mainly for control / configuration purposes  
- The raw data rate is 1 Mbit/s  
- The bus features a synchronous serial data exchange and time-management  
- RBI (Remote Bus Interface) ASIC introduction with Envisat (launch 2000)  
|
| CAN (Controller Area Network)           | - CAN was originally developed for automobiles and industrial use  
- CAN uses a two-wire differential bus  
- The CAN interface is a 2-wire asynchronous transmission scheme controlled by start and stop bits at the beginning and end of each character  
- Information is passed from transmitters to receivers in a data frame  
- CAN employs a serial protocol, with data rates up to 1 Mbit/s  
- It implements distributed real time control and multiplexing  
- The CAN specification defines the data link layer, ISO 11898 defines the physical layer of the ISO (International Organization for Standards) networking model  
- CAN was initially introduced onboard the satellite FaSat—Alfa (Aug. 31, 1995) and UoSat-12 (launch Apr. 21, 1999) of SSTL, UK. It is also being flown on SNAP-1 and Tsinghua-1 (both launched Jun. 28, 2000), TiungSat (launched Sep. 26, 2000), all S/C were developed by SSTL. The TOPSAT mission of QinetiQ (UK, built by SSTL) with a launch Oct. 27, 2005, uses CAN as well as SMART-1 of ESA (launch Sept. 27, 2003, built by SSC). CAN is also being used by many microsatellite missions. |
| I²C (Inter-Integrated Circuit) data and control bus | - A low-cost commercial data bus (in consumer, telecommunication and industrial electronics appliances)  
- I²C (also I2C) employs a master-slave architecture  
- CNES selected the I2C bus for its microsatellite family of Myriade [DEMETER (launch June 29, 2004) PARASOL (launch Dec. 18, 2004), Picard, etc.]; at the start of the 21st century, there are several I2C space-based applications in development. Stanford University is using I²C on Emerald, Orion, etc.  
- I²C is compatible with the following OSI layers: physical layer, data-link layer (medium access control), and data-link layer (logical link control)  
- Only two bus lines are required; a serial data line and a serial clock line  
- I²C is a multi-master bus including collision detection and arbitration  
- Serial, 8-bit oriented, bidirectional data transfers can be made at up to 100 kbit/s in standard mode or up to 400 kbit/s in the fast mode |

Bus designation | Main Characterization
--- | ---
IEEE1394 bus, also referred to as FireWire | - An industry/commercial high-speed and low-power serial bus for data communications among multiple nodes (introduced in 1999).
- Communication speeds of up to 400 Mbit/s
- It supports a transmission mode which guarantees bandwidth
- The supported chipsets are Texas Instruments PCI/ lynx/PCI Lynx2 and OHCI (Open Host Controller Interface) compliant chips (produced by various companies)
- It's a thin twisted cord with a 6-pin connector up to 4.5 in length
- The bus connects CPUs, telecommunications equipment, and instruments
- The bus allows for multiple masters and provides an isochronous channel that gives developers the means to schedule regular and synchronous activities.
- A key concept of the bus architecture is the symmetry between flight and ground software.

SpaceWire | - A European-born initiative in 1998 (ESA, industry, academia, etc.) and US cooperation on CCSDS-SOIF (Spacecraft Onboard Interfaces)
- First onboard introduction on Rosetta and Mars Express mission of ESA
- Point-to-point serial links (an onboard network with routers)
- Mainly intended for the transfer of data; remote configuration tasks are possible because links are bi-directional.
- 1.25 Mbit/s < data rate < 400 Mbit/s (on one point-to-point link). The performance is scalable if the number of links increases.
- Key principles of SpaceWire are: modularity, scalability, and reconfigurability

Onboard LAN | - NASA plans the introduction of an onboard LAN with TCP/IP protocols in the time frame 2006 (see also 1.4.7.4.)

Table 47: Overview of some common onboard buses/networks

At the start of the 21st century, the use of onboard LAN systems is emerging; the non-selection of LANs in the past was mostly due to non-availability of space-qualified components. However, the data communication requirements of many advanced space missions involve seamless, transparent connectivity between space-based instruments, investigators, ground-based instruments and other S/C.

1.4.5.1 MIL-STD-1553B

The digital communications bus MIL-STD-1553B has become an established global spacecraft data bus standard (a deterministic, command-and-response protocol) with roots in military aircraft avionics. The serial bus protocol was first introduced by the USAF in Aug. 1973 as MIL-STD-1553 and experienced a number of revisions. The tri-service approved version MIL-STD-1553A was released on April 30, 1975. The F-16 aircraft program of the USAF was the first user of the “A” version. The early Space Shuttle program adopted a preliminary version of the not-yet-released MIL-STD-1553 bus standard already in 1974. All previous onboard systems (in the US) had used bundles of wires, each one dedicated to a specific signal - for system interconnection. The sheer weight of the wiring became simply intolerable. \(^{(860)}\)

The latest version of the standard, 1553B, was released on Sept. 21, 1978. The 1553B bus is a redundant bus for which compact and reasonably priced (compared to other space qualified solutions) interface circuits are available. At the start of the 21st century the standard is still at the “B” level. Changes to the standard were made in 1980 with Notice 1, and in 1986 with Notice 2 (common set of operational characteristics). The military standard was converted to its commercial equivalent as SAE AS-15531 (part of the US government’s effort to increase the use of commercial products). Practically all spacecraft of NASA employ the 1553B bus standard, this applies also to JAXA (formerly NASDA) spacecraft.

The ISS implementation of the 1553B bus system includes multiple redundant buses, each with dual channels and controllers, and multiple redundant MDM (Multiplexer/Demulti-
plexer) at each level of hierarchy. The ISS 1553B bus architecture consists of a 3 tier C&DH
(Command and Data Handling) system composed of a number of specialized computers
called MDMs (Multiplexer/Demultiplexer) interconnected by MIL-STD-1553B buses.
The reason for its use on ISS: the 1553B is well-proven in space; additionally, it has signifi-
cant built-in redundancy capabilities that make it a good choice for space applications.
However, as the ISS grows in size, functionality and complexity, new solutions must be de-
developed to overcome the low transmission rate (1 Mbit/s) of the 1553B bus. 862) 863)
The Chinese technology demonstration satellite SJ-5 (Shi Jian-5, launch May 10, 1999) em-
ployed also the 1553B bus. Another example of a 1553B bus implementation (onboard com-
munication via discrete point-to-point lines as well as via a 1553B bus) is the SMOS mission of
ESA (launch 2007) flown on a Proteus platform of Alcatel Space.

The MIL-STD-1553B is a common hardware selection for custom C&DH interfaces; it de-
fines TDM (Time Division Multiplexing) as “the transmission of information from several
signal sources through one common system with different signal samples staggered in time
to form a composite train.” The standard defines four hardware elements: transmission
media, remote terminals, bus controllers, and bus monitors. The structure of the bus con-
ists of a single bus controller connected to remote terminals (up to 31 max can be used).
The use of the MIL-STD-1553B communications bus in combination with CCSDS proto-
cols is increasingly being used in the design of small satellite command and data handling
systems. In this way, they function as standard spacecraft-to-payload interfaces and proto-
cols. 864)

MIL-STD-1773B (up to 10 Mbit/s fiber optic bus). Optical interconnects have long prom-
ised significant advantages over their electrical counterparts. Specific advantages include
increased bandwidths at long (10 m or more) interconnection distances, immunity to EMI
(Electromagnetic Interference) effects, negligible crosstalk, reduced size, and lower
weight. Optical interconnects have some heritage in a range of ground based and aircraft
applications, however they are only beginning to gain acceptance in spaceborne systems (in
1990s). Examples: 865) 866)

- The SAMPEX mission of NASA (launch July 3, 1992) employs a fiber-optic data bus
  based on MIL-STD-1773 (see K.23.1).
- The HST (Hubble Space Telescope) mission was launched April 24, 1990 on Shuttle
  flight STS-31; it uses the MIL-STD-1773 data bus.
- The Lewis S/C of NASA (launch Aug. 23, 1997 - but no S/C operations could be initi-
  ated) was also equipped with a fiber-optic data bus.
- The EO-1 mission of NASA (launch Nov. 21, 2000) was initially planning to use the
  IEEE 1393 SFODB (Spaceborne Fiber Optic Data Bus), instead of MIL-STD-1773. How-
  ever, due to technical and budgetary problems, SFODB had to be removed from EO-1
  (hence, there was no fiber optic bus on EO-1). EO-1 ended up using the conventional MIL-
  STD-1553B data bus.
- The CryoSat mission of ESA (launch Oct. 8, 2005 — but launch failure) uses the MIL-
  STD-1553B bus for the low rate data channels (handling of onboard communications) and

862) D. P. Fletcher, R. Alena, “A Scalable, Out-of-Band Diagnostics Architecture for International Space Station Sys-
Space Station utilizing Telemetry Data,” Proceedings of the SPIE Aerosense Conference, Orlando, FLA, April
space Conference, Big, Sky, MT, March 9-16, 2002
space Conference, Big Sky, MT, March 8-15, 2003
high-speed serial links (IEEE 1355) for payload interfaces. The LISA Pathfinder mission of ESA (formerly SMART-2, launch 2009) is also planning of using the 1553B data bus.

- The next-generation high-resolution imaging satellite series of CNES, Pleiades, is using the MIL-STD-1553 bus. Pleiades-1 is planned for launch in 2008.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>up to 1 Mbit/s</td>
</tr>
<tr>
<td>Word length; data bit per word</td>
<td>20 bit; 16 bit</td>
</tr>
<tr>
<td>Message length</td>
<td>32 data words maximum</td>
</tr>
<tr>
<td>Transmission technique</td>
<td>Half-duplex</td>
</tr>
<tr>
<td>Operation</td>
<td>Asynchronous</td>
</tr>
<tr>
<td>Encoding</td>
<td>Manchester II Bi-phase</td>
</tr>
<tr>
<td>Protocol</td>
<td>Command-response</td>
</tr>
<tr>
<td>Bus control</td>
<td>Single or multiple</td>
</tr>
<tr>
<td>Message formats</td>
<td>BC-RT (Controller-to-Terminal)</td>
</tr>
<tr>
<td></td>
<td>RT-BC (Terminal-to-Controller)</td>
</tr>
<tr>
<td></td>
<td>RT-RT (Terminal-to-Terminal)</td>
</tr>
<tr>
<td>Number of remote terminals</td>
<td>31 (max)</td>
</tr>
<tr>
<td>Terminal types</td>
<td>RT (Remote Terminal),</td>
</tr>
<tr>
<td></td>
<td>BC (Bus Controller),</td>
</tr>
<tr>
<td></td>
<td>BM (Bus Monitor)</td>
</tr>
<tr>
<td>Transmission media</td>
<td>Twisted shielded pair of cable</td>
</tr>
<tr>
<td>Coupling</td>
<td>Transformer or direct</td>
</tr>
</tbody>
</table>

Table 48: Summary of the MIL-STD-1553B data bus characteristics

1.4.5.2 OBDH (On-Board Data Handling)

The OBDH bus was developed by ESA in the 1970s as a standard spacecraft data bus (ESA-STD-OBDH). Its high reliability and performance has been demonstrated through applications to missions such as Giotto (1985), Olympus (1989), HIPPARCOS (1989), ERS-1 (1991), ERS-2 (1994), Cluster (Cluster-I in 1996, Cluster-2 in 2000), Envisat (2002), all SPOT series satellites of CNES, the STRV missions of DER, UK, as well as many other European missions (SSTL satellites, TUBSAT series, etc.). The ESA standard OBDH data bus is a synchronous serial data exchange and time-management network used onboard ESA spacecraft. \(^{867}\) \(^{868}\) \(^{869}\)

The OBDH bus of Envisat employs for the first time RBI (Remote Bus Interface), an ASIC (Application-Specific Integrated Circuit) which implements the OBDH high-level protocol and which allows direct transfers of data packets into the memory of the payload computer memory without involving its software. The RBI is implanted in each computer in the payload, where it provides a command and control interface to the platform. The RBI is also implemented/considered for all ESA missions [XMM-Newton (launch Dec. 10, 1999), MSG series (MSG-1 launch Aug. 28, 2002), Integral (launch Oct. 17, 2002 from Baikonur), MetOp series (MetOp-A launch Oct. 19, 2006), etc.]. The main benefits accruing from using a standard bus coupler on-a-chip are:

- Reduced cost: one common development can be applied to all payloads whose data interfaces exhibit the same behavior
- Easy accommodation, small size and low power consumption
- Easy to use since the user need not know the protocol involved.

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\(^{867}\) http://esapub.esrin.esa.it/pf/pf/v6n4/polv6n4.htm
\(^{868}\) ESA TTC-B-01, Spacecraft Data Handling Interface Standards.
\(^{869}\) Note: Development of a standard and modular interface ASIC was started in 1993. The RBI design and development, a common module for onboard computers, was funded by the Envisat program. The device is fabricated using MITELs (ABB-Hafo, Sweden) radiation-hardened silicon-on-sapphire process and encapsulated in a 132-pin package.
The OBDH bus standard (is not an international standard) includes such features as: a) broadcast distribution of synchronous pulses, b) memory access (load/dump), c) a large number of remote terminals (up to 62) can be supported in a distributed environment. The FLEXBUS design of Astrium is using the OBDH bus on such missions as CHAMP and GRACE. The OBDH bus is also being used on a number of commercial satellites (Eurostar-2000 platform series, Spacebus-3000 platform series, etc.).

1.4.5.3 CAN (Controller Area Network)

CAN is a field bus, a COTS (Commercial-off-the-Shelf) lightweight product. CAN is a commercial standard, a fault-tolerant multipoint field bus suitable for a distributed data-handling architecture, originally developed for industrial process control and automotive use in 1983 by the German company Robert Bosch GmbH of Stuttgart in cooperation with Intel Corporation. In particular, CAN was spawned by the needs of the automotive industry to handle the increasing connectivity requirements of modular electronic systems (the objective was to create a faster and more interference-resistant data network).

In February of 1986, Bosch proposed the serial CAN bus system at the SAE (Society of Automotive Engineers) Congress in Detroit, MI. It was the hour of birth for one of the most successful network protocols ever. It was based on a non-destructive arbitration mechanism, which would grant bus access to the message with the highest priority without any delays. There was no central bus master. The first CAN bus installation in a car (Mercedes 600 series) was realized in 1992.870 871

A CAN bus system usually consists of a bus wire, bus terminations and a bus station. The bus station includes a microcontroller, the bus controller and the bus driver. Twisted cable or coaxial cable are usually used as the cable composing the bus, but the cable specifications are not included in the standard. There is no bus controller for CAN system. Whenever a unit wins the bus and starts the communication, the other units automatically become receiver.

In the meantime, the CAN bus is ubiquitous in the auto industry; it is also being used in medical equipment, marine electronics, consumer products, building automation, and in many other application fields. The serial CAN bus consists essentially of a pair of twisted wires connecting a number of CAN nodes. The CAN protocol and physical layer, as defined in ISO-11898 (for high-speed applications) and in ISO 11519 (for lower-speed applications), provides reliable data transmission, error detection, message identification, and excellent immunity to EMI (Electromagnetic Interference). 872

There is also considerable interest by the space community to use this affordable COTS solution, but there are also concerns with regard to the required radiation hardness of CAN components for support in long-term space missions. A typical industrial component will survive a radiation dose in the order of 8-40 krad. Many spacecraft have survived using industrial electronics alone. So far, no CAN node failures in spacecraft have been observed.

As of 2005, “CANopy” is a VHDL [VHSIC (Very High Speed Integrated Circuit) Hardware Description Language] IP (Intellectual Property) Core developed at ESA/ESTEC which implements in hardware the basic features of the higher layer protocol for CAN bus on board spacecraft applications. This includes the basic CANopen features as well as several add-ons that are result of the efforts realised to date by the ESA—Industry Working

Group on CAN bus. CANopy implements the basic features of CANopen protocol and the extra features defined in the CAN Working Group draft recommendation. Its main intention is to serve as the higher layer protocol engine in CPU-less nodes like in μRTUs (Remote Terminal Unit). CANopy can be useful for Space projects using CAN bus allowing simple remote terminals to run the higher layer protocol without any software, and reducing the processor load for handling communications when integrated in a system-on-chips.

Some examples of CAN implementations in spaceborne missions are:

- SSTL of Surrey, UK, pioneered the implementation of CAN data handling technology on its spacecraft platforms starting with FASat-Alfa (launch Aug. 31, 1995; note, the launch was successful but the S/C failed to separate - making operations of FASat impossible). The CAN bus was also flown on UoSAT-12 with a launch Apr. 21, 1999 as well as on SNAP-1 (launch June 28, 2000), a nanosatellite. In addition, the SGR (Space GPS Receiver), an ESA-funded device of SSTL missions, supports the CAN bus interface. A CAN bus of SSTL is also part of the DMC microsatellite constellation, the UK TopSat mission (launch Oct. 27, 2005) and of FalconSat-2 of USAFA (launch March 24, 2006, but launch failure). In short, the CAN bus has become a standard for SSTL missions.

- The SMART-1 satellite of ESA (launch Sept. 27, 2003) features two CAN buses: the spacecraft platform units are connected to the system CAN bus, and the payload (scientific instruments) are connected to the payload CAN bus.

- With the production of a space-worthy (i.e. a radiation-tolerant) CAN ASIC, EADS Astrium Ltd. has implemented the CAN configuration successfully within radar instruments such as the sensor electronics of the Radarsat-2 mission (launch 2007). The TerraSAR-L mission of ESA (launch 2009) is also going to use CAN as well as a MIL-STD-1553B bus for its L-SAR instrument.

- IHIAerospace of Japan (formerly Nissan), in partnership with AeroAstro Inc. of Herndon, VA, have developed OBCA (On-Board Computer using Automotive electronics), an example of bringing high-reliability high-production automotive technology to the high-reliability low-production market of space systems. OBCA is an embedded processing system designed for use in spacecraft and other high-reliability environments. Much of its electronics, particularly the central microprocessor, are taken from an automotive screening process. A CAN bus is being used to interconnect the onboard components for vehicle control and data exchange. AeroAstro developed an OBCA/Bitsy-DX computer board.

### 1.4.5.4 I²C (Inter-IC or Inter-Integrated Circuit)

The I²C (also I2C spelling) bus is generically a fieldbus. The I²C name literally explains it’s purpose, namely to provide a communication link between ICs. The small bus concept was developed in the early 1980s by the Philips Laboratories in Eindhoven (The Netherlands) with the objective to provide an easy way to connect a CPU to peripheral devices in a TV-set. I²C performs chip-to-chip communications using only two wires in a serial interface. The data rate can be 100 kbit/s, 400 kbit/s or 3.4 Mbit/s. The bus may be about 3 m long at most.

In the 1990s, the bus was generally accepted as a de-facto industry standard (by its widespread use as a small diagnostic and control network for chip-to-chip interfacing). The I²C

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bus design employs a master-slave architecture; it maximizes hardware efficiency and circuit simplicity with a bi-directional two-wire design (a serial data line and a serial clock line). Although this bus standard is very popular in industry, it is not inherently providing a means of error detection. 876) 877)

The trend in spacecraft design toward micro-nano- and picosatellite platforms has also lead to the selection of a small and low-cost bus, like \( I^2C \), into onboard spacecraft applications, often in combination with other buses such as IEEE 1394 and/or MIL-STD-1533B. The \( I^2C \) bus is mostly used for such tasks as low-speed engineering data collection because of its simplicity and reliability. In 1999, Stanford University and Santa Clara University selected a \( I^2C \) bus variation (as one of the onboard buses) for the Emerald and Orion spacecraft design. In 2001, CNES selected the \( I^2C \) bus for its Myriade microsatellite family [DEMETER (launch June 29, 2004) PARASOL (launch Dec. 18, 2004), Picard, etc.]. The \( I^2C \) bus is often being used in CubeSat projects.

1.4.5.5 FireWire / IEEE 1394

The IEEE 1394 (FireWire) high-speed and low-power serial bus standard is gaining acceptance in spacecraft design. The standard is well matured and developed. IEEE 1394 defines techniques for serial digital data communications up to 400 Mbit/s among multiple nodes (up to 63 devices). The FireWire harness consists of two conductor pairs for signals and one pair for power and ground (six wires). Two modes of data transfer are available asynchronous and isochronous. The asynchronous mode provides guaranteed delivery of the data via receiver acknowledgement and isochronous provides guaranteed bandwidth and latency where data accuracy is less important than assuring the sender’s data buffers do not overflow from large quantities of data.

There are two revisions to the FireWire standard. In IEEE 1394a, the number of wires is reduced to 4 (power and ground wires are removed). In IEEE 1394b released in 2002, higher data rate (up to 1600 Mbps) and a longer cable length (up to 100 m with glass optical fiber) are supported.

FireWire implementation are also being used in combination with MIL-STD-1553B. Example of IEEE 1394 interfaces:

The VIIRS (Visible/Infrared Imager and Radiometer Suite) instrument of NPOESS (see G.10.5) utilizes an IEEE 1394 cable. The NPP (NPOESS Preparatory Project), a NASA/IPO spacecraft with a launch in 2009, employs the IEEE 1394a-2000 (FireWire) data bus for communications with CrIS and VIIRS (first use of the 1394 data bus in a satellite). 878) 879) 880)

The IEEE P1393-1999 standard SFODB (Spaceborne Fiber Optic Data Bus), developed jointly by DoD and NASA, specifies a wide bandwidth (1 Gbit/s), low-power, highly reliable, fault-tolerant fiber-optic network compatible with the harsh thermal, mechanical, and radiation environments of space missions. The SFODB high-speed architecture is based upon the commercial ATM (Asynchronous Transfer Mode) communications standard which implements a redundant, cross strapped, ring-based configuration; it includes one controller node and up to 127 transmit/receive nodes.


1.4.5.6 X2000 bus

The X2000 bus is of NASA/JPL. In 1997/8, NASA/JPL began the development of its X2000 bus, a generic multi-mission avionics system, based on the IEM (Integrated Electronics Module) architecture design, intended to support NASA's future planetary exploration program such as the Europa Orbiter and Mars Missions. Both JPL and JHU/APL, as well as several commercial enterprises, are using similar IEM architectures for their new spacecraft. The IEM contains most of the major spacecraft subsystems, including command and data handling, guidance and control, RF communications, and, when applicable, GPS navigation (a transceiver system, consisting of uplink and downlink cards, is used for RF communications instead of a coherent transponder).

The communication of the various subsystems in the X2000 bus architecture is based on two redundant, industry standard, buses: namely the scalable high-speed IEEE 1394 (FireWire), and the low-power, low-speed I2C of Philips Laboratories. In both cases the serial approach essentially eliminates miles of harnessing compared to the conventional box approach [Note: the harness refers to the cabling and connectors between flight units, accounting for as much as 10% of the dry mass of a modern spacecraft. The conventional harness comprises the cabling and connectors for power distribution, exchange of data between onboard units, acquisition of data from sensors and the control of actuators. Typically, the power cabling accounts for about 25% of the harness mass, while data cabling to sensors and actuators and between on-board units account for around 55% of the harness mass. The remaining 20% is made up of mechanical fasteners and additional shielding.]

The enabling technologies for this onboard system design approach are the 1394 bus interface chip and the generic RIO (Remote Input Output) chip of JHU/APL. This generic RIO chip is a mixed-signal ASIC with the objective to enable distributed spacecraft and instrument health data collection through the low-speed I2C bus, as well as local data collection through a standard parallel bus. A first tested version of the RIO, with a focus on tempera-
tures and voltages, is TRIO (Temperature Remote Input/Output). The TRIO chip is part of the X2000 bus. In addition to temperatures, TRIOs are used with pressure sensors in the propulsion system, and for radiation dose profile measurements throughout the S/C. TRIO is a low-power device (chip), that greatly enhances the present capabilities of sensor data acquisition in spacecraft applications.

The X2000 bus architecture is a distributed, symmetric system of multiple computing nodes and device drivers that share a common redundant bus architecture. Most notably, all interfaces used in this distributed architecture are based on COTS (Commercial-Of-The-Shelf) components. That is, the local computer bus is the PCI (Peripheral Component Interface) bus (handling of high-speed C&DH functions); the “system” buses are the IEEE 1394 bus and the I2C bus (both are COTS products). Within each node, there is also a separate “subsystem” I2C bus for sensors and instruments control. A multi-level fault protection methodology is employed to achieve high reliability. The X2000 bus provides data rates of 100 Mbit/s permitting multiple computers and scientific instruments to connect into a single local area network. The total dose requirement for the X2000 avionics at the part level is 1 Mrad (radiation hardness).

In Oct. 2000, JPL selected the FlexWire™ (Link and Digital PHY Layer cores) implementation of Innovative Semiconductors (Cupertino, CA), based on the IEEE 1394 standard, for use in the X2000 bus. As of 2004, a standard is being developed for the use of TCP/IP over FireWire.

Spaceborne implementation examples are: The NPP satellite (launch 2009) and the NPOESS satellite series (starting launches in 2010) are using the IEEE 1394 standard as their high-speed data bus. The Europa Orbiter mission of NASA/JPL (launch in 2008) considers the X2000 bus.

1.4.5.7 SpaceWire

SpaceWire is an enabling communication switched network standard for onboard space applications, composed of nodes and routers, interconnected through bi-directional high-speed digital serial links, operating at 2–400 Mbit/s (high-speed data-handling network for connecting together sensors, processing elements, mass-memory units, downlink telemetry subsystems and EGSE equipment). SpaceWire introduces specifications for packet-switching, and therefore aims at providing the full potential of the concept SpaceWire (i.e. Network capabilities based on point-to-point serial links).

SpaceWire is regarded a lightweight network (simple, low gate count implementation) that provides low-latency communication, throughput scalability and fault tolerance capability. One of the principal aims of SpaceWire is the support of equipment compatibility and reuse at both the component and subsystem levels. The concept provides an infrastructure for

895) Note: The IEEE 1394-b standard of 2002 upgrades the prior standards by allowing for gigabit signaling and by extending signaling distance to 100 m (vs. 4.5 m in IEEE 1394 of 1995)
896) Note: The IEEE 1394 standard is a low cost serial interface intended for transferring high speed data, especially video, between and among computing and consumer devices. An implementation of IEEE 1394 is FlexWire™ of Innovative Semiconductors (Cupertino, CA), offering a series of application-specific IEEE 1394 Link Layer controller cores.
900) http://www.estec.esa.nl/tech/spacewire/index.html
Earth Observation History on Technology Introduction

connecting together sensors (e.g. optical or radar instruments), processing elements (e.g. Digital Signal Processors), MMUs (Memory Management Units), and downlink telemetry subsystems. 903)

The SpaceWire standard is based on two existing commercial standards, which have been combined and adapted for onboard use: IEEE 1355-1995 standard and LVDS (Low Voltage Differential Signaling) device interfaces. Furthermore, the SpaceWire framework provides capabilities for integration and test of complex onboard systems, with EGSEs (Electrical Ground Support Equipment), plugging directly into the onboard network. 904) 905) 906) 907)

Pre-launch monitoring and testing can be carried out with a seamless interface into the onboard data-handling system. SpaceWire aims also at SMCS (Scalable Multi-channel Communication Subsystem) back compatibility. Special advantages of the SpaceWire concept are: a) the protocol is the most versatile with respect to network topology of the buses considered (it permits loops in the network), b) it provides high bandwidth, compact logic design (low power), simple user interface, very small buffer sizes (because of wormhole routing), very quick recovery from errors (20 μs), deterministic time distribution and protocol flexibility (send any packet structure across it). However, SpaceWire does not define a mechanism for reliable transport across the network, i.e., an acknowledgement/retry scheme (transport layer).

Background: The SpaceWire concept, initiated in 1998 in Europe (first discussions started in 1995 at ESTEC in an “open interface data link” round table), is the result of the efforts of many individuals within ESA, the European space industry and in academia. Also, in 1999 a new panel (P1K) of CCSDS (Consultative Committee for Space Data Standards) was set up to address satellite onboard communication. In addition, there is ECSS (European Cooperation for Space Standardization), an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities. SpaceWire is also an ECSS standard (ECSS-E-50-12A, SpaceWire, Links, Routers and Networks) as of Jan. 2003. 908) The aim of the initiative is to provide a common set of protocols to sit on top of existing onboard data buses and networks. A unified data-handling architecture is considered essential for future cost-effective missions. SpaceWire technology is based on the > 10 years of legacy of transputers and the serial links to communicate them (SpaceWire is a derivative of the INMOS transputer link architecture). 909) Those links are derived in the IEEE 1355 standard.

The SpaceWire standard covers the following protocol levels: 910)

- Physical level: Defines connectors, cables and EMC (Electro-Magnetic Compatibility) specifications.

- Signal level: Defines signal encoding, voltage levels, noise margins and data rates. DS (Data-Strobe) encoding is used. This is a coding scheme which encodes the transmission

906) http://www.estec.esa.nl/tech/spacewire/
907) Note: A SpaceWire router ASIC is being funded/developed by ESA, it is expected to be available by 2004. It is likely that many future missions may select SpaceWire and the ECSS standard because of its potential router function.
909) Note: The INMOS transputer was a pioneering concurrent computing microprocessor design of the 1980s from INMOS, a British semiconductor company based in Bristol, UK
clock with the data into data and strobe so that the clock can be recovered by simply XORing (XOR stands for eXclusive OR) the data and strobe lines together.

- Character level: Defines the data and control characters used to manage the flow of data across a link
- Exchange level: Defines the protocol for link initialization, flow control, fault detection and link restart
- Packet level: Defines how a message is delivered from a source node to a destination node.
- Network level: Wormhole routing, path addressing, logical addressing, header deletion, group adaptive routing, how to do broadcast or multicast, network errors and recovery.

The main features of the SpaceWire specifications (DS-links, up to 200 Mbit/s per link) are already implemented in a set of TEMIC chips (TSC 21020) SpaceWire interface controllers SMCS-332 (3 DS links) and SMCS-lite or SCMS-132 (1 DS-link with up to 200 Mbit/s transfer rate per direction). These controllers are manufactured in accordance with space equipment requirements. A SpaceWire PCI (Peripheral Connection Interconnect) board, prototype developed by the University of Dundee and 4Links Ltd. (UK) under ESA funding, serves in support of links and networks using the SMCS-332 chip developed by Astrium GmbH. Software drivers for Windows, Linux and VxWorks are available. A TCP/IP driver (as well as other network protocols like Ethernet) is also available, providing Internet services over a SpaceWire network. TCP/IP can be used to provide Network and Transport Layer functionality over SpaceWire.

Note: A TEMIC DSP (Data Signal Processor) with a TSC 21020 device is flown in the CHRIS (Compact High Resolution Imaging Spectrometer) instrument on ESA's PROBA mission (launch Oct. 22, 2001). The PROBA spacecraft is also using the SMCS devices.

The MCM (Multi-Chip Module) DSP (Digital Signal Processor) is an integrated and cost effective solution providing a DSP subsystem in a radiation-tolerant technology qualified for space applications.

The MCM can suit any embedded application thanks to its powerful computation unit based on the TSC21020E floating point DSP, the DPC co-processor, 128 kwords on-module SRAM memory for both program and data, and the various microcontroller type peripheral components.

911) Note: The TEMIC TSC21020 processor is the radiation-hardened compatible version of the industry known Analog Devices Inc. ADSP-21020 with performances up to 60 MFLOPs [the original design was licensed to BAE Systems (formerly Lockheed Martin Space Electronics and Communications) and ATMEL Wireless and Microcontrollers (formerly TEMIC Semiconductors) for the development of radiation tolerant versions]. The TSC21020’s Off-Chip Harvard Architecture maximizes the signal processing performance and makes the TSC21020 one of the most powerful DSPs available today for space exploration. The TSC21020 can perform multiple floating-point processes simultaneously (superscalar) and can calculate in 32-bit or 40-bit IEEE floating point data formats. The TSC21020 is also very powerful with fixed-point (integer) processing and can perform 32-bit integer operations with the enhancement of an 80-bit accumulator.

912) Note: SMCS-332 / SMCS-Lite are chips from the same family called SMCS. SMCS (Scalable Multi-channel Communication Subsystem), designed by EADS Astrium GmbH and manufactured by ATMEL in radiation tolerant technology since 1998.


914) http://www.estec.esa.nl/tech/spacewire/standards/ccsds010/ccsds_prototypes.pdf


als like cascadable timers, full duplex UARTs, input/output serial links, watchdog timers and PWM (Pulse Width Modulator) channels.

![Example of a SpaceWire network configuration](http://www.estec.esa.nl/tech/spacewire/literature/dice/dice_finalreport.pdf)

An embedded flow-through EDAC protection on both program and data memory paths enhances the MCM’s SEU tolerance. The module’s total dose radiation tolerance level is better than 50 krad.

Subsystem integration into a larger system is achieved thanks to the MCM DSP open architecture. It is possible to exchange data with the module via the FIFO memory interface, the optimized user interface or the standards IEEE-1355 high speed serial links. Both data and program memory signals are brought off-module for interfacing with expansion memory or other peripherals.

**Some early SpaceWire implementation examples are:**

- The Rosetta comet-chasing mission of ESA features the first SpaceWire implementation. [Note: Rosetta, a fully developed spacecraft, was set for a fixed launch date at the end of Jan. 2003. But due to persisting problems with the Ariane 5 rocket and the expiring launch window, the project has been postponed. Rosetta was originally intended to rendezvous with Comet Wirtanen in 2011 (to study both its nucleus and coma through an orbiting

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919) http://www.estec.esa.nl/tech/spacewire/literature/dice/dice_finalreport.pdf
spacecraft and a landed platform)]. — A new destination for Rosetta was found in May 2003. Rosetta will now set its sights on Comet 67P/Churyumov-Gerasimenko. The spacecraft was launched March 2, 2004 from Kourou, using an Ariane-5 G+ launcher. The rendezvous with the new target comet is expected in the summer of 2014.

- The Mars Express science mission of ESA employs SpaceWire (as implemented on Rosetta). A launch of the satellite (439 kg S/C bus, 60 kg lander, 116 kg payload, 427 kg propellant) took place on June 2, 2003 on a four-stage Soyuz Fregat launch vehicle from Baikonur. The cruise phase to Mars lasts some six months. 922)

- A SpaceWire has also been implemented on the SWIFT (Catching Gamma-Ray Bursts on the Fly) satellite, a NASA space science mission in the MIDEX class with international partners in Europe [ASI; Leicester University; Mullard Space Science Laboratory of the University College, London; CESR, Toulouse; MPE, etc. ]. The launch of SWIFT took place on Nov. 20, 2004. - The GSFC SpaceWire implementation on the SWIFT mission is using the SpaceWire protocols and physical layer, but only as a collection of point-to-point links, and is not really a “network” in the classical sense. It is used from the instrument to the instrument electronics only, and the rest of the onboard system uses the MIL-STD-1553 bus as the network for commanding, telemetry collection, etc.

- The InmarSat—IV spacecraft series are using SpaceWire (launch of InmarSat—IV—F1 on March 11, 2005; launch of InmarSat—IV—F2 on Nov. 8, 2005). The two operational spacecraft (a total of 3 spacecraft are planned) are providing instant broadband Internet access.

- The CoRoT (Convection Rotation and planetary Transits) mission of CNES and international partners (ESA, Austria, Belgium, Germany, Spain and Brazil.), launch Dec. 27, 2006, is using SpaceWire.

- The GOCE (Gravity field and steady—state Ocean Circulation Explorer) mission of ESA (launch 2007) is using SpaceWire.

- EDR (European Drawer Rack) of ESA, part of the Columbus Laboratory of ISS (International Space Station), uses the early version of SpaceWire (data rate of 32 Mbit/s).

- HSO (Herschel Space Observatory) of ESA (launch 2007) is being designed with a SpaceWire bus.

- The LRO (Lunar Reconnaissance Orbiter) mission of NASA (launch 2008) is using SpaceWire.

- The CryoSat satellite of ESA (launch on Oct. 8, 2005 — but launch failure) employs two fast IEEE 1355 standard links (for the two high-rate interferometric data channels) of the SIRAL instrument and the MIL-STD-1553 bus for the low rate data channels. CryoSat—2 (launch 2009).

- The future GOES program (NASA/NOAA) is considering to use SpaceWire (IEEE-1355) for the next—generation spacecraft starting with GOES—R. So are the future NASA missions JWST (James Webb Space Telescope), GLAST (Gamma-ray Large Area Space Telescope), and SDO (Solar Dynamics Observatory).

- JWST (James Webb Space Telescope) of NASA/ESA/CSA (launch 2013). 923) The avionics design of JWST employs the FPE (Focal Plane Electronics) onboard network which uses the SpaceWire specification and a transport layer (not part of SpaceWire). SpaceWire is used to provide point-to-point links to ISIM (Integrated Science Instrument Module). A MIL-STD-1553 data bus is being used to communicate with ICEs (Instrument Control Electronics) of each instrument, and FGS (Fine Guidance Sensor).

922) Information provided by Josep Resollo and by Pierre Fabry of ESA/ESTEC. http://sci.esa.int/marsexpress/
• The following commercial imaging missions are using the IEEE-1355 SpaceWire standard: a) the TerraSAR-X spacecraft of DLR/EADS Astrium GmbH (launch June 15, 2007), b) RADARSAT-2 (launch 2007) of CSA and MDA; c) the COSMO-SkyMed constellation of ASI (launch of the first S/C on June 8, 2007), d) TanDEM of DLR/EADS Astrium (launch 2009).

• The DoD is using SpaceWire on the GPS–III spacecraft generation as well as on ORS (Operationally Responsive Space) initiative.

• The SAC–D/Aquarius project of CONAE (Argentina) and NASA is using SpaceWire (launch 2009).

• JAXA is collaborating with ESA on Bepi–Colombo, using SpaceWire, and developing several chips including a large routing switch.

As the benefits of SpaceWire are realized by the space community, further improvements can be expected. These will include improvements in performance and in higher-level protocols.

### 1.4.5.8 SpaceLAN (Spacecraft Local Area Network)

7) SpaceLAN\(^{924}\)\(^{925}\) is a further entry into the ring of onboard networks (to give designers a choice for different networking solutions). The networking efforts of NASA/GSFC concentrate on the development of SpaceLAN, an Ethernet (IEEE 802.3) implementation (along with a new space-qualified physical layer) with associated standard switching components as well as a standard package of interfaces and services on a spacecraft. The intent is to replace the MIL-STD-1553/1773 bus implementations of past decades (with custom interfaces, etc.) with a more capable network in particular with regard to communications performance. - The first NASA mission candidates considered for a SpaceLAN Ethernet implementation are SDO (Solar Dynamics Observer) in 2008 and GPM (Global Precipitation Mission) in 2009. A significant effort is underway at NASA to produce a network switch that will tie together multiple nodes on the network.

<table>
<thead>
<tr>
<th>Parameter / Protocol</th>
<th>CAN</th>
<th>P²C</th>
<th>SpaceWire</th>
<th>MIL–STD–1553</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (Mbit/s)</td>
<td>1</td>
<td>up to 3.4</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Topology</td>
<td>Bus</td>
<td>Bus</td>
<td>Point to Point</td>
<td>Bus</td>
</tr>
<tr>
<td>No of nodes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– No repeaters</td>
<td>30</td>
<td>1024</td>
<td>Not limited</td>
<td>31</td>
</tr>
<tr>
<td>– Repeaters</td>
<td>2048</td>
<td>(10 bit addressing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max length:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– @ min speed</td>
<td>10 km</td>
<td>3 – 4 m</td>
<td>10 m</td>
<td>122 m</td>
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<tr>
<td>– @ max speed</td>
<td>40 m</td>
<td>3 – 4 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access to medium</td>
<td>CSMA+AMP</td>
<td>start/stop condition</td>
<td>Time windows for real–time</td>
<td>Bus controller</td>
</tr>
<tr>
<td>No of master</td>
<td>30</td>
<td>– – –</td>
<td>Not limited</td>
<td>1 per cycle</td>
</tr>
<tr>
<td>Node to node com-munication</td>
<td>Yes</td>
<td>Yes</td>
<td>yes</td>
<td>– – –</td>
</tr>
<tr>
<td>Broadcasting</td>
<td>Yes</td>
<td>Yes</td>
<td>– – –</td>
<td>Only master</td>
</tr>
<tr>
<td>Error detection</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

Table 49: Comparison of some bus characteristics\(^{926}\)

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1.4.5.9 Wireless interfacing on spacecraft (proximity networks)

In the early 21st century, the wireless commercial technologies have reached a considerable state—of—the—art level and are advancing at a rapid pace. The wireless architecture — eliminating the cables and reducing the harness from the data bus — has also significant implications in the context of future intra-spacecraft data handling, inter-instrument communications, as well as communications outside the spacecraft (inspection services, extra—vehicular activities, etc.). In addition, the wireless link technology of a “proximity network,” a “WSN (Wireless Sensor Network),” or a WLAN (Wireless Local Area Network)” domain offers mobility and flexibility for man or machine. Depending on the distributed nature of a WSN concept, the term “wireless” may also imply the need for self—powered sensor units within the network. There is considerable interest in spaceborne WSN/WLAN implementations due to the potential of mass, power and cost reductions as well as a number of other benefits.  

A wireless bus architecture may be based on various communication techniques, among them may be implementations in optical or RF (Radio Frequency) link technology.

1) Optical wireless technique: Optical wireless interfaces could be divided to two classes, line—of—sight and diffuse. The line—of—sight technique is a point—to—point data transmission method which requires a clear line of sight between the communication parties, is less flexible for monitoring the data; however, its data rate can be very high and can be very long range. Careful aiming of the receiver and transmitter is also required. — The diffuse technique is more flexible; however. its range of operation is shorter and transmission is not guided. Thus, this method is a point—to—multipoint communication technique.

2) RF technique: RF wireless interfaces use omni—directional, short—range radio links between units. The major benefits of a RF wireless interfaces over an optical interface are that all data traffic on the links can be monitored very easily during the integration and test, and integration is greatly simplified because the units need only be within range of the RF links to operate. The spacecraft units can therefore be operated on the bench during check—out and then progressively integrated into the spacecraft without the need for any special harness. One disadvantage with RF wireless interfaces is that they may be susceptible to RF interference, and may also interfere with other equipment.

Among the different developed wireless communication standards, developments based on the IEEE 802.15.4 and Bluetooth for limited distances and low speed are generally the preferred options. Moreover, the IEEE 802.15.4 standard, which is ultra low power with sleep mode, has attracted more attention. Also the family of IEEE 802.15.3 (WiMedia) standard seems to be very promising for high data rate and short range intra—spacecraft communications. For longer range communication (i.e. inter—spacecraft communication), the IEEE 802.11 family of standards (specially revision “n”) suits the application. Network topology, bandwidth, power consumption, EMC (Electromagnetic Compatibility) requirements, intrinsic robustness and implementation complexity are the factors to be considered before using any of the wireless standards in the applications.

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928) Overview of Space related Wireless Activities, Workshop on Spacecraft Data Systems, May 5—7, 2003, ESA/ESTEC, URL: conferences.esa.int/03C20/2b—03.ppt
The main motivations and benefits for developing a wireless data communication system onboard spacecraft can be summarized as:

- Reducing the time and cost of the AIT (Assembly, Integration and Test) process
- Inherently providing galvanic isolation
- Simplifying integration tests and verifications
- Reducing the harness and the complexity of connections
- Reducing the harness of cable connectors
- Removing the risk of happening a mechanical damage to interfaces during the tests
- Possibility of monitoring the data communication without adding new units and cables to the data bus
- Flexibility in upgrading and replacing the units
- Flexibility in designing deployable parts and moving subsystems
- Possibility of integration with new power scavenging techniques for designing totally wireless and autonomous modules
- Possibility of reusing the same hardware design and interface for other missions

A WSN may consist of tiny energy efficient, battery—powered sensor nodes, with built—in wireless transceivers. The nodes are able to do much more than simple sampling and transmission of data. A WSN is able to setup multi—hop wireless ad—hoc networks automatically.

On the other hand, there are some drawbacks concerning the security and EMC issues of wireless interfaces. Almost all of the available wireless interfacing standards are designed to operate in open environment, and not a close environment such as the area within a spacecraft. It is important to make sure that the wireless interfaces are not sensitive to disturbances made by other on—board electronics, and also are not interfering with other equipments.

**Wireless spaceborne implementations:** Several types of wireless devices and sensors have already flown on space missions, others are awaiting launch:

- **WNE (Mir Wireless Network Experiment),** a portion of a joint US/Russian program with Yuri Gawdiak and Richard Alena (both of NASA/ARC) as PI and Co—PI. The third Space Shuttle — Mir Station Docking Mission was flown on STS—76, (March 22—31, 1996). The WNE, a client—server network using a spread spectrum RF technology in the frequency range of 2.400—2.483 GHz, was conducted for the first time in a space environment (close proximity operations and docking) aboard Shuttle and MIR. The WNE system for the MIR station was already launched and installed on the previous STS—74 flight (Nov. 12—20, 1995). 932) 933) 934)

The WNE consisted of three computers: a ruggedized Pentium—based portable computer functioning as WNS (Wireless Network Server); the other two components were a HP Omnibook Subnotebook computer (SNB), and a NORAND Pen*Key Personal Digital Assistant (PDA).

The objective of this demonstration was to: a) evaluate the function of this system as part of remote communication planning for ISS, b) to test commercial radio frequency wireless da-

933) http://www.hq.nasa.gov/osf/station/issphase1sci.pdf
934) “Mir Wireless Network Experiment (MWNE),” URL: http://spaceflight.nasa.gov/history/shuttle—mir/science/iss/sc—iss—mwne.htm
ta links and mobile computer equipment to determine effective ranges and data throughput rates, c) to investigate the effects of radiation on advanced computer systems, and d) to investigate human/computer interaction factors in the microgravity environment. The experiment (WNE) was performed aboard STS—76 and MIR—Spektr in March 1996. Results:

- Sustainable network throughput of 200—400 kbit/s
- Operating range: within two adjacent station modules
- Passed flight qualification, electromagnetic compatibility and safety review
- No computer failures during operation after 4 months of stowage aboard MIR Spektr
- Reduced power radios will work, but coverage and range is affected
- Radio had mechanical capacitor adjustment drift due to launch vibration resulting in 10% decreased throughput.

The µWIS (Micro Wireless Instrumentation System) of NASA consists of autonomous, tiny sensors for data acquisition. The instrument was flown on several missions:

- STS—96 (May 27—June 6, 1999); the objective was to demonstrate the micro WIS transmitter and recorder
- STS—101 (May 19—29, 2000); the objective was to demonstrate the operational utility and functionality of µWIS on—orbit, initially in the crew cabin of the Shuttle Orbiter and then in the ISS.
- STS—106 (Sept. 8—20, 2000); objective same as on STS—101
- STS—104 (July 12—24, 2001); objective same as on STS—101

The ISS (International Space Station) has two wireless RF systems in operation, developed by Invocon Inc., Conroe, TX, USA. 935)

- IWIS (Internal Wireless Instrumentation System)
- EWIS (External Wireless Instrumentation System)

IWIS was deployed by astronauts [launched on assembly flight 4A, STS-97 flight of Endeavour (Nov. 30 - Dec. 11, 2000)] inside the partially completed ISS to collect data on the impulse response of the structure (strain gauges and temperature sensors are placed at various locations of the ISS structure). This data is used to verify the structural integrity of the ISS on orbit. It is also be used to update models predicting the modal response of the ISS. Complete understanding of the resonant modes of the structure will allow effective planning of the rein—boost and Reaction Control System (RCS) firing sequences when the Shuttle is docked with the Station. Since this data will change as the Station is assembled, it is important to keep this data current with each addition to the Station. The wireless nature of the data acquisition network minimizes the time necessary for deployment and recovery of the system.

The first element of EWIS was deployed by the STS-115 crew (flight 12A of Atlantis, Sept. 9—21, 2006) as part of the installation of the P3/P4 truss. EWIS was developed as a system for acquiring vibration data from the truss structure to monitor the health of the truss components. The single EWIS Remote Sensor Unit (RSU) attached to the truss is currently collecting vibration data. This vibration data will be downloaded when the EWIS Network Control Unit (NCU) is installed during a future mission. Note: the P5 Truss on STS-116 flight (Dec. 10—22, 2006) contains a remote sensor box, two tri—axial accelerometers, and two antenna assemblies as part of its EWIS assembly.

- The experimental microsatellite (20 kg) of INTA (Instituto Nacional de Técnica Aeroespacial), the Space Agency of Spain, called NanoSat—01 (launch Dec. 18, 2004), features two OWLS (Optical Wireless Links for intra—Satellite) communication demonstration experiments, representing the first OWLS in—orbit application. NanoSat—01 is operating nominally as of 2007.

- The Delfi—C3 nanosatellite of TUDelft (Delft University of Technology, Delft), The Netherlands, with a launch in mid—2007, has an experiment AWSS (Autonomous Wireless

935) http://www.invocon.com/IVC_on_ISS.html
Sun Sensor) of TNO, Delft. The tiny prototype sensor is self-powered and demonstrates a wireless data link to the CDHS (Command & Data Handling Subsystem) of the spacecraft.

- A further OWLS experiment of INTEA will be flown on the Foton-M3 mission of Russia (Roskosmos spacecraft), with a planned launch in the fall of 2007. The objective of OWLS is:
  - Assessment and validation of the Optical Wireless technology for a future data-harnessing substitution in the Foton capsule
  - To implement the CAN protocol (Controller Area Network) using an optical wireless physical layer. The wireless Foton experience will be the first OWL–CAN inside an spacecraft. 936)

1.4.6 Onboard data compression techniques

Vast amounts of source data, generated by satellite high-resolution data instruments, such as hyperspectral imagery or SAR imagery, require data reduction algorithms to alleviate high-volume data handling and processing problems. These problems are severe (a limiting operational factor) in particular for the functions of onboard storage and high-volume data transmissions to the ground segment. They also permeate throughout the ground segment in communications, data processing (memory), archiving and dissemination. \(^{937}\) \(^{938}\) \(^{939}\)

The development of compression algorithms requires a complete understanding of the characteristics and the use of the data. \(^{940}\) \(^{941}\) In particular, data compression techniques require internal redundancy in the data sequence if compression is to work. Streamlined approaches of compression are in use by various reversible (lossless) as well as irreversible (lossy) methods for reduction of data. Statistical codes (e.g. Huffman, Shannon-Fano, etc.), statistical methods (e.g. run length and arithmetic coding), vector quantization (e.g. block truncation coding, JPEG) encoding by transformations [e.g. FFT (Fast Fourier Transformation) and wavelet transformations] and fractal approaches (e.g. contracting mappings) depict some examples of the first, second and third generation approaches for data compression. \(^{942}\) \(^{943}\) \(^{944}\)

As of 1999, JPEG-LS (JPEG lossless) is the new lossless/near-lossless compression standard (predictor based) for continuous-tone images, ISO-14495-1/ITU-T.87. The standard is based on the LOCO-I algorithm (LOw COmplexity LOssless COmpression for Images) developed at Hewlett-Packard Laboratories. Speed is the overriding issue for all real-time compression applications. The compression of video or still image data is widely known in the commercial world. The JPEG and MPEG standards compete with new methods based on DWT (Discrete Wavelet Transform). These techniques can cover the whole range from lossless compression with a factor of 1.5-2 to compression factors 50 or higher.

The Canadian Space Agency (CSA) developed a new algorithm for hyperspectral imagery compression, called SAMVQ (Successive Approximation Multi-stage Vector Quantization). Evaluation and comparison with JPEG-2000 resulted in superior performance. \(^{945}\)

The JPEG-2000 standard \(^{946}\) \(^{947}\) makes use of several recent advances in compression technology in order to achieve certain features, such as improved compression efficiency, lossy to lossless compression, embedded bit-stream, multiple resolution representation, region-of-interest coding, error resilience, and random codestream access. It is based on replacing the DCT by the DWT, where integer DWT filters are mainly used to provide both


\(^{942}\) Note: In “lossy compression” information is thrown away during compression, so that the original data cannot be recovered by decompression. The decompression produces an approximation to the original data, with the level of approximation dependent on the compression ratio. In “lossless compression” the original data is reproduced exactly by decompressing the compressed stream.


\(^{946}\) http://www.jpeg.org/

lossless and lossy compression within a single compressed bit-stream. Furthermore, JPEG-2000 offers a choice of either the (9,7), or the (5,3) filter-bank for lossy compression.

Some examples of data compression implementations in past, current, and planned space-borne systems:


- The MOMS-02 (Modular Optoelectronic Multispectral Scanner), a stereoscopic along-track imaging system of DLR - flown on Shuttle flight STS-55 in April/May 1993, followed by a MOMS-02 relift on MIR/Priroda (launch of Priroda April 23, 1996) - employed DPCM to compress its data from 8 bit to 6 bit.

- PoSAT-1 (launch Sept. 26, 1993), UoSAT-12 (launch April 21, 1999), Tsinghua-1 (launch June 28, 2000) of Tsinghua University in Beijing, China - all S/C built by SSTL, use a compression algorithm by the name of AMPBTC (Adaptive Moment-Preserving Block Truncation Coding), achieving compression ratios of 2.5:1 and 4:1.

- TRACE of NASA/GSFC (launch April 2, 1998) uses a data compression scheme.

- KITSAT-3 of KAIST/SaTReC, Korea (launch May 26, 1999) uses onboard image data compression in JPEG, GIF and DPCM.

- The MTI (Multispectral Thermal Imager) mission of DOE (launch March 12, 2000) employs image data compression with the USES (Universal Source Encoder for Science data) chip for lossless compression (Rice coding algorithm, developed at JPL); the compression ratio is 2.5:1. 948) 949)

- Kodak developed an algorithm by the name of ADPCM (Adaptive Differential Pulse Code Modulation) for imagery compression. It is applied to Ikonos-2 (launch Sept. 24, 1999) and QuickBird-1 (launch Nov. 20, 2000 - launch failure) imagery. The real-time technique compresses 11-bit digital imagery to average values of 2.6 bit/pixel (reduction of 4.25:1) with little detectable loss in image quality. The compression rate enables more efficient onboard storage and downlink transmission of the data.

- The EO-1 satellite of NASA (launch Nov. 21, 2000) carries WARP (Wideband Advanced Recorder Processor) to demonstrate a number of high density electronic board advanced packaging techniques. Besides storage functions, it provides also a data compression of imagery.

- SPIHT (Set Partitioning in Hierarchical Trees) is a wavelet-based image compression method introduced in 1995 by Rensselaer Polytechnic Institute, Troy, NY. SPIHT is a method of coding and decoding the wavelet transform of an image. 950) By coding and transmitting information about the wavelet coefficients, it is possible for a decoder to perform an inverse transformation on the wavelet and reconstruct the original image. The entire wavelet does not need to be transmitted in order to recover the image. Instead, as the decoder receives more information about the wavelet, the inverse-transformation will yield a better

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948) Note: “Rice” is an adaptive variable-length compression scheme on images, an algorithm developed by Robert F. Rice of JPL and implemented by Frank Rabe of the Technical University in Braunschweig, Germany for the Mars Pathfinder Lander IMP imaging system.


quality reconstruction of the original image. As of 2002, a NASA-sponsored project is implementing an optimized SPIHT compression routine into adaptive hardware using FPGA (Field Programmable Gate Array) technology. \(^{951} \) \(^{952} \)

- **WPEB (Wavelet Packet Embedded Block Coding)** is an evolutionary method based on SPIHT. \(^{953} \)

- The **APCA (Adaptive Principal Components Analysis)** algorithm is a slightly lossy compression algorithm that uses the noise statistics of the data to preserve information content while maximizing compression ratios. APCA is particularly effective for the compression of hyperspectral imagery providing compression ratios of about 10 to one. The effectiveness of the algorithm has been tested on data sets of airborne hyperspectral imagers like AVIRIS, HYDICE, and HyMap. \(^{954} \)

- The **MSG-1 (Meteosat Second Generation -1)** satellite (i.e., Meteosat-8) of EUMETSAT (launch Aug. 28, 2002) uses encryption and JPEG compression on the HRIT (High Rate Information Transmission) data stream.

- **IRS-P5 (CartoSat-1)** of ISRO (launch May 5, 2005) uses an onboard ADPCM/JPEG compression algorithm of 3.2 : 1 to reduce the source data rate of 338 Mbit/s to 105 Mbit/s in the downlink.

- ESA sponsored the development of a quasi-lossless data compressor ASIC (Application Specific Integrated Circuit) which exploits the advantages of a wavelet-based data compression. The ASIC, developed by Saab Ericsson of Sweden, employs the Rice algorithm defined by CCSDS (with some additional features improving the functionality but maintaining the compatibility with the standard). The ASIC, referred to as TSC21020F, is installed in the PDU (Payload Processing Unit) of the PROBA satellite (launch Oct. 22, 2001). The PDU provides all data handling and processing of payload data including the data compression of the camera images (CHRIS).

- **NASA/GSFC** is developing a high-performance lossy data compression technique to support high-speed pushbroom frame-based imaging applications. \(^{955} \) The algorithm is based on MLT (Modulated Lapped Transform) and DCT techniques combined with bitplane encoding. Flight qualified hardware implementations are in development. A functional chip set is expected by the end of 2001. The chip set is being designed to compress data in excess of 20 Msamples/s and support quantizations from 2-16 bit.

- As of 2002, NASA and industry (LMSS, ASIT) are developing a real-time onboard processing system to compress hyperspectral imagery. The goal is to reduce the downlink by a factor > 100 while retaining the necessary spectral fidelity of the sensor data. The approach taken integrates state-of-the-art DSP and FPGA technologies. \(^{956} \)

- **The ALOS satellite of JAXA** (launch Jan. 24, 2006) compression of optical data. It uses a lossy data compression technique DCT (Discrete Cosine Transformation) and Huffman coding on PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) to reduce the source data rate (1 Gbit/s) to about 240 Mbit/s in the downlink. DPCM is used on AVNIR-2 data (reduction from 160 Mbit/s to 120 Mbit/s in the downlink).


JPEG 2000 is a fairly new international standard for image data compression, defined by the International Standards Organization (ISO). Part 1 of the standard, ISO/IEC 15444-1, is the Core Coding System containing the features that all decoders must support, in order to be called JPEG 2000 compliant. JPEG 2000 Part 2, ISO/IEC 15444-2, includes many optional features that are useful for special applications, including the downlink and archiving of Earth science data. As of 2002, SAIC (Science Applications International Corporation) is developing a low-memory version of JPEG 2000, sponsored by NASA, including both Part 1 and Part 2 features, for use in future ESE (Earth Science Enterprise) missions. 

1.4.6.1 Onboard SAR data compression

The output of a conventional as well as a state-of-the-art SAR instrument delivers essentially raw data (block format), consisting of a vast number of echo measurements, there is actually no image as in optical sensor outputs. Digitization and compression of the raw data is normally the next processing step prior to onboard storage and/or downlink transmission, followed by an offline ground-based processing of the reconstructed SAR signal into image data. An onboard real-time generation of SAR imagery hasn’t been attempted so far due to the current processing power limitations. But spaceborne capabilities (with corresponding ASIC implementations and more) can certainly be anticipated for the SAR image generation function in the not-so-distant future.

The BAQ (Block Adaptive Quantization) compression technique is most suitable (and a de-facto standard) for raw SAR data compression. The BAQ algorithm allows in general to reduce the data volume to a rate of 8 bits per complex sample without introducing significant distortion. The method is based on the estimation of the standard deviation value and on the coding of the real and imaginary component value of the elements (a data procedure exploiting the statistical behavior of source data, for direct onboard data compression). Also, quasi-logarithmic data coding of raw data can be implemented as BAQ in typical SAR systems; the achievable data reduction is about 2-4.

- The BAQ compression technique was probably first introduced and tested in spaceborne applications by the radar instrument (Venus Radar Mapper, operating in 3 modes: SAR, altimeter, and radiometer) of the NASA/JPL Magellan mission to Venus [Launch of Magellan on STS-30, May 4, 1989, arrival at Venus in Aug. 1990, Magellan orbited Venus for 4 years; at the end of its mission, it was commanded to plunge into the atmosphere.]

Note: The image formation from the radar echo of the SAR instrument involves a highly sophisticated processing effort. In the early history of SAR imaging, processing was done by analog optical focussing of the SAR raw data. Digital processing of SAR data was introduced in the early 1970’s. The method forms the basis of today’s highly flexible, accurate and error compensating SAR image formation. So far, all SAR image generation takes place offline in a ground based facility. The SAR raw data are stored on the satellite, transmitted to the ground station with only low or no compression and are then transferred to the processing facility.

sphere of Venus on Oct. 11, 1994]. The objective of the mission was to map the surface of Venus through thick atmospheric clouds. 967)

- The ASAR instrument of ESA’s Envisat (launch Mar. 1, 2002) mission employs FBAQ (Flexible Block Adaptive Quantization) implemented in space qualified ASIC technology of Saab-Ericsson. The algorithm compresses the ASAR raw data from 8 bits to either 2, 3, or 4 bits (sign and magnitude are selectable). 968)

- The TerraSAR-X satellite of DLR/EADS Astrium (launch June 15, 2007) employs the BAQ algorithm. The BAQ compression is applied to blocks of 128 consecutive samples with a selectable compression rate of 8 to 4, 3, 2 bits per sample.

- At the start of the 21st century, more advanced techniques (BAQ scheme variants) have been proposed for improved compression performance at the expense of higher processing effort. Among them are:
  - FBAQ (Flexible Block Adaptive Quantization)
  - ECBAQ (Entropy-Constrained Block Adaptive Quantization) 969) 970)
  - FFTBAQ (Frequency Domain Block Adaptive Quantization) 971)
  - FFT-BABC (Frequency Domain Block Adaptive Bit—rate Control) 972)
  - First wavelet algorithms for SAR data compression are being proposed as of 2003. 973)

967) The mission was named on honor of Ferdinand Magellan (1480-521) of Portugal. He led the first to circumnavigate the globe in the services of King Charles V of Spain. He died during his voyage of discovery on the Island of Mactan in the Philippines, 27 April 1521.
970) T. Algra, “Data compression for operational SAR missions using Entropy—Constrained Block Adaptive Quantiz—
1.4.7 Spacecraft communications

Background: The telecommunication technology itself predates the space age by over a century. The discovery of electromagnetism in 1820 by the Danish physicist Hans Christian Ørsted (1777-1851) allowed for the development of the electrical telegraph, the first practical application of electricity. The first electromagnetic telegraph messages in history were relayed in May 1844 between Washington and Baltimore using a telegraph system invented by the American Samuel F. B. Morse (1791-1872). The revolutionary invention of the electromagnetic telegraph and the demonstration of a successful message relay resulted in the installation of the first electric message network.975) 976)

Within ten years after the first telegraph line opened, 38,000 km of wire crisscrossed the USA, affecting profoundly the development of the West. The messages transmitted by telegraph consisted of the so-called “Morse Code” - sputtering dots and dashes that trained radio operators could decode into a message. In 1853, the Austrian physicist Julius Wilhelm Gintl (1804-1883) invented two-way communication. He realized his idea with two batteries. Gintl’s method was called the method of compensation. In 1855, the German inventors Werner Siemens (1816-1892) and Johann Georg Halske (1814-1890), founders of the Siemens & Halske company, improved on this compensation method using only one battery. The first transatlantic telegraph message was relayed in 1866. In 1853, a national authority to deal with the telegraph was created, namely “The Royal Electrical Telegraph Administration,” in Sweden.

The first workable telephone was designed in America in 1876 by the inventor Alexander Graham Bell (1847-1939, born in Edinburgh, Scotland) a pioneer in the field of telecommunications. By 1878, Bell had set up the first telephone exchange in New Haven, Connecticut. -The wireless radio transmission technology required many inventions, based on work of Faraday, Maxwell, Hertz, Lodge, Righi and Tesla, and others. The first successful attempt to transmit by wireless over the Atlantic was carried out from a radio station in England in 1901. The demonstration was done by the Italian inventor/physicist Guglielmo Marconi (1874-1937). Marconi was the first with a workable radio transmitter and receiver. Marconi is credited with the invention of “wireless telegraphy” in 1896. The early radio became possible in 1906 with the invention of the amplifying valve. In 1905, the Canadian Reginald A. Fessenden (1866-1932) invented a continuous-wave voice transmitter, using a high-frequency alternator developed by Charles Steinmetz at GE (General Electric, Schenectady, NY) in 1903. On Christmas eve 1906, Fessenden made the first voice broadcast from USA over the North Atlantic, paving the way for both radio broadcasting and radiotelephony. Fessenden sold to Westinghouse in 1910 the patent for a heterodyne receiver that used the joint operation of two AC currents for a third frequency. In 1913, the invention of the amplifying vacuum tube by the physicist Harold D. Arnold of Western Electric (by then an AT&T subsidiary, later the organization eventually became Bell Labs) permitted the first coast-to-coast (USA) telephony and the first transatlantic radio transmission in 1915.

In 1937, the English scientist Alec H. Reeves (1902-1971) received a patent on the topic of PCM (Pulse Code Modulation) while working at the ITT (International Telephone and Telegraph) laboratories in Paris. Reeves proposed a radical alternate method of signal transmission to Alexander Bell’s “voice-shaped current” (i.e. the valve-based technology of the time). His solution was that the sound be sampled at regular intervals. The values of these samples would be represented by binary numbers and transmitted as unequivocal on-off pulses. However, sending recognizable speech by this method meant networks would have to carry millions of pulses a second. It implied that PCM transmissions could not be

975) Note: The electromagnetic telegraph was predated by the optical telegraph (referred to as semaphore), invented by the Frenchman Claude Chappe in 1793, and a few months later by the Swede Abraham N. Edelcrantz. In 1794, Edelcrantz relayed successfully optical messages in Sweden.

976) Note: The words telegraph and semaphore first entered the human vocabulary in the late 18th century. They are of Greek origin, though they are not part of the original language. Tele means “at a distance,” graphos means “writer” or “signaler.” Sema means “sign” or “symbol,” and phoros means “bearer” or “carrier.”
done economically until the discovery of the **transistor effect** and the development of the first device in 1947 at Bell Labs by John Bardeen, Walter H. Brattain and William Shockley (the three received the Nobel Prize in physics in 1956). Today, PCM is a digital transmission method with built-in mathematical redundancy and error checking of the received signal offering a high degree of noise rejection and response speed. The modulation may vary the amplitude (PAM or pulse amplitude modulation), the duration (PDM or pulse duration modulation), or the presence of the pulses (PCM or pulse code modulation). For space data transmissions, PCM is the most important modulation type because it can be used to transmit information over long distances with hardly any interference or distortion. Although PCM transmits digital instead of analog signals, the modulating wave is continuous. Digital modulation begins with a digital modulating signal. The two most common digital modulating techniques are PSK (Phase-Shift Keying) and FSK (Frequency-Shift Keying). Without PCM, there would be no Internet, no digital radio or television, no digital land-line or mobile telephones, no CDs, DVDs or CD-ROMs.

### 1.4.7.1 Spacecraft RF (Radiofrequency) communications

- Telecommunication is the basic means of (wireless) message transfer between a satellite and the ground. All satellite links are based on wireless communication technology [the fundamental distinction of wireless communication is its ability to “communicate on the move” with changing geometry (and signal) characteristics between the communication participants]. Different streams of data [TTC (Telemetry, Tracking & Command) are being mainly used for S/C operations; in parallel there is the user signal or the observed instrument] are being transmitted in various directions at different data rates. In general, the downlink data rate is much higher than the uplink (command, etc.) data rate for an EO satellite. The early-history of satellite operations used frequencies in the bands HF (3<30 MHz) or VHF (30<300 MHz) for low-rate communications [Sputnik-1 (launch Oct. 4, 1957) and Sputnik-2 frequency of 20/40 MHz; Explorer-1 (launch Jan. 31, 1958) frequency of 108 MHz]. UHF transmissions (300<3000 MHz) followed soon, in particular S-band (2000-4000 MHz), as the communication demands increased with higher instrument rates. Eventually, the S-band became the standard support for all “low-rate” TT&C services of S/C operations. On the user side, however, the transmission demands kept steadily climbing for the EO missions requiring first S-band support, later C-, X-, Ku-, K- and Ka-band to get the instrument data to the ground during the short contact periods with a ground station. The switch to a higher transmission band involved always a considerable investment for each agency, in particular for the upgrading of the ground segment.

Note: Only a few highlights of telecommunication history are provided, otherwise the scope of the documentation would be unduly expanded.

- **Spacecraft onboard recorders.** There was a need for onboard data recording from the very beginning of the space age. TIROS-1 with a launch on April 1, 1960, had already a tape recorder. The first satellite electronic memory in space (384 bits of magnetic core register - required to store its own orbit ephemeris) was flown on Transit-3B (Feb. 21, 1961). Science data storage into solid-state memory followed much later this trend. Some S/C with the provision of solid-state memory are: SAMPEX (NASA, launch July 3, 1992), ALEXIS (LANL, launch Apr. 25, 1993), TEMISAT (Telespazio, launch Au. 31, 1993), PoSAT-1 (SSTL, launch Sept. 26, 1993), FASat (SSTL, launch, Aug. 31, 1995).

The ERS-1 spacecraft (launch July 17, 1991) featured an onboard storage volume of 6.5 Gbit, yet the sytem was only used for low rate data storage; it was not capable to store real-time SAR source data at 105 Mbit/s. – An onboard storage capacity of 1 Gbit was first realized with FAST (NASA, launch Aug. 21, 1996), followed by ACE (NASA, launch Aug. 25, 1997) with 2 Gbit, and Equator-S (MPE, launch Dec. 2, 1997) with 1.5 Gbit. EarlyBird (Earthwatch, launch Dec. 24, 1997) had a storage capacity of 16 Gbit.

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The STEX (Space Technology Experiment) mission of NRO (launch Oct. 3, 1998) has a 51 Gbit solid-state recorder (a new storage level in S/C data) and features 64 Mbit DRAM technology. ARGOS of DoD (launch Feb. 23, 1999) provides a storage volume of 64 Gbit as well as Ikonos-2 (Space Imaging, launch Sept. 24, 1999). The Landsat-7 storage capacity (NASA, launch April 15, 1999) is 378 Gbit. The EO-1 (Earth Observing-1 of NASA, launch Nov. 21, 2000) demonstrates with WARP (Wideband Advanced Recorder Processor) a number of high density electronic board advanced packaging techniques. WARP utilizes advanced integrated circuit packaging (3-D stacked memory devices) and “chip-on-board” bonding techniques to obtain very high density memory storage per board (24 Gbit/memory card). It also includes a Mongoose V processor which can perform on-orbit data collection, compression and processing of land image scenes. WARP consists of a high-rate (up to 840 Mbit/s capability), high-density (48 Gbit storage), low weight (< 25 kg) solid-state recorder/processor with X-band modulation capability. ALOS of JAXA (launch Jan. 24, 2006) provides a storage capacity of 768 Gbit for its high-resolution optical and SAR imagery. The CNES Pleiades S/C series (first launch in 2008) has 600 Gbit of image storage capacity.

- **Store & Forward (S&F) satellite communication.** The UoSAT-2 S/C (SSTL, launch March 1, 1984) carried the first digital S&F payload in orbit using a protocol suite by the name of PACSAT.

- **Satellite crosslink communication** refers to intersatellite links (i.e. communication from satellite to satellite without the use of an intermediate ground relay station). The first such crosslink communication demonstration took place in Dec. 1995 between two Milstar communication satellites of DoD (USA) in GSO. All Milstar satellites incorporate two crosslink dish antennas located at opposite ends of each spacecraft. Security is assured by conducting crosslink operations exclusively in a high gain, narrow beamwidth mode at or near frequencies that are absorbed by the Earth’s atmosphere (SHF, EHF). Hence, these types of crosslink transmissions cannot be received on Earth. The crosslink communication concept represents in effect a “switchboard-in-the-sky” monitoring and control capability of all satellites in a constellation from a single ground location (a cost-saving feature for constellation operations support). Milstar-2 is a four-satellite communication constellation with the MDR (Medium Data Rate) payload; MDR has 32 channels with data rates up to 1.5 Mbit/s. Block-I satellites (first generation), DFS-1 (Development Flight Satellite-1) and DFS-2, were launched into GEO Feb. 7, 1994 and Nov. 6, 1995, respectively. The last Milstar-2 spacecraft of the series, DFS-4, was launched Apr. 7, 2003.

Features that support the system’s robustness include frequency-hopping, extensive onboard processing, and crosslinks. Features that support flexibility include multiple uplink and downlink channels operating at various rates; multiple uplink and downlink beams, including agile beams; and routing of individual signals among uplinks, downlinks, and crosslinks. Milstar is the first satellite communications system of any kind that uses signal processing algorithms onboard the satellites, allowing an authorized user to establish customized networks within minutes, using his mobile terminal (the terminals are compatible among all US military services). For the Block-II series, data rates up to 1.544 Mbit/s are provided (on-demand availability of interactive voice, video, and data links). The onboard digital processing subsystem, combined with the RF subsystem, is called MDR (Medium Data Rate) payload electronics package. For the Block-II series, every MDR payload has eight antennas, each independently steerable and operating in the EHF (Extremely High Frequency) range. Terminal users may communicate with other users within the same antenna beam or with users located in other MDR antenna beams from any of the Block-II satellites. The on-orbit digital router establishes and maintains links within and among beams and responds to users’ changing and differing bandwidth requirements.

The crosslink communication feature can be regarded as a new and capable networking and

978) http://www.aero.org/publications/crosslink/winter2002/01.html
distributing resource for future satellite generations in support of a wide field of applications - including formation flying services. 979)

- ETS-VIII (Engineering Test Satellite - VIII), a GEO technology spacecraft of JAXA (planned launch in 2006, launch delay of 2 years due to H-2A launcher problems). The objective is to demonstrate mobile satellite communications and broadcasting system technologies (in S-band) with small-scale ground terminals such as hand-held terminals. ETS-VIII features two LDAR (Large-scale Deployable Antenna Reflector), each approximately 19 m x 17 m in size, to support the experiments to mobile users. The lightweight reflector features a new structural concept: a combination of module structures, cable/metallic mesh tensile structure and deployable frame structures.

- Communication downlink experiment. XPAA (X-band Phased Array Antenna) is a communication experiment on EO-1 (launch Nov. 21, 2000) of NASA/GSFC with the objective to demonstrate link-pointing capability with the use of a body-fixed low-mass and low-cost phased array antenna (data rate of 105 Mbit/s). XPAA is composed of a flat grid of 64 radiating elements whose transmitted signals are combined spatially to produce the desired antenna directivity. An inherent advantage of the body-fixed design (mass of 5.5 kg) is to permit simultaneous capture and transmission of data, avoiding perturbations to instrument measurements.

- Introduction of Ka-band (30 GHz uplink/ 20 GHz downlink) RF communications in GEO satellite systems to allow for high data rate transmissions. 980) 981) 982) The demand for increased bandwidth necessitates the move to higher frequency bands such as Ka-band at the start of the 21st century. The use of Ka-band frequencies in satellite communications enables a significant reduction in the size and cost of tracking terminal antenna reflectors for comparable data rates in systems operating at X-band frequencies. An electrically steered Ka-band reflectarray based on low-loss ferroelectric materials offers the low cost and high efficiency of a gimbaled parabolic dish, and fast, vibration-free beam steering of a direct radiating phased array. It should also be pointed out that most RF propagation effects are considerably more severe at Ka-band frequencies than at X-band.

- In Japan, the actual development of satellite communication technology started with CS-1 (Communications Satellite - 1), a spin-stabilized S/C of 676 kg of TSCJ (Telecommunications Satellite Corporation of Japan), which was launched Dec. 15, 1977 on a US Delta 2914 launch vehicle from Cape Canaveral. The objective of CS-1 was to establish fixed satellite communication using Ka-band frequency technology. This represented in fact the first demonstration of Ka-band communications in the world. The technology has since been introduced to successive GEO satellites in Japan such as the CS-2 (1983), CS-3 (1988), etc.

- ItalSat-1 (launch Jan. 15, 1991 from Kourou) Italy’s first pre-operational communications satellite (built by Alenia Spazio) in GEO at 13.2º E (also first use of Ka-band in space). ItalSat-1 carried 3 Ka-band transponders (30/20 GHz) for national coverage, and 6 multibeam Ka-band transponders (2 in 30/20 GHz, 4 in 60/20 GHz). National/global coverage multibeam telephone and TV services; TDMA, onboard regeneration; six spotbeams generated by two 2 m antennas; three transparent transponders, 40 MHz bandwidth. The Ka-band transponders provided onboard switching of signals using a baseband switch matrix. The ItalSat program was sponsored by ASI as a national space system for advanced tele-

communications. ItalSat-2 (launched in Aug. 8, 1996) of ASI featured in addition to the Ka-band payload EMS (European Mobile Services) of ESA.

- ACTS (Advanced Communications Technology Satellite), an experimental NASA S/C (built by Lockheed Martin) in GEO (at 100° W) with a launch on Shuttle mission STS-51 (Sept. 12-22, 1993). The objective of ACTS was to test new communication technologies: a) Ka-band (30/20 with 2.5 GHz bandwidth) operation, b) demonstration of onboard switching, and the use of “hopping” spot beams, c) testing of ATM (Asynchronous Transfer Mode) technology offering networked connectivity. By the mid-1990s, ATM had established itself as the network infrastructure of the Internet Age. In Nov. 1997 a record data rate of 520 Mbit/s TCP/IP (Transmission Control Protocol/Internet Protocol) was achieved using ATM via ACTS and several ground stations. The transmission experiment involved government agencies and commercial partners (the ACTS 118 consortium of researchers) to test their COTS products, all were interested in testing the ability of ATM technology to transfer data at high rates over satellite. ACTS communication capabilities continued to be used by industry, universities, and government to develop new satellite services, including real-time TV transmission to airliners.  

983) The ACTS program was managed at NASA/GRC; on May 31, 2000 the ACTS experiments program officially came to a close. Experiments were continuously supported for 78 months of operations. However, NASA extended ACTS availability for education and research purposes to an education-based consortium in Ohio. The deactivation of ACTS occurred on April 28, 2004 when funding was stopped. 984)


- ARTEMIS (launch July 12, 2001) of ESA (built by Alenia Spazio) uses Ka-band feeder links at 30/20 GHz. ARTEMIS is providing communications support for Envisat as of March 2003. See M.4.

- DAVID (Data and Video Interactive Distribution) 985) 986) is the second S/C project in the ASI small satellite scientific missions program with a planned launch in 2007. The objective is to test W-band (75-110 GHz) RF communications in LEO for very wide-band satellite transmission demands of the future and the effectiveness of resource sharing techniques to countermeasure the propagation channel behavior. DAVID is a minisatellite on the PRIMA platform built by Alenia Spazio. The choice of the W-band is rather challenging, it is still unexplored for telecommunications. The S/C carries two experiments: 987)

- DCE (Data Collection Experiment). The frequency bands chosen for uplink and downlink are in the 85.5 GHz and 75.7 GHz range respectively. 988) DCE uses the W-band link to collect and forward interactively to Internet a high volume of information data, through a LEO-GEO network architecture by using the ARTEMIS satellite of ESA. An additional feature concerns the possibility to test an experimental service towards very remote regions of the Earth, like Antarctica. Also, test of the feasibility of a satellite communication system able to collect a large amount of data from CPS (Content Provider Station) to final fixed users connected to the Internet.

- RSE (Resource Sharing Experiment) to test and validate at 22 GHz a new technique for sharing common system resources (power, codes, time) among a grid of

986) http://www.asdc.asi.it/asdc_description/node10.html
Earth terminals, and the characterization of the satellite-to-multipoint transfer medium.

- Introduction of EHF-band [30 < 300 GHz, EHF (Extremely-High Frequency)] RF communication in satellite systems. EHF communication satellites have the potential to provide protected, jam-resistant, low probability of intercept, and survivable (anti-scintillation) communication services. EHF communication can experience significant signal fading resulting from cloud penetration and moist atmospheric layers. At the start of the 21st century, all EHF communication is still on a demonstration level. Some projects:

  - The US Navy has been upgrading its UFO (Ultra-High Frequency Follow-On) program and GEO network in the 1990s. The first EHF payload was launched with the EHF-F4 satellite on Jan. 28, 1995 (launch on Atlas-II vehicle from Cape Canaveral on a commercial satellite). The launch of the EHF-F-5 followed on May 31, 1995. Both S/C were built by HSC (Hughes Space and Communications, El Segundo, CA) on the HS-601 platform. The satellites F1 through F3 carry UHF and SHF (Super-High Frequency) payloads. In F4, F5 and F6 (launch Oct. 1, 1995), there is an additional EHF payload. A GBS (Global Broadcast Service) package is part of F8 (launch March 16, 1998) through F10 (launch Nov. 23, 1999) spacecraft providing limited capabilities with a Ka-Band package. The EHF payload includes 11 EHF channels distributed between an Earth coverage beam and a steerable 5º spot beam (multiple uplinks distributed between the Earth-coverage antenna and the deployed steerable spot-beam antenna). Each uplink is time-shared by multiple users. The downlink (at 20 GHz) is a combination of all the uplinks (at 44 GHz). Both links are frequency-hopped. The EHF subsystem provides enhanced anti-jam telemetry, command, broadcast, and fleet interconnectivity communications using advanced processing techniques. The UFO-F11 satellite (launch Dec. 18, 2003) on a BSS-601 platform, is equipped with a UHF and EHF payload and an advanced tunable digital receiver (41 channels).

  - In 2001, the USAF awarded a contract for the development of an Advanced EHF satellite program (2 demonstration satellites) to Lockheed Martin and TRW. Each AEHF satellite employs more than 50 communications channels via multiple, simultaneous downlinks. For global communications, the Advanced EHF system uses inter-satellite crosslinks, eliminating the need to route messages via terrestrial systems. The first AEHF satellite is projected for launch in 2006.

  - SECOMS (Satellite EHF Communications for Mobile Multimedia Services) was a 3-year EU project until the end of 1998 [in the framework of the ACTS (Advanced Communications and Technologies) program]. A series of demonstrations were conducted in the 20/30 GHz band using ItalSat-1 in GEO.

<table>
<thead>
<tr>
<th>ITU Band Name</th>
<th>Old radar band name, IEEE standard (GHz)</th>
<th>Name of Frequency Band (ITU)</th>
<th>Frequency Band (ITU)</th>
<th>Wavelength (λ) range</th>
<th>Comments/Use</th>
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<tr>
<td>HF</td>
<td>High Frequency (Decametric waves)</td>
<td>3 &lt; 30 MHz</td>
<td>100 - 10 m</td>
<td>Radiotelephony, radio</td>
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<tr>
<td>VHF</td>
<td>Very-High Frequency (Metric waves)</td>
<td>30 &lt; 300 MHz</td>
<td>10 - 1 m</td>
<td>Radio, TV, radio navi-</td>
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<tr>
<td>UHF</td>
<td>Ultra-High Frequency (Decimetric waves)</td>
<td>300 &lt; 3000 MHz</td>
<td>1 m - 0.1 m</td>
<td>TV, radio beacon, sat-</td>
<td></td>
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<td>SHF</td>
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<td>10 - 1 cm</td>
<td>Most radar bands, gen-</td>
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<tr>
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<td>Extremely-High Frequency (Millimetric waves)</td>
<td>30 &lt; 300 GHz</td>
<td>10 - 1 mm</td>
<td>New field of telecom-</td>
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<td>1.0 - 0.1 mm</td>
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Table 50: Some ITU frequency band allocations of the EMS (Electromagnetic Spectrum)

- **SICRAL** (Italian Satellite System for Military Communications), Italy's first military satellite in GEO (16.2º E, design life of 10 years) with a launch on Feb. 7, 2001 on Ariane-4 from Kourou. The objective is to provide communications (EHF, SHF, and UHF) to fixed and mobile terminals operated by Italy’s military. SICRAL has been designed and built as a transmitter able to operate on three frequency bands (multi-payload and multi-transmission) -- EHF, UHF and SHF -- with a repeater for each band. Onboard processing functions do not include demodulation and remodulation for EHF.

- **DVB** (Digital Video Broadcast). DVB is an open standard initiative for TV broadcast services introduced by European industry and institutions in 1992/3, and managed/published by ETSI (European Telecommunications Standards Institute), CENELEC (Center for Electrotechnical Standards) and EBU (European Broadcasting Union). In the broadcasting market, DVB has been used since the mid 1990s by such companies as SES Astra of Luxembourg. The DVB project quickly expanded to include multimedia applications as well as television. DVB provides in effect unprecedented flexibility in combining digital data (video, audio, Internet content, databases, file transfer, multimedia, etc.) into a multiplexed transport stream. Introduction of DVB-IP (Internet Protocol) in 1997/8. The DVB-IP technology permits a service distributor to maximize the bandwidth (many support options are available).

At the start of the 21st century, DVB has become an integral part of global broadcasting (over 200 organizations in over 30 countries), setting the global standard for satellite, cable and terrestrial transmissions and equipment. The main transmission standards of DVB are: DVB-S (satellite), DVB-C (cable) and DVB-T (terrestrial). While DVB was primarily designed for one-way (forward) broadcast of digital data, DVB-RCS (DVB-Return Channel via Satellite) provides a two-way broadband Internet access solution with its multicast capability. In 2000, DVB-RCS became an ETSI standard (EN 301 790) for GEO satellite interactive networks with fixed RCST (Return Channel Satellite Terminal) support (use for regenerative satellite multimedia systems). DVB-RCS offers satellite based Internet service providers the opportunity to use a common service architecture to deliver a wide range of support options at reasonable costs. - Another ETSI standard under definition is DVB-MHP (DVB-Multimedia Home Platform), a framework for developing iTV (interactive TV) applications. DVB applications use mostly frame format MPEG-2 encoding/compression at data rates between 2-10 Mbit/s. The DVB-IP technology is increasingly being considered in support for such applications as Earth observation satellite missions. Examples:

- The Envisat (launch March 1, 2002) mission of ESA uses DVB-IP services of commercial satellite service providers to distribute its data products to the user community.

- AmerHIS (the first DVB-RCS access and switching node in space) is an advanced communication payload of ESA, a regenerative multimedia system onboard Hispasat’s Amazonas satellite (built by CDTI, a Spanish subsidiary of Alcatel Espacio), which was launched into GEO (61º W) on Aug. 5, 2004. AmerHIS operations are based on Alcatel’s 9343 DVB OnBoard Processor. This processor has the demodulation, decoding, switching encoding and modulation capabilities needed for the 4 transponders on Amazonas. Each transponder covers one of the four geographical regions served by the satellite — namely Europe, Brazil, North and South America. The AmerHIS concept puts the hub onboard the system.
satellite, saving the delay of 250 ms caused by the additional second hop. The regenerative payload thereby enables realtime broadband connections between small user terminals. The complete AmerHIS system consists of: 991)

- The regenerative payload onboard Amazonas
- A network management system, containing the NCC (Network Control Center) and associated management control, responsible for managing the onboard resources and the user terminals
- User terminals using RCST (Return Channel Satellite Terminal) technology oriented towards the commercial demonstration of new services
- Use of RSGW (RCST Satellite Gateways) that provide the system with access to terrestrial networks.

• Amateur radio communications via satellite.992) The amateur X.25 radio communication protocol, referred to as AX.25, is a modified version of the commercial communication X.25 protocol standard. It was developed in the early 1980s. Digital “packet radio” was initially authorized by Canada in 1979 and used by Canadian hams (amateur radio operators). In 1978, Doug Lockhart of Vancouver, British Columbia, developed a device that he called TNC (Terminal Node Controller). It worked with a modem to convert ASCII to modulated tones and convert the demodulated tones back to ASCII. “Packet radio” is a system that uses TNCs and amateur radio transmitters and receivers to send information in AX.25 from place to place (for instance via Internet). It can be used for electronic mail, message transmission, emergency communications, or just plain tinkering in the world of digital communications.

A TNC is a “little black box” permitting a radio to be plugged into any computer that supports the standard RS-232 protocol/port and to communicate ASCII text. The TNC handles all the hardware aspects of data communication automatically, such as modulating [AFSK (Amplitude Frequency Shift Keying)] and demodulating of the digital signals and audible tones for broadcast as well as the software aspects such as forming data packets.

TNCs are increasingly being installed on AMSAT microsats in support for amateur radio satellite communications, they are also being used for many university/student-built satellites. The concepts are being considered by some space agencies as well. The communication data rates supported by TNC are normally at 1200 baud or at 9.6 kbaud at VHF frequencies of 145.825 MHz. The application spectrum of a TNC device onboard a nano- or microsatellite may not only be used to provide the dedicated up- and downlinks and command/control channels, but may also serve as a generic relay for other applications on a secondary basis. Some examples of TNC satellite uses are:

• An early TNC installation on a spacecraft was provided for the Russian MIR station in 1990 by MIREX (Mir International amateur Radio Experiment), an amateur radio group formed to assist with MIREX. Other examples are:

• The DOVE (Digital Orbiting Voice Encoder) spacecraft, designed and built by AMSAT-Brazil (launch Feb. 22, 1990), uses an onboard TNC for all communications.

• SPRE (SPARTAN Packet Radio Experiment), a payload on Shuttle flight STS-72 in Jan. 1996; SAREX-II (Shuttle Amateur Radio Experiment II) was flown on STS-93 (July 23-28, 1999) which included a TNC.

• PCSat (Prototype Communications Satellite)993)994), a student demonstration nanosatellite of the US Naval Academy, Annapolis, MD (launch Sept. 30, 2001), uses a TNC (Terminal Node Control) device as its onboard computer and employs the APRS (Automatic Packet Reporting System) satellite service.

matic Position Reporting System) protocols (with generic digipeating capabilities) of AM-
SAT to permit hundreds of users per pass to access the spacecraft (via AX.25 protocol). **PCSat is the first satellite to use the TNC function as the complete spacecraft system controller with no other CPUs onboard** (see N.20). An advantage of the AX25 protocol is that any node in the system can be used for relaying data between any other nodes. Thus, the TNC can not only provide the dedicated up and downlinks and command/control channels, but also serve as a generic relay for other applications on a secondary basis. Further examples of TNCs on orbit are: SAREX, ISS, ÒPAL, SAPPHIRE, and STARSHINE-3.

### 1.4.7.2 Introduction of CCSDS protocols

- Spacecraft data transmission (telemetry and telecommand) using CCSDS protocols. The first recommendations for a CCSDS (Consultative Committee for Space Data Systems) standard were released in 1987, allowing information from different parts of a satellite to be placed into packets and to be sent to a ground station (or to be uplinked as telecommand data). By using a standard method of processing and distributing satellite data, one ground station can handle data from different satellites. The ERS-1 mission of ESA was the first one to introduce CCSDS formats and protocols. The SAMPEX mission was the first in USA to implement the CCSDS communication standards. TEAMSAT (launch Oct. 30, 1997) is the first ESA spacecraft flown with telemetry and telecommand systems both fully compatible with CCSDS standards; it is also the first spacecraft to exploit the self-adaptive asynchronous telemetry capabilities successfully that the CCSDS recommendations support. [The communication system excepts user data as randomly occurring squirts of various sizes or as fully asynchronous individual bytes. The bandwidth on the link is shared among the users according to allocation ratios. Any bandwidth not taken up by one user is offered to the other users in the proportionate ratios].

The CCSDS standard offers a number of significant advantages over the more traditional ‘mission-specific’, fixed-format data frames, such as:

- Very reliable uplink, with automatic retransmission capability
- Cost reducing, commercial off-the-shelf onboard components
- Potential for inter-operability with other ground stations/segments
- A CCSDS protocol design in combination with a MIL-STD-1553B communications bus can provide substantial advantages in terms of spacecraft/payload decoupling. Such a design is for instance implemented in the IMAGE satellite of NASA. 996) As of 2001/2 SSTL (Surrey, UK) was implementing a CCSDS project (single-chip CCSDS-based development) in which a simplified version of the CCSDS protocol has been adapted for small satellite communications. 997) 998)

As commercial satellite manufacturers adopt the CCSDS recommendations, the scope for international inter-operability will offer significant opportunities for collaborative programs resulting in a reduction in ground control facility costs.

- Encrypted CCSDS protocol demonstration. The STRV-1d mission of QinetiQ (formerly DERA, UK) with a launch on Nov. 16 2000 (see M.41.2.2), carries ECSE (Encrypted CCSDS Space Experiment). The objective is to test a prototype secure CCSDS packet TM/TC system in an operational environment. a) Demonstration of ESA Packet Telecommand

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encrypt/decrypt, authentication, validation and anti-replay attack functionality; b) ESA Packet Telemetry encrypt/decrypt functionality, c) Extraction of security management functions onboard the spacecraft and simplified processing of these security management functions.

<table>
<thead>
<tr>
<th>Satellite (Agency)</th>
<th>Launch Date</th>
</tr>
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<tbody>
<tr>
<td>ERS-1 (ESA)</td>
<td>July 17, 1991</td>
</tr>
<tr>
<td>SAMPEX (NASA in SMEX program)</td>
<td>July 3, 1992</td>
</tr>
<tr>
<td>EURECA (ESA)</td>
<td>July 31, 1992, retrieval June 21-July 1, 1993</td>
</tr>
<tr>
<td>MSTI-1 (DoD), MSTI-2, MSTI-3</td>
<td>November 21, 1992, May 9, 1994, May 16, 1996</td>
</tr>
<tr>
<td>Spacelab-D2 (DLR/ESA)</td>
<td>April 26 - May 6, 1993</td>
</tr>
<tr>
<td>STRV-1a and -1b (DERA, UK)</td>
<td>July 17, 1994</td>
</tr>
<tr>
<td>ERS-2 (ESA)</td>
<td>April 21, 1995</td>
</tr>
<tr>
<td>RADARSAT-1 (CSA)</td>
<td>November 4, 1995</td>
</tr>
<tr>
<td>SOHO (ESA/NASA)</td>
<td>December, 2 1995</td>
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<tr>
<td>Cluster-I (ESA)</td>
<td>June 4, 1996</td>
</tr>
<tr>
<td>TEAMSAT/YES (Young Engineers’ Satellite) (ESA)</td>
<td>October 30, 1997</td>
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<tr>
<td>TRMM (NASA/NASA)</td>
<td>November 27, 1997</td>
</tr>
<tr>
<td>ETS-VII (NASDA)</td>
<td>November 27, 1997</td>
</tr>
<tr>
<td>DSI (NASA/JPL)</td>
<td>October 24, 1998</td>
</tr>
<tr>
<td>ROCSAT-1 (NSPO, Taiwan)</td>
<td>January 26, 1999</td>
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<tr>
<td>Ørsted (DRSI, Denmark)</td>
<td>February 23, 1999</td>
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<tr>
<td>Landsat-7 (NASA)</td>
<td>April 15, 1999</td>
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<tr>
<td>SJ-5 (Shi Jian - 5) of CAST and CSSAR, China</td>
<td>May 10, 1999</td>
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<tr>
<td>QuikSCAT (NASA)</td>
<td>June 19, 1999</td>
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<tr>
<td>MTSAT (NASDA/JMA, Japan)</td>
<td>November 15, 1999</td>
</tr>
<tr>
<td>Terra (EOS/AM-1 of NASA)</td>
<td>December 18, 1999</td>
</tr>
<tr>
<td>KOMPSAT-1 (KARI, Korea)</td>
<td>December 20, 1999</td>
</tr>
<tr>
<td>MTI (DOE)</td>
<td>March 12, 2000</td>
</tr>
<tr>
<td>IMAGE (NASA)</td>
<td>March 25, 2000</td>
</tr>
<tr>
<td>MTA (ASI)</td>
<td>July 15, 2000</td>
</tr>
<tr>
<td>CHAMP (GFZ/DLR)</td>
<td>July 15, 2000</td>
</tr>
<tr>
<td>Cluster-2 (ESA)</td>
<td>July 16, (1st launch), Aug. 9, 2000 (2nd launch)</td>
</tr>
<tr>
<td>QuickBird-1 (EarthWatch)</td>
<td>November 20, 2000</td>
</tr>
<tr>
<td>STRV-1c and -1d (DERA, UK)</td>
<td>November 16, 2000</td>
</tr>
<tr>
<td>EO-1 (NASA)</td>
<td>November 21, 2000</td>
</tr>
<tr>
<td>QuickBird-2 (DigitalGlobe, former EarthWatch)</td>
<td>October 18, 2001</td>
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<tr>
<td>PROBA (ESA), BIRD (DLR)</td>
<td>October 22, 2001</td>
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<tr>
<td>TIMED (NASA), Jason-1 (CNES)</td>
<td>December 7, 2001</td>
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<tr>
<td>GRACE (NASA/DLR/GFZ)</td>
<td>March 17, 2002</td>
</tr>
<tr>
<td>Aqua - formerly EOS/PM1 (NASA)</td>
<td>May 4, 2002</td>
</tr>
<tr>
<td>ICESat (NASA),</td>
<td>Jan. 13, 2003</td>
</tr>
<tr>
<td>DSP (Double Star Project) of CNSA, China and ESA</td>
<td>Dec. 29, 2003 (DSP-1) July 25, 2004 (DSP-2)</td>
</tr>
<tr>
<td>GP-B (Gravity Probe-B), NASA/Stanford</td>
<td>April 20, 2004</td>
</tr>
<tr>
<td>Myriade (CNES Microsatellite Program) with DEMETER, PARASOL, Microscope, and Picard</td>
<td>start in 2004 with DEMETER (launch June 29)</td>
</tr>
<tr>
<td>MTSAT-1R (JAXA/JMA, Japan)</td>
<td>Feb. 26, 2005</td>
</tr>
<tr>
<td>ALOS (JAXA), Japan</td>
<td>Jan. 24, 2006</td>
</tr>
<tr>
<td>MTSAT-2 (JAXA/JMA, Japan)</td>
<td>Feb. 18, 2006</td>
</tr>
<tr>
<td>COSMO-SkyMed (ASI, ESA)</td>
<td>June 8, 2007 (launch of first S/C in a 4 S/C constellation)</td>
</tr>
<tr>
<td>TerraSAR-X (DLR/EADS Astrium GmbH)</td>
<td>June 15, 2007</td>
</tr>
</tbody>
</table>
### FSO (Free-Space Optics) communications with satellites

FSO is an emerging wireless communications technology at the start of the 21st century that transports data from point-to-point and multipoint via laser technology. Commercial FSO systems became available in the 1990s, primarily to interconnect buildings and campus LANs (short-distance interconnections). The technology is based on connectivity between FSO units, each consisting of an optical transceiver with a laser transmitter and a receiver to provide full duplex (bi-directional) communications. The interest here is focused on FSO links between a satellite and the ground as well as on optical ISLs (Intersatellite Links) or IOLs (Inter-Orbit Links). 999)

- Laser links have the potential to offer much higher transmission rates (up to 10 Gbit/s) for LEO-to-ground communications than conventional TT&C radio frequency (i.e., RF-based) links which are limited to rates of about 300 Mbit/s to 1 Gbit/s maximum. The optical information bandwidth of a signal is only a fraction of the RF carrier frequency, typically 0.1 that of RF systems. Extremely high ‘antenna’ gains with relatively modest apertures are obtained in optical communication systems, resulting in very low carrier power (for instance 60 mW in SILEX (Semiconductor Intersatellite Link Experiment) data transmissions of 50 Mbit/s over a distance of 42,000 km). The optical spectrum for TT&C applications may range in bandwidth from about 532 nm (563 THz) to about 1550 nm (194 THz), providing for many GHz of information transfer on optical carriers. Space laser optical communications benefit from the intrinsic high operating frequency (200 to 400 THz) leading to very high optical antenna gains (> 110 dB). This intrinsic advantage comes with a beam divergence of a few µrad, requiring accurate antenna pointing.

One of the main advantages of laser links — apart from the intrinsic benefits of low power consumption and the potential of very high data rates — is that by their very nature, there can be no interference between optical and radio transmissions. Hence, FSO systems offer the perfect answer to some of the main requirements for secure communications, in particular with respect to counter-measures. It is very difficult to detect optical transmissions (unless being exactly within the transmission path), it is very difficult to locate such a communication, and to jam it. Naturally, such security aspects are of great interest for a variety of applications in the military, commercial and to some extent also in the Earth observation fields. 1000) 1001) 1002)

The technical challenge of the technology demonstration involves in particular alignment and stabilizing issues, it requires pointing errors of <10 µrad (or < 0.0005º). This pointing accuracy is several orders of magnitude lower (better) than open-loop pointing of a typical platform. Also, platform jitter caused by the operation of other payload instruments, must be mitigated. Other constraints to be considered deal with eye-safety issues and with weather and atmospheric effects. The optical signals can be greatly attenuated by the weather and

<table>
<thead>
<tr>
<th>Satellite (Agency)</th>
<th>Launch Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamant-1 OHB-System, Bremen</td>
<td>planned for 2007</td>
</tr>
<tr>
<td>X-Sat (NTU, Singapore)</td>
<td>planned for 2008</td>
</tr>
<tr>
<td>Pleiades (CNES, ESA)</td>
<td>planned for 2008</td>
</tr>
</tbody>
</table>

Table 51: Some CCSDS protocol implementations on satellite missions

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the atmosphere. Numerous applications of optical communication links are envisioned, such as: Space-to-ground, interorbit (LEO-GEO), intersatellite (LEO-LEO or GEO-GEO), or deep space to ground. The laser technologies used for space optical communications are inherited from commercial terrestrial applications:

- 0.8 µm technology, commercially used in printer and CD applications
- 1.06 µm technology, commercially used in scientific and lidar applications
- 1.55 µm technology, commercially used in terrestrial telecommunications (fiberoptic networks). A fairly large number of component manufacturers exists.

Although some functions are common to all technologies, the laser wavelength drives key optical terminal elements such as the transmitter, the receiver, the acquisition and tracking sensors.

Some early demonstrations in space are:

- **LCE** (Laser Communication Equipment),\(^{1003}\) a CRL (Japan) payload flown on ETS-6 (Experimental Test Satellite-6) of NASDA and NTT. Launch of ETS-6 on Aug. 28, 1994. Note: ETS-6 attained a highly elliptical orbit (instead of a planned GEO) due to a failure in the launch vehicle propulsion system. In spite of this misfortune, some LCE experiments were conducted with ground stations in Japan and at JPL (low data rate transmissions of 1 Mbit/s were conducted, mostly due to the use of a small optical antenna and non-diffraction-limited optics on the spacecraft).

- **SILEX** (Semiconductor Intersatellite Link Experiment), an ESA technology demonstration of an optical link system, built by EADS Astrium SAS (formerly MMS). SILEX consists of two optical terminals, a LEO and a GEO terminal, namely **PASTEL** (PAssager SPOT de Télécommunication Laser, mass of 162 kg), a LEO terminal onboard SPOT-4 (launch March 22, 1998) on the anti-Earth side of the SPOT platform, and **OPALE** (Optical Payload for Intersatellite Link Experiment) a GEO terminal mounted on ESA’s geostationary satellite ARTEMIS. ARTEMIS was launched on July 12, 2001. The ARTEMIS downlink to the ground segment at CNES Toulouse uses a conventional radio transmission (Ka-band). See also SILEX under D.46.2. The SILEX experiment has a twofold objective: validation of the laser transmission concept and operational transmission of SPOT 4 imagery to the ground. \(^{1004}\)\(^{1005}\)\(^{1006}\)

The SILEX technology was selected in early 1990s. Since this time, several technological improvements have come about. These improvements allow today simplified and more powerful optical terminals with the following technologies:

- More powerful laser diodes: 0.4 W output power compared to 60 mW used on SILEX LEO terminal
- Full communication chain (transmit and receive chains) completely validated and performance correlated up to 600 Mbit/s
- CMOS detector availability: CMOS detector (750 x 750 pixels) sampled at 8 MHz with windowing capability permits to only a single detector for acquisition and tracking. This simplification reduces the optical path and increases the available power for tracking and communication
- SiC technology qualification: this technology, now mature and implemented on several optical payloads, allows simplifying telescope and focal plane design and increases stiffness, mass and stability performances.

\(^{1003}\)http://www.wtec.org/loyola/satcom/c6_s1.htm


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link range</td>
<td>45,000 km to SPOT-4/ARTEMIS (worst case configuration)</td>
</tr>
<tr>
<td>Link capacity</td>
<td>Forward link (GEO --&gt; LEO): 2 Mbit/s capability&lt;br&gt;Return link (LEO --&gt; GEO): 50 Mbit/s of SPOT-4 useful data rate</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>800 - 852 nm</td>
</tr>
<tr>
<td>Key components</td>
<td>Laser diodes, CCD detectors, APD (Avalanche Photodiode) sensor</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>250 mm</td>
</tr>
<tr>
<td>Optical power</td>
<td>Communication laser diodes power set-point: 60 mW (LEO), 40 mW (GEO)&lt;br&gt;Beacon laser diodes power: 9.5 W (19 diodes x 500 mW)</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>Communication beam: 4 μrad (LEO) and 8 μrad (GEO)&lt;br&gt;Beacon beam (GEO): 750 μrad</td>
</tr>
<tr>
<td>Link performances</td>
<td>Acquisition: 240 s duration (worst case) with 0.95 probability of success achievable down to 13º sun aspect angle&lt;br&gt;Data transmission: average BER better than 10⁻⁸ (return link); limited occurrence of errors (short term quality), achievable down to 1º sun aspect angle</td>
</tr>
<tr>
<td>Availability</td>
<td>better than 92.5% of the LEO-GEO annual visibility</td>
</tr>
<tr>
<td>Operations</td>
<td>Autonomy w.r.t. ground: 24 hours operation without ground command&lt;br&gt;Autonomy w.r.t. satellite: Onboard processor and software, integrated thermal control, safe configuration&lt;br&gt;GEO multi-user capability (operation of 2 LEOs in an interleaved way)</td>
</tr>
<tr>
<td>Typical terminal data</td>
<td>Pointing accuracy: about 2 μrad&lt;br&gt;Optical quality: better than λ/10 on each optical path&lt;br&gt;Isolation between paths: better than 10⁻¹⁰&lt;br&gt;Defocus: better than 10 μm</td>
</tr>
</tbody>
</table>

Table 52: Overview of SILEX optical link characteristics

- **LUCE** (Laser Utilizing Communications Equipment), a Japanese payload (built by NEC) flown on OICETS (Optical Interorbit Communications and Engineering Test Satellite) of JAXA (launch Aug. 23, 2005). OICETS in LEO conducts interorbit communications experiments with ARTEMIS of ESA in GEO (50 Mbit/s using a 25 cm telescope on both ends of the link). - From Sept. 9-14, 2003, JAXA conducted successfully communication experiments (link tests) between the ground-based LUCE engineering model via ARTEMIS and OGS (Optical Ground Station) on Tenerife, operated by IAC (Instituto de Astronómica de Canarias), Spain.

- **Lasercom** (Laser Communication Experiment), an experiment on the AFRL mission TSX-5 and its payload STRV-2 (launch on June 6, 2000), see M.48.

- **A first optical data transmission test, using the laser link between ARTEMIS (ESA) and SPOT-4 (CNES), was realized on Nov. 21, 2001** on four consecutive SPOT-4 orbits for contact periods between four and 20 minutes each. The SILEX terminal onboard ARTEMIS, in a parking orbit of 31,000 km, activated its optical beacon to scan the area where SPOT was expected to be (LEO at 830 km). When contact was made, SPOT-4 responded by sending its own laser beam to ARTEMIS. On receiving the SPOT-4 beam, ARTEMIS stopped scanning and the optical link was maintained for a pre-programmed period lasting from 4 to 20 minutes. Data rates of 50 Mbit/s were reached transmitting test data from SPOT-4 via ARTEMIS to the ground. An extremely low bit error rate of the data stream was confirmed at at ESA's test station in Redu (Belgium) and the SPOT 4 receive station in Toulouse, France. On Nov. 30, 2001, the first-ever civil transmission of an image by laser link took place from one S/C to another. - In the meantime, many operational validation tests have been conducted with optical transmissions of the SILEX system. It turns out that the SILEX configuration via ARTEMIS offers significant observation coverage and transmission advantages, practically in real-time.

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• The TerraSAR-X mission of DLR and EADS Astrium GmbH (launch June 15, 2007) will be flying a secondary experimental payload by the name of LCT (Laser Communication Terminal), a regenerative system designed by Tesat–Spacecom of Backnang, Germany. LCT provides either a high data rate, bidirectional communications link for binary digital data transfer between two satellites, or between one satellite and an optical ground station, the on-orbit verification of the first coherent optical communication system on a satellite.

With constantly increasing communication rates, optical systems (ISLs) are also being considered for small satellites. Apart from governmental/institutional research in the area, a significant driver for the development of advanced TT&C systems is the prospect of commercial LEO communication systems, such as the Teledesic/Celestri constellations which include laser communication intersatellite crosslinks (ISLs) as part of their baseline design. Note: The planned Teledesic constellation, with up to 840 satellites to provide “Internet in the Sky”, was never realized.

• Internet fiber-based communication using OEIC (Optoelectronic Integrated Circuit) technology. The monolithic integration of high-speed electronic and optoelectronic devices into (OEICs) is very attractive for use as optical receivers (photoreceiver) and transmitters in fiber-optic communication systems. The OEIC scheme utilizes an on-chip technology containing light sources, photodetectors, modulators, and VLSI-density electronic circuitry. The OEIC technique offers a higher bandwidth and an improved functionality at a reduced cost, as compared with hybrid solutions, making it possible to utilize the potential of optical fibers for high-speed communication. Photoreceivers for several bit rates ranging from 10 to 40 Gb/s have been fabricated in the late 1990s and installed for internet applications. Demands for greater bandwidths have driven the telecommunication research communities to realize complex OEICs such as transceivers, switching systems, low chirp optical sources and multichannel optical distribution systems.

The next logical step to optical fiber-based Internet communications are FSO (Free Space Optics) network applications of OEIC technology (support of mobile communications with ubiquitous connectivity). The photoreceiver array employs unique optical amplifier and conversion technologies that provide the ultra-sensitivity required for free space optical communications networks. This sensitivity is achieved by monolithically integrating a VCSEL (Vertical Cavity Surface Emitting Laser-diode) optical preamplifier with a photodiode receiver and related amplifiers and filters on the same chip, resulting in sensitivities as low as -47 dBm (62 photons/bit at 2.5 Gb/s).
Parameter | OPALE on ARTEMIS | PASTEL on SPOT-4
---|---|---
FOV | ±4000 μrad | ±4000 μrad
Isolation | better than $10^{-10}$ | better than $10^{-10}$
Pointing accuracy | 2.3 μrad ($3\sigma$) | 2.2 μrad ($3\sigma$)

Table 53: Instrument and view parameters of the two optical terminals

### 1.4.7.4 Internet access for future spacecraft LAN services

The Internet embodies a key underlying technical idea, namely that of open architecture networking.\(^{1014}\)\(^{1015}\)\(^{1016}\) It provides a good example of a scalable, robust, efficient, and adaptive network architecture that could support future orbiting sensor webs. The use of Internet Protocols in the space segment (i.e., for onboard LAN use as well as for data transmission services) is attractive because it provides for easy interconnection with the terrestrial Internet. IP (Internet Protocol) enables advanced mission concepts (e.g., collaborative science) and allows better alignment with industry standards and products (end-to-end network solutions). IP supports a simpler, yet more capable, overall mission design and enables a simpler operations solution. The SBI (Space-Based Internet), also referred to as NGSI (Next Generation Space Internet), is a satellite network system in which each satellite is capable of originating traffic, terminating traffic, and switching traffic traveling between other satellites and the ground.

At the start of the 21st century, developments in the TCP/IP protocol to handle mobility of Internet hosts for mobile data communications (proposed standards), are being carried out under the auspices of the IETF (Internet Engineering Task Force). IETF has designed the so-called MIP (Mobile Internet Protocol) architecture to support mobility on the Internet. The MIP concept features a routing protocol that allows hosts (and networks) to seamlessly "roam" among various IP subnetworks (an essential in wireless networks). The basic idea of the MIP concept is a multi-technology architecture mainly independent of the underlying physical layers, where all functions, either related with end-to-end communications or with internal network management and control, are performed at the IP level. Some examples of emerging MIP services and applications are:\(^{1017}\)

- MIP does not have any restrictions related to geographical regions or service providers
- MIP works in conjunction with the standard IP protocol, maintaining transparency with the higher layer protocols
- MIP is not tied to any specific access technology. It can work with wireline and wireless technologies.
- The IP protocol allows the use of MDP (Multicast Dissemination Protocol), which only requires a one-way link. This is an advantage in the event of a temporary receiver failure on a satellite, because the satellite will be able to send data to the ground station without being commanded.
- Using IP also allows secure communications via applications like SSH (Secure Shell), SCP (Secure Copy), and NTP (Network Time Protocol) techniques.
- At the transport layer, TCP (Transmission Control Protocol) or UDP (User Datagram Protocol) may be used to package the application layer data. This package communication contains the data and the necessary error protection sections to ensure a safe data transmission within the overall network.

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\(^{1016}\) Note: The sensor web concept refers to a group of sensors (distributed), whether spaceborne, ground-based or airborne which act in a collaborative autonomous manner to produce more value than would otherwise result from the individual observations.

\(^{1017}\) Note: IETF is a large open international community of network designers, operators, vendors, and researchers concerned with the evolution of the Internet architecture and the smooth operation of the Internet. The first meeting of IETF was held in January 1986 in San Diego, CA.
MIP (Mobile IP) is a mechanism for maintaining transparent network connectivity to mobile hosts. The MIP protocol enables a mobile host to be addressed by the IP address it uses in its home network (home IP address), regardless of the network to which it is currently physically attached. Therefore, ongoing network connections to a mobile host can be maintained even as the mobile host is moving from one subnet to the other.

Some background on Internet: The first proposal for a “global hypertext system” based on TCP/IP was made at CERN (European Organization for Nuclear Research, Geneva, Switzerland) by Tim Berners-Lee in 1989, and further refined by him and Robert Cailliau in 1990. At the time, the science community world was yearning for interconnection services in the midst of proprietary and incompatible networks by various computer companies. By the end of 1989, prototype software for a basic system was already being demonstrated at CERN. The early Internet included a WWW browser that could be run on any system. 1018) At the beginning of 1993 there were about 50 known information servers. An International World-Wide Web Consortium, “W3C”, was set up in Oct. 1994 comprising a body of institutes and companies from all over the world. The W3C is run jointly by INRIA, the Institut National pour la Recherche en Informatique et en Automatique (for Europe), MIT, the Massachusetts Institute of Technology (for the USA) and Keio University (for Asia). Today, the overall architecture of the Web consists of three levels: the physical connections (the cables or infrastructure), the common behavior (the Internet, i.e., the communication protocols) and the services provided (electronic mail, file transfer, remote log-in, bulletin boards, information access, directory services, and multimedia streaming). Tomorrows Internet will include the services of multicast and telephony.

Basic Internet ideas (of a connected set of networks, specifically those using TCP/IP) were already realized with the packet-switching ARPANET, BITnet, NSFNET, etc., developed in the 1970s and 1980s on a regional scale (first node of ARPA in 1969 at UCLA; by 1983 every machine connected to ARPANET had to use TCP/IP). In 1990, the ARPANET simply grew into the Internet. - The development of capable browsers and the provision of Internet servers by many organizations throughout the world made the newly created Internet rather useful and successful to an ever increasing user community. By the end of 1994, the Web had 10,000 servers, 2,000 of which were commercial, and 10 million users. In 1997, there were more than 650,000 servers registered in Internet (1000 new ones added every day) - making Internet with its communication services a truly global utility. Most Internet traffic of today is carried by backbone networks of independent ISPs (Internet Service Providers), including MCI, AT&T, Sprint, UU.net, BBN planet, and many more.

- The first Internet broadcasts appear to have started in 1993 when the IMS (Internet Multicasting Service) was set up in Washington, D.C., as a non-profit experiment. At the start of the 21st century, literally thousands of radio broadcasting stations are on the Internet, broadcasting from all over the world. In all of these services, the satellite functions only as a reflector for point-to-point or point-to-multipoint transmissions (various topologies for interconnecting segments of a network). However, this is different from a satellite onboard LAN providing communication services to its payload.

- Demonstrations of the TCP/IP (Transmission Control Protocol/Internet Protocol) suite occurred through space (ground-to-space-to-ground) 1019) utilizing mostly bent-pipe configurations on GEO satellites such as ACTS (Nov. 1997), TDRS relay service [installed on TDRS-1 in Dec. 1997 to give the US South Pole Station an Internet connection to White Sands, NM (two-way IP and one-way file transfer)], and commercial platforms (for future multimedia broadband services). 1020) - In wireless channels, packet losses can occur due to transmission errors. TCP interprets these losses as congestion and initiates its congestion

1018) http://public.web.cern.ch/Public/ACHIEVEMENTS/WEB/history.html
1020) http://www.nren.nasa.gov/workshop/workshop6/presentations/israel_demo.ppt
control algorithms (slow start, congestion avoidance), resulting in a performance degradation.

- The routing of commercial Internet service links (so-called bend-pipe systems) via GEO satellite transponder started with the availability of wideband ATM (Asynchronous Transfer Protocol) services in the time frame 1997-1998. One to the commercial Internet access providers is Hughes Network Systems of Hughes Electronics Corp. In 1997, Hughes started offering such services as DirectPC and DirecTV to its customers (requiring the installation of VSATs). Its Spaceway project is a next-generation Ka-band satellite system with service introduction in 2004. SPACEWAY employs high-performance, onboard digital processing, packet switching and spot-beam technology to offer single-hop broadband connectivity, regardless of location. The Spaceway mesh architecture permits customers to communicate directly via satellite, without connecting through a central retransmission service or hub.

- A demonstration of Internet access to flying LEO spacecraft was performed by SSTL (Surrey Satellite Technology Ltd) using its UoSAT-12 (launch April 21, 1999) minisatellite. The demonstrations consisted of uploading an IP (Internet Protocol) software stack to the UoSAT-12, including simple modifications to the SSTL ground station, and a series of tests to measure the performance of various Internet applications (UoSAT-12 was assigned an IP address). The UoSAT-12 S/C was reconfigured on-orbit. The initial tests included basic network connectivity (PING), automated clock synchronization with NTP (Network Time Protocol), and FTP (File Transfer Protocol) transfers. The UoSAT-12 (SSTL) Internet demonstration was carried out in the time frame April-June 2000 within the OMNI (Operating Missions as Nodes on the Internet) project of NASA/GSFC. The UoSAT-12 spacecraft was selected because of its ability to support the HDLC (High-Level Data Link Control) framing in hardware for link-level protocol on space-to-ground links. This allowed simple and straightforward interfacing with existing commercial routers. UoSAT-12 was an ideal test platform because it already used HDLC framing for its AX.25 (Amateur radio X.25) protocol. Follow-on work is to demonstrate the following functions and additional protocols: http file delivery, mobile IP, security, store-and-forward commanding, data delivery using SMTP (Simple Mail Transfer Protocol), and VPN (Virtual Private Network) to enable automated, operational S/C communication. The use of IP communications over a satellite link is also referred to as “IP in Space.” On January 25, 2001, the UoSAT-12 spacecraft became the world’s first web server in space (HTTP was used to transfer real-time telemetry and stored image data directly to the user). The demonstration was carried out by the OMNI Lab of NASA/GSFC.

- The DMC (Disaster Monitoring Constellation) microsatellites, built by SSTL, are using IP-based protocols for all routine operations, as pioneered on UoSAT-12. The payload downlink also implements the new CCSDS File Delivery Protocol over IP on the 8 Mbit/s payload downlink. AlSat-1 (Algeria Satellite-1) was launched Nov. 28, 2002 (Cosmos-3M launch vehicle from Plesetsk, Russia). A further DMC launch from Plesetsk took place Sept. 27, 2003, consisting of BilSat-1 (Turkey), NigeriaSat-1 and UK-DMC. The UK–DMC spacecraft flies a COTS internet router referred to as CLEO (Cisco router in Low Earth Orbit), provided by Cisco Systems Inc., as a test bed for a range of mobile Internet Protocol (IP) applications.

1022) http://ipinspace.gsfc.nasa.gov/general/
• The Rubin-2 microsatellite of OHB-System, Bremen (launch Dec. 20, 2002) uses the commercial Orbcomm constellation of 30 LEO satellites for a demonstration of near real-time spacecraft monitoring and control functions via the Internet (demonstration mission). The performance tests of message delivery show that 90% of the messages, whose length is at most 229 bytes, reach the user within 10 minutes, and 30% within 1 minute.

• The CHIPSat microsatellite of UCB (University of California, Berkeley; launch Jan. 13, 2003 from VAFB), within NASA’s UNEX (University-class Explorer) program, employs the TCP/IP and UDP/IP (User Datagram Protocol/Internet Protocol) protocol suite to communicate all data between the S/C and the ground user directly (see N.8). The interface between the S/C and the ground segment consists of an HDLC point-to-point link layer. Layered within the HDLC frames is a standard TCP/UDP/IP protocol stack that, combined with VPN (Virtual Private Network) and firewall-protected use of the commercial Internet, utilizes end-to-end TCP/IP-based connectivity up to each S/C subsystem and down to the ground station router and the ground segment centers.

• The commercial satellite e-Bird™ of Eutelsat (launch Sept. 27, 2003, located at 33º E, GEO, servicing Europe and the Middle East, 10 year design life) is the first satellite worldwide specifically designed for 2-way broadband communications dedicated to Internet applications. Built by BSS, e-Bird is spin-stabilized (376 platform), it carries 20 active Ku-band transponders, each powered by a 33 W TWTA (Traveling Wave Tube Amplifier).

• As of 2003, EMS Technologies Ltd. of Canada developed SpaceMux™, an onboard processor architecture specifically designed for Internet services (support of single hop interconnectivity between small low-cost terminals). The onboard processing approach (mesh network configuration) of SpaceMux achieves the following advantages compared to a star configuration which would require a double hop: 1) minimizes the latency by reducing the roundtrip delay in half; 2) halves the capacity utilized; and, 3) provides signal regeneration, additional coding gain and switching. SpaceMux will be flown as a demonstration payload of Anik-F2, a GEO commercial service satellite (on a BSS 702 platform, 38 Ka-band transponders, 32 Ku-band transponders and 24 C-band transponders) of Telesat Canada (launch July 18, 2004). Provision of single hop interconnectivity between user terminals and regeneration and format conversion from the DVB-RCS MF-TDMA (Multifrequency-Time Division Multiple Access) uplink to the DVB-S downlink.

• Internet hardware on spacecraft (next generation communication architecture for a “Space Internet”). As of 2001, a NASA/GRC project objective is to develop prototype network hardware in cooperation with industry partners (Cisco, Ball Aerospace, etc.) enabling the use of the TCP/IP protocol for satellite onboard communication services to/from its payload. The four main element requirements of the Space Internet architecture are:

1) Security (access control, authentication, and encryption). Under joint DoD/NASA sponsorship, a set of Internet protocols were specified for use in bandwidth-constrained environments. This work, known collectively as SCPS (Space Communications Protocol Suite) includes a Security Protocol, known as SCPS-SP. SCPS-SP provides the same security services as its Internet counterpart, IPSec (IP Security), but with significantly less overhead.

2) A Mobile IP (Internet Protocol) implementation that takes advantage of scheduled contacts to reduce the overhead involved in setting up Mobile IP tunnels. An orbiting

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S/C, connecting first to one ground station and then to another, fits the definition of a “mobile agent.”

3) Resource reservation mechanisms that allow applications to ensure that data are not lost and/or are delivered in a timely manner (subsequent retransmission is of great concern). This is particularly difficult in the case where multiple semi-autonomous spacecraft need to share communications resources in a controlled manner and in an automated fashion. The RSVP (Resource Reservation Protocol), an end-to-end protocol for resource reservation used in Internet, can prevent data loss.

4) A link-layer driver that allows to easily connect ground and space networks. Conventional CCSDS links transport relatively statically scheduled streams of CCSDS data units encapsulated in virtual channels that may be transferred over several physical links to a control or processing center. In an internetworking environment, however, the virtual channels will transport dynamically changing streams of Internet Protocol packets that are extracted and routed at each spacecraft in a network before being routed to the ground. An efficient driver (for packing, transporting, and extracting IP packets for each space link) implements the CCSDS protocol suite.

The onboard LAN hardware includes a switch and a NIC (Network Interface Card). Future plans include utilizing these components as building blocks for a space-based router. The idea behind SND (Space Network Devices) is to take concepts and technologies developed for the Internet and use them to communicate onboard a spacecraft. This technology is considered a first step in transitioning to a space communications paradigm where seamless interoperability is possible using TCP/IP onboard a spacecraft, between a spacecraft and the ground, and from spacecraft to spacecraft.

- **CANDOS** (Communications and Network Demonstrations on Shuttle) is a NASA Hitchhiker payload (one of six payloads called FREESTAR, namely: MEIDEX, SOLSE-2, CVX-2, SOLCON-3, SEM-14, and CANDOS), flown on Shuttle flight STS-107 (Jan. 16-Feb. 1 2003) which ended tragically on its reentry. The CANDOS experiment consisted of the LPT (Low Power Transceiver), three S-band antennas, and one L-band antenna; the end-to-end data flow architecture is based entirely on standard IP protocols and HDLC data framing (see J.6). All data routing was accomplished via IP source/destination addresses over NASA’s existing closed IONet, an operational IP network which is physically isolated from the open Internet. - The LPT (developed by ITT Industries, see also LPT under 1.4.9.2) is a multi-channel, software programmable transceiver, capable of transmitting and receiving SN mode (Space Network) or GN mode (Ground Network) S-band signals while simultaneously receiving L-band GPS signals. The objective was to test ground networking techniques in cooperation with CANDOS. Demonstration of autonomous network scheduling, prioritization, handoffs, and resource allocation management (including link optimization through autonomous spacecraft acquisition and antenna pointing) using the MDP (Multicast Dissemination Protocol).

The LPT of CANDOS was used to directly contact either ground stations or TDRS, independent of the Shuttle communications system. During all events, payload (LPT) telemetry was being transmitted in UDP (User Datagram Protocol) packets continuously, providing a real-time housekeeping data stream. The use of MIP (Mobile IP) aided the use of the TCP/IP protocols; it reconfigured the data paths between the control center and the payload automatically as the link switched between ground stations (allowing the LPT address to re-

1032) http://ipinspace.gsfc.nasa.gov/CANDOS/
main static). The CANDOS flight represented the first practical demonstration of the MIP technique. All experiments were a complete success, throughout the course of the mission, CANDOS had almost 60 hours of total contact time via its own communication system. The CANDOS operation on STS-107 represents the second web server implementation in space (the first web server demonstration was being conducted on UoSAT-12 of SSTL on Jan. 25, 2001 - HTTP was used to transfer real-time telemetry and stored instrument data directly from UoSAT-12 to an end user).

![Figure 23: Overview of the CANDOS architecture (image credit: NASA)](image)

- The OMNI (Operating Missions as Nodes on the Internet) project of NASA/GSFC conducted a testbed demonstration of the IP mission concept in the lab in 2003. The representative mission employed unmodified off-the-shelf Internet protocols and technologies for end-to-end communications between the spacecraft/instruments and the ground system/users. The elements used in the test consisted of: Triana mission flight software, a web-enabled camera (as onboard instrument) connected to the S/C computer via an Ethernet LAN, the HDLC link layer, UDP/TCP transport layer protocols, and MDP file delivery protocol. This activity demonstrated end-to-end satellite data flow concepts in a realistic space and ground system hardware/software environment.

- The requirements of the GPM (Global Precipitation Mission) constellation of NASA and JAXA (launch in 2009) call for the full use of an IP implementation. The GPM onboard data handling architecture approach employs fault-tolerant concepts with dual Ethernet Local Area Networks (LANs), dual OBCs (On-Board Computer), and dual up/down cards that also perform more routing functions. The particular design features are:

- Substitution of the conventional onboard storage concept with a file management system of a modern operating system. All source science data will be stored as files. This replaces the conventional technique of storing the data as a stream onto a recorder. A file system has two advantages: automatic storage management and random playback. Hence, a COTS package can be used. By organizing the data into files, each file can be


downlinked using a generic file transfer application, such as MDP, that assures data quality by automatically performing error correction and/or retransmission as needed.

- The onboard Ethernet LANs (redundant) support data transfer between the science instruments (using UDP/IP on Ethernet), the OBCs, and the up/down cards using UDP/IP (User Datagram Protocol/Internet Protocol) packets to transport the data. However, a MIL-STD 1553 data bus is still being used as the data transport mechanism among other S/C subsystems using the current data packet concepts (e.g., between the attitude control subsystem and the OBC).
- HDLC (High-Level Data Link Control) framing for the link layer (as compared to CCSDS framing) of the space-ground RF transmissions is considered.
- The use of a standard internet router at the ground station is considered with the corresponding IP mobility and security protocols enabled.
- Data downlink, including the real-time S/C housekeeping data (in UDP/IP packets) and science data file transfer using the multicast dissemination protocol (MDP) application.
- TCP/IP for reliable real-time commanding and ack/nack confirmations.
- UDP/IP for commanding in the blind.

- **BGAN (Broadband Global Area Network).** BGAN is the world's first commercial mobile communication service to deliver voice and broadband data simultaneously. Initial service introduction at the end of 2005 with the Inmarsat—4F series to deliver Internet and intranet content and solutions, video on demand, LAN services, e-mail, phone, etc.). BGAN is part of the satellite component of the Third Generation (3G) IMT—2000/Universal Mobile Telecommunications System (UMTS).

The BGAN program of Inmarsat is supported by the ARTES (Advanced Research in Telecommunications Systems) Program of ESA. BGAN is designed to provide a portfolio of packet-mode and circuit-mode based services, offering speech telephony, ISDN calls and ‘always-on’ Internet/Intranet IP-based mobile data communications at up to 492 kbit/s for Internet access, mobile multimedia and other advanced applications. Future extensions of the multi-service and multi-user detection capability can build on the complementary role of mobile satellite by seamlessly extending GSM (Global System for Mobiles), UMTS and WLAN services to users of terrestrial mobile networks when operating out of reach of cellular coverage.

### 1.4.7.5 Relay satellites

- Relay satellites for data communication from Earth observation and space exploration S/C. The introduction of space agency relay satellite constellations (in GEO) opened up entirely new coverage capabilities in data communication. Operationally, it represents a definite advantage (although more expensive) over the conventional distributed ground-station concept in combination with S/C recorders. Relay stations in space permit extended or continuous (three satellites) coverage between a S/C in LEO and the ground. This can be a decisive advantage to some missions (for instance to Shuttle missions, space station operations, etc.). Extended contact periods permit also the transfer of vast amounts of data.

- The TDRS (Tracking and Data Relay Satellite) series of NASA (built by TRW for TDRS-1 to -7) pioneered this relay technology. The communication services provided by TDRS include such items as: a) simultaneous tracking of multiple satellites, b) multiple access schemes of S-band and Ku-band, etc. The TDRS antenna module consists of seven antennas: two single-access antennas that support both Ku-band and S-band user S/C communications (each 4.9 m diameter); a multiple access S-band phased array consisting of 30 helix-antenna elements; a 2 m diameter space-ground link antenna in K-band; an S-band om-

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1036) [http://broadband.inmarsat.com](http://broadband.inmarsat.com/)
nidiational antenna for TT&C support; a C-band antenna for commercial communications, and a K-band commercial communications antenna.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDRS-1 (NASA), launch Apr. 4, 1983 (STS-6), TDRS-1 is also refereed to as TDRSE</td>
<td>Position at 41º W, also support of first SVLBI experiment tests carried out on Aug. 2, 1986</td>
</tr>
<tr>
<td>Luch-1 (NPO PM) Russia, launch Oct. 25, 1985</td>
<td>Position at 95º E</td>
</tr>
<tr>
<td>TDRS-B (NASA), launch Jan. 28, 1986 (STS-51L)</td>
<td>Challenger accident !!</td>
</tr>
<tr>
<td>TDRS-3 (NASA), launch Sept. 29, 1988 (STS-26)</td>
<td>Position at 84.75º E (as of 2003)</td>
</tr>
<tr>
<td>TDRS-4 (NASA), launch March 13, 1989 (STS-29)</td>
<td>Position at 41º W, replaced TDRS-1. Introduction of commercial C-band services</td>
</tr>
<tr>
<td>TDRS-6 (NASA), launch Jan. 13, 1993 (STS-54)</td>
<td>Position at 46º W</td>
</tr>
<tr>
<td>TDRS-7 (NASA), launch Jul. 13, 1995 (STS-70)</td>
<td>Position at 150º W (deletion of K- and C-band packages)</td>
</tr>
<tr>
<td>COMETS (NASDA), launch Feb 21, 1998, H-II launch vehicle</td>
<td>Position at 121º E, a prototype data relay and tracking satellite (DRTS) system with S-band and Ka-band services</td>
</tr>
<tr>
<td>ARTEMIS-1 (ESA), launch July 12, 2001</td>
<td>Position at 21.5º E, a prototype DRS with S-band, Ka-band, and optical communication tests. Note: ARTEMIS reached its GEO location at the end of Jan. 2003 (18 months after launch) - with an ion engine providing the last 5000 km of orbit raising</td>
</tr>
<tr>
<td>TDRS-9 (NASA), launch Mar. 8, 2002 (TDRS-I)</td>
<td>Initial problems to get from GTO into GEO. Final GEO position was reached Sept. 30, 2002</td>
</tr>
<tr>
<td>DRTS (JAXA), launch Sept. 10, 2002 (Kodama)</td>
<td>Position at 90.77º E (DRTS), S-band and Ka-band</td>
</tr>
<tr>
<td>TDRS-10 (NASA) launch Dec. 5, 2002 (TDRS-J)</td>
<td>Position at 150.5º W,</td>
</tr>
</tbody>
</table>

### Table 54: Overview of relay satellites operated by space agencies

A new TDRS generation started with TDRS-H (TDRS-8 in orbit, launch of TDRS-H on June 30, 2000), built by BSS (Boeing Space Systems) at El Segundo, CA. A Boeing 601 S/C platform structure is used (dry mass = 2910 kg, 2.04 kW power). A new feature of the spacecraft is its innovative springback antenna design. A pair of 5 m diameter, flexible mesh antenna reflectors fold up for launch, then spring back into their original cupped circular shape on orbit. These steerable, single-access antennas (for Ku- and Ka-band) can simultaneously transmit and receive at S-band and either Ku- or Ka-band (additional capability), supporting dual independent two-way communications. The selection of Ku- or Ka-band communications is done on the ground. The receive (return link) data rates are 300 Mbit/s for Ku-band (at 13.7-15.0 GHz), up to 800 Mbit/s for Ka-band (22.5-27.5 GHz), and 6 Mbit/s for S-band (at 2.0-2.3 GHz). Transmit (forward link) data rates are 25 Mbit/s for Ku- and Ka-band, and 300 kbit/s for S-band. In addition, the phased-array antenna in S-band can receive signals from five different S/C simultaneously, while transmitting to one of them. A major payload feature of the TDRS-H, -I, -J series, not available on the previous satellites, is the use of onboard beam forming for the multiple access (MA) system. Advanced multimode RF feed systems are used for the Ku and Ka services via the single-access antennas. TDRS-H, I, J S/C use microstrip patch radiating elements for the multiple access antennas. The TDRS-I (TDRS-9 in orbit) launch took place on Mar. 8, 2002 on an Atlas-2A vehicle from Cape Canaveral, FL (launch mass of 3,192 kg).

The list of TDRS users is long, but one can cite for instance such missions as: Landsat – 7, HST (Hubble Space Telescope), Space Shuttle, TOPEX/Poseidon (Ocean Topography Experiment), EOS missions like: Terra, Aqua, Aura, XTE(X-ray Timing Explorer), TRMM (Tropical Rainfall Measuring Mission), ISS (International Space Station).

- Russia established also a relay satellite network, similar to NASA’s TDRS system. The first satellite in the series, Luch-1 (Kosmos-1700), was launched Oct. 25, 1985. It was used to

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1038) [http://tdrs.gsfc.nasa.gov/Tdrsproject/technologies.htm](http://tdrs.gsfc.nasa.gov/Tdrsproject/technologies.htm)
relay communication to the new MIR station (launched in 1986). A controlled reentry of MIR occurred on March 23, 2001 over the Pacific Ocean.

- Japan (JAXA, CRL, JST, etc.) started its geostationary DRTS (Data Relay and Tracking Satellite) system with two test satellites: 1) ETS-VI (launch 1994) equipped with the intersatellite communication device with data rates of up to 10 Mbit/s (only a portion of the tests could be conducted because ETS-VI did not make it to GEO); and 2) the launch of a prototype satellite, called COMETS (Communications and Broadcasting Engineering Test Satellite), on Feb. 21, 1998. COMETS provides S-band and Ka-band communication services. In addition, the satellite is used to test the following technologies: a) Inter-orbit communications for relay of communications between observation satellites or space stations in low-altitude circular orbits (LEO) and Earth stations; b) Advanced satellite broadcast technology for broadband region-specific broadcasts and high definition television (HDTV) broadcasts using Ka-band frequency bands. Note: a second-stage problem failed to put COMETS into GEO.

The DRTS S/C (wet mass of 2800 kg, power of 2.1 kW, design life of 7 years) was launched on Sept. 10, 2002 (positioned at 90.75º E), to complement the system (Japan refers to DRTS as “Kodama”). The objectives are to test and verify advanced receivers, an advanced intersatellite communications antenna (Ka-band, max data rate of 240 Mbit/s, and S-band for TT&C), and a high-performance tracking and acquisition system, to improve data relay speed and performance. Demonstration of intersatellite communications to relay data between a LEO S/C (ALOS, JEM, OICETS) and ground stations. 1039)

- ARTEMIS (Advanced Relay and Technology Mission Satellite) of ESA has been developed for testing and operating new telecommunications techniques in GEO environment, a prototype data relay system for the planned DRS (Data Relay Satellite) system. ARTEMIS features S-band and Ka-band communication services. In addition, ARTEMIS is used to test the following technologies: a) an L-band land mobile payload allows two-way communications, via satellite, between fixed Earth stations and land mobiles - trucks, trains or cars - anywhere in Europe and North Africa; b) a laser-optical payload with a relay terminal called SILEX (Semiconductor Intersatellite Link Experiment), see M.4. - Some users of the ARTEMIS’ communication services are: SPOT-4 (CNES), OICETS (JAXA), Envisat (ESA), and ISS.

1.4.7.6 DAB (Digital Audio Broadcasting)

At the start of the 21st century, DAB is a new and emerging technology to transmit sound (and data) efficiently, it is designed to remedy the weaknesses of conventional analog broadcasting systems. DAB introduces a completely new concept into the world of radio broadcasting, namely to share a unique network of transmitters among several programs. DAB represents in effect the most fundamental advance in radio technology since the introduction of FM stereo radio. Within the context of DAB, a transmitter network can be shared by a group of service providers delivering their contents to an ensemble operator, who assembles the DAB multiplex function. Moreover, the ensemble multiplex function is, by its very essence, a dynamic structure. 1040) 1041)

The DAB digital sound is far superior to AM or FM in audio quality, bandwidth, and dynamic range. Digital transmission techniques, which, when suitably applied, can lead to a more “effective and more efficient” utilization of the frequency spectrum, providing a means of reducing future spectrum needs, while satisfying increasing program requirements.

1040) http://www.eurekadab.org/frame.htm
1041) http://www.worlddab.org/
The DAB system concept was developed by the Eureka 147 project (founded in 1986 and originally only European), an international consortium of broadcasters, network operators, consumer electronic industries, and research institutes. In January 2000, the Eureka 147 consortium merged into the World DAB forum.

The DAB concept works by combining essentially two digital technologies, namely **data compression** and **data coding**.

- **MUSICAM** (Masking-pattern, Universal Subband Integrated Coded And Multiplexing) is a compression system that discards sounds that cannot be perceived by the listener, thereby reducing the vast amount of digital information required for broadcasting. MUSICAM allows a data rate of 1411 kbit/s, necessary to deliver a stereo signal on a compact disc, to be reduced to as low as 192 kbit/s (i.e. a reduction by a factor > 7), for delivery of a stereo broadcast program, the quality of which is indistinguishable from that of the original source. MUSICAM was developed at IRT (Institut für Rundfunktechnik) in Munich, Germany (at IRT DAB development started in 1981). The standardized ISO-MPEG layer-2 audio compression algorithm (MUSICAM) is used in DAB to broadcast up to six stereo channels with a “crystal clear” CD quality.

- **COFDM** (Coded Orthogonal Frequency Division Multiplexing) is applied to shape the DAB signal. By using a precise mathematical relationship, the MUSICAM signal is split across many different carrier frequencies (e.g. for mode I transmission, the number of carrier frequencies is 1,536) and also across time. This process ensures that even if some of the carrier frequencies are affected by interference, or if the signal is disturbed for a short period of time, the receiver is still able to recover the original sound. The signal is then transposed to the appropriate radio frequency band, amplified and transmitted. The COFDM technique was originally developed in the 1980s at the French research laboratory CCETT (Centre Commun d’Etudes de Télécommunications et de Télédiffusion), Rennes, France. One of the main assets of DAB is its spread-spectrum modulation technique (COFDM) which, among others, allows several transmitters to operate in the same radio frequency channel [SFN (Single Frequency Network)]. Further, the modulation scheme COFDM is well suited for overcoming the problems with multipath that FM suffers from. This allows a far better reception quality especially for mobile users; it also improves the situation for home listeners as well because stationary listeners are not immune from the problems of multipath.

The DAB standard (ETS 300 401) was first published in Feb. 1995, second edition in May 1997. This ETS (European Telecommunication Standard) on DAB (Digital Audio Broadcasting) is based on the overall system and service requirements adopted by the ITU-R (International Telecommunication Union - Radiocommunication). DAB is intended to supersede eventually the existing analog AM (Amplitude Modulation) and FM (Frequency Modulation) techniques.\(^{1042}\) The DAB interface standards include:

- **STI** (Service Transport Interface) standard ETS 300 799 (1997). It defines the way for service providers to deliver their contents to the ensemble provider
- **ETI** (Ensemble Transport Interface) standard ETS 300 797 (1997). It defines the link used to distribute the DAB Ensemble multiplex to the transmitter sites
- **DAB** radio broadcasting systems standard ETS 300 401 (1997). It defines the on-air signal as it has to be processed by the DAB receivers.

Digital techniques allow continuous (analog) sound signals to be converted into discrete (digital) signals. The discrete nature of these signals means that they are well-defined to within a large margin of error, and thus do not loose their identity along the transmission path (under normal circumstances). Error correction methods are also available which can further increase the “fidelity” of the transmission. This is the “secret” of the compact disk.

The various advantages offered by a common distributed network infrastructure to broadcast radios on different RF media have been early detected by the French operators Globe-
cast and TDF (TéléDiffusion de France) of France Telecom. In the period 1997/9, they started with the deployment of such collect & distribution networks to feed, on the French territory, the FM, AM and DAB transmitters. After a few months of operation in France, both the network operators and the radio broadcasters have experienced the following advantages of such a network infrastructure: 1043)

- The service provides a “universal & professional system” which completely fits the radio and operators expectations
- It provides a high-quality audio signal over several networks and offers sufficient additional data to face the various operational situations in regions
- It is fully DAB compliant, allowing to smoothly increase the DAB coverage in France with additional investments limited to the transmitters themselves
- The new service saves operational costs permitting to share the costly satellite link between several programs and services (AM, FM, DAB).

DAB services can be ground based, referred to as T-DAB (Terrestrial DAB), as is the case with Eureka 147. This system, which is on its way to becoming the de facto world standard, operates in the L-band in France, Canada, Germany (and most of Europe), it is in total operation in the UK, using the higher frequencies of VHF. In 1992, WARC (World Administrative Radio Conference) allocated the L-band frequency range to digital broadcasting, both terrestrial and satellite. Initial T-DAB services (pilot projects) started in 1998. Commercial DAB receivers have been on the market since the summer 1998. The DAB service spectrum will eventually lead into “multimedia broadcasting” in which all forms of information can be conveyed via the common transmission medium DAB.

In 2002, several commercial S-DAB (Satellite Digital Audio Broadcasting) projects (payloads of commercial communication satellites) are in the planning stage.

1043) http://www.broadcastpapers.com/radio/HarrisDABDeployment.doc
1.4.8 Spacecraft Operations

There are very many aspects to the wide field of “spacecraft operations” dealing with operation centers, the RF communications to and from the spacecraft, and the onboard spacecraft operations. Only a few topics have been selected to give the reader a better idea of technology introduction in some representative aspects of spacecraft operations and services.

1.4.8.1 Introduction of computers in spaceflight

By today’s (21st century) technical standards of virtually omni-present computers, programmable logic devices, and Internet availability — one would expect that computers were part of every spacecraft since the very beginning of the space age. However, this was not the case because the “computer age” was in its infancy at the launch of Sputnik-1 in Oct. 1957 — just 11 years after ENIAC (Electronic Numerical Integrator and Calculator), commonly thought of as the first electronic computer in USA. In fact, the very idea of a computer on a spacecraft was rather farfetched at the time. The transistor was invented in 1947/8 at Bell Labs by John Bardeen, Walter Brattain and William Shockley, who discovered the transistor effect and developed the first device. The Integrated Circuit (IC) was invented in 1958 by Robert Noyce of Fairchild and by Jack Kilby of Texas Instruments; the first microprocessor was introduced in 1971 (Intel 4004; 4 bit, 2,300 transistors). 1044)

The early manned spaceflights (of the USSR as well as of NASA) were guided by navigational computers on the ground; onboard computation was simply non-existent. 1045) 1046) 1047)

Prior to ISS, NASA conducted five manned spaceflight programs: Mercury, Gemini, Apollo, Skylab, and Shuttle. There was no onboard computing capability on any Mercury mission at all (six manned flights in the period 1961-1963). The latter four programs produced spacecraft that had onboard digital computers. The Gemini computer was a single unit dedicated to guidance and navigation functions. It is considered the first computer in orbit with a launch in 1965 (Gemini-3).

- 1962 — IBM received a contract from NASA to build the first guidance computer for the Gemini spacecraft series. [Note: Gemini-1 was launched Apr. 8, 1964 with no crew aboard; Gemini-3 (launch March 23, 1965) was the first crewed Earth-orbiting spacecraft of the Gemini series. Gemini-12 (launch Nov. 11, 1966) was the last spacecraft of the series.] The Gemini computer’s memory was a random-access, nondestructive readout design with flexible instruction and data storage organization. The custom-built computer had a mass of 27 kg and performed more than 7,000 calculations/s. Onboard computing power enabled Gemini to carry out eventually tasks such as rendezvous and docking even though the computer was underpowered by today’s standards:
  - Its nominal capacity was 4,096 words (39 bit/word) of core memory
  - Its operational capacity was 12,288 13-bit word instructions, 26 bit data
  - The computer was programmed in octal by hand

- 1961 — Start of the AGC (Apollo Guidance Computer) development program. NASA contracted with the MIT Instrumentation Laboratory for the design, development, and construction of the Apollo guidance and navigation system, including software (a challenging undertaking at the time). The AGC hardware is considered the first recognizably mod-

1047) Note: Unfortunately, I wasn’t able to find any documentation on the introduction of computer technology in spacecraft of the former USSR
ern “embedded system” and the first flight computer using ICs (Integrated Circuits), launched in 1968. AGC consisted of:
- Memory: 256 words total of 16 bit erasable memory; 4,000 words of non-erasable memory (core ropes)
- Later upgraded to 2k erasable and 36k non-erasable memory
- Timing: AGC was controlled by a 2.048 MHz crystal clock
- Central register: the AGC had four 16 bit registers for general computational use.

Note: In the early 1960s the so-called minicomputer had not emerged yet and there was no commercial computer suitable for use in the Apollo mission. Most of the technologies that were eventually used in the Apollo computer were just emerging from research and development efforts. The design was mainly a task of fitting the components together in order to meet the mission requirements for computational capacity and miniaturization. 1048)

Apollo-7 was launched from Cape Kennedy, FLA, on Oct. 11, 1968 (first flight of the Apollo program — the Apollo-1 crew (Edward H. White, Virgil I. Grissom, Roger B. Chaffee) was lost in a tragic fire accident during prelaunch tests on Jan. 27, 1967). The last Apollo flight in the program was Apollo-17 (launch Dec. 17, 1972).

Each Apollo mission carried two AGCs, one in the command module and one in the lunar module. The AGC system served well on the Earth-orbital missions, the six lunar landing missions, the three Skylab missions, and the Apollo-Soyuz test project. Even though plans existed to expand the computer to 16k of erasable memory and 65k of fixed memory, including making direct memory addressing possible for the erasable portion, no expansion occurred. The Apollo computer that controlled the first lunar landing (Apollo-11, July 20, 1969) had only 32,000 words of memory.

- 1970 — Apollo astronauts carry portable programmable calculators as backup to the navigation computer (i.e. AGC)
- 1973 — Skylab (total of 3 manned missions in 1973/4) had a dual computer system for attitude control of the laboratory and pointing of the solar telescope. The primary objectives of the Skylab missions were to establish a manned workshop in Earth orbit, and to develop orbital operation techniques. Skylab and, later, the Shuttle, used ”off-the-shelf” IBM 4Pi series processors (Note: the Gemini and Apollo computer systems were custom-built processors). The 4Pi descended directly from the System 360 architecture of IBM developed in the early 1960s. The 4Pi model chosen for Skylab was the TC-1 (16-bit word length), adapted for use on Skylab by the addition of a custom input/output assembly to communicate with the unique sensors and equipment aboard the laboratory. A TC-1 processor, an interface controller, an I/O assembly, and a power supply made up an ATMDC (Apollo Telescope Mount Digital Computer). Each TC-1 (there 2 on Skylab) had a memory of 16,384 words. 1049)
- 1981 — Space Shuttle (launch of STS-1 on Apr. 12, 1981), the reusable Space Transportation System (STS) of NASA, used closely coupled computers for digital flight, and a multithreaded parallel computer configuration for I/O. The onboard computers were part of IBM’s Advanced System/4 Pi, avionics computer series (also referred to as AP-101). The Shuttle’s general purpose computer was one of five computers — four of which were arranged in a redundant configuration, with a fifth computer acting as a backup unit — allowing early Shuttle missions to continue even if multiple failures were experienced.

Unmanned space missions:

There were no onboard computers in the early space age (the technology didn’t exist). Onboard operations (enacting decisions) evolved with automatic sequencing devices (lots of

relays and timers) to activate and command experiments (i.e. mission events) according to the logic of predefined schedules. These onboard operations of event sequences applied also to the launch phase of a spacecraft, triggered by onboard sequencers or by ground command.

- The early Earth-orbiting spacecraft of NASA, like TIROS-1 (launch Apr. 1, 1960) and follow-up weather satellites of the series, employed sequencers to facilitate onboard operations.

- The early Pioneer spacecraft series [launch of Pioneer-1 in 1958, launch of Pioneer-13 (last of the series) in 1978] as well as the Lunar Orbiters of NASA used to map the moon in the early 1960s — they did not carry onboard computers. Like their Earth-orbiting cousins and the first JPL probes, they used sequencing devices to activate and command experiments.

- The Ranger spacecraft series of NASA (9 missions, 1961-1965) carried a "Central Computer and Sequencer" to back up the direct command system. Activated before lift-off, it counted the hours, minutes, and seconds until a specified mission event was to occur and then executed a set of commands that performed the required functions. If the uplink radio channel failed, the mission would proceed according to a prepared plan.

At the same time that the Rangers were being built, JPL designed and flew the first Mariners. Mariner’s initial mission was a Venus flyby launched in 1962. In the case of this spacecraft and its later brethren, the Central Computer and Sequencer was the prime source of commands, at least for cruise and encounter portions of the mission. The time delay for commands to travel to Venus and Mars defeats real-time control from the ground.

- The Mariner-2 spacecraft to Venus (1962), Mariner-4 to Mars (1964), and Mariner-5 to Venus (1967) carried the same Central Computer and Sequencer.

- The Mariner-6 and -7 missions to Mars (1969) carried a **programmable** Central Computer and Sequencer (12 kg) designed at JPL and built by Motorola. The Sequencer commanded all spacecraft systems, including the Attitude and Pointing System and Flight Data System, each of which evolved to include their own computers by the time JPL designed the outer planets Voyager in the 1970s. — Original requirements for Mariner Mars 1969 called for 20 words of memory, making the 128-word version more than enough. Yet the memory was quickly exceeded, necessitating the use of "creative" programming techniques for the duration of the mission.

- 1971 — Mariner Mars spacecraft computer — upgraded to 512 words

- 1976 — Beginning with the Viking missions to Mars, reprogrammable digital computers showed up on NASA interplanetary spacecraft.

- The first spaceborne microprocessor (Intel 8080), introduced by JHU/APL, was flown on the SEASAT mission of NASA/JPL (launch June 27, 1978). 1050

- 2000 — The SNAP-1 nanosatellite mission of SSTL (Surrey, UK, launch June 28, 2000), with a total mass of 6.5 kg, used a StrongARM onboard computer (4 MB EDAC memory), a CAN bus for data handling, three-axis attitude determination and control, a GPS receiver (SRG-05), power subsystem (4W/9W average/peak, 6-cell NiCd battery), a CMOS camera that served as its primary payload, and a microthruster of 30 µN with a Δv capacity of 3 m/s (the micro-propulsion system had the size of a pencil).

- An automobile of today 1051 (2004, with cell phones, appliances, radio frequency ID tags, etc.) has more computing power than the Apollo 13 spacecraft (launch Apr. 11, 1970).

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The computers used in spaceflight have always been a mixture of leading and lagging technology (unfortunately mostly lagging) introduction. On one hand, space programs like Apollo gave a strong boost to advanced small and rugged computer technology; on the other hand, the introduction of onboard state-of-the-art computer technology was always delayed due to such requirements as “space qualification” (radiation hardened components, etc.) or due long waiting periods caused by long project planning and development times, and/or by waits for a launch opportunity. For large and complex space missions, in particular for new-generation missions involving the specification and development of new observation instruments, the lead times are so enormous (a decade for the EOS missions of Terra, Aqua and Aura, a decade for Envisat and MSG-2, a decade and more for NPOESS and GOES-R) that meanwhile up to 2 new computer generations have already been introduced on the market. And the selection of a computer system has to be made fairly early in the project. In addition, monitoring missions like MSG-2, MetOp, NPOESS, and GOES-R consist of a series of spacecraft (put into storage), each with operational lifetimes of at least 7 years, which are being launched successively, ending with at least 2 decades of operational service. No wonder, technology is outdated after such long periods of service.

Updates of onboard computer software has been practised for a long time (uploads of new and improved algorithms, etc). On the hardware side, updates of computer configurations can now be made with the introduction of FPGA (Field Programmable Gate Array) technology (see chapter 1.4.5 on FPAGAs). An FPGA controller provides the capability to directly generate the logical configuration of FPGA gates from a C-like high level language without producing the machine code for a processor.

When development times are fairly short (1-2 years from planning to launch), like in micro-, nano-, or picosatellite projects, and COTS (Commercial-Off-The-Shelf) components can be used, then the chances for state-of-the-art computer technology introduction become much better.

1.4.8.2 Onboard operating systems

- **Introduction of onboard resource brokering systems.** DoD/AFRL developed DHS (Data Handling System), a package with the objective to establish a plug-and-play space experiment brokering system. The ETB (Electronics Testbed)/DHS is flown on two satellites: (see M.48.1).
  - STRV-2 (Space Technology Research Vehicle-2) which is part of the TSX-5 (Tri-Service Experiments Mission 5) mission of AFRL. TSX-5 was launched June 7, 2000. This interface was developed so that it can be used on other space missions (STRV-1d, etc).
  - STRV-1d (Space Test Research Vehicle-1d) of DER A, UK (launch of STRV-1d on Nov. 16, 2000). The AFRL science payload on STRV-1d consists of ETB, nine sub-experiments (5 NASA, 3 DoD, 1 DREO, Canada), and DHS, which in turn interfaces with OBC (On-Board Computer) of STRV-1d (this is an advanced version of the DHS flown on STRV-2).

The DHS improves on-orbit use of individual sub-experiment resources by recording experimental results, storing them locally, and communicating the results to the S/C for downlink transmission. The intent of DHS is to reduce the risk to the mission by providing a degree of separation between the spacecraft and less-proven new technologies contained in each experiment, and by providing a similar degree of separation between the experiments.

- New DHS concepts may eventually lead to tiny, embeddable processors that contain the ability to self-organize fault-tolerant networks of experiments that can be arbitrarily distributed in a S/C.

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Onboard payload data processing systems. At the start of the 21st century there is an increasing demand for advanced concepts of onboard payload processing, data handling, and data storage functions. The technologies needed most focus on functional support for: data compression, event recognition and response, hyperspectral and radar data onboard processing, autonomous event detection and response, and situation-based data compression and processing. 1053)

The first Linux operating system in space was flown on Shuttle flight STS-83 (Apr. 4-8, 1997). The MLS (Microgravity Science Laboratory) on STS-83 carried an experiment in hydroponics, the growth of plants without soil was being tested (that could eventually provide oxygen and food to astronauts). 1054)

The computer controlling the experiment was a specially-modified PC-104 running Linux. - As of 2002, NASA introduced FlightLinux, a concept that uses a real-time variation of the open source Linux Operating System (GNU license) for onboard spacecraft use. Generally, Linux requires a MMU (Memory Management Unit) for page-level protection, as well as dynamic memory allocation. The advantages of a Linux operating system in space applications are seen in a number of functions provided: reliability, performance, portability (support of a heterogeneous environment and vendor independence), affordability, a number of new onboard capabilities are becoming available such as web serving and file transfer (Linux makes the support for onboard LAN services relatively easy due to its networking and multiprocessing features). The CANDOS (Communications and Network Demonstrations on Shuttle) payload processor on STS-107 (Jan. 16, Feb. 1, 2003) was flying a Linux operating system (see CANDOS description below). 1055) 1056) 1057)

ESA has selected Linux as the operating system for two software products which will control the rendezvous and docking operations for a servicing spacecraft called ATV (Automated Transfer Vehicle) of ESA. ATV is a cargo resupply vehicle for ISS to be launched by Ariane-5 in the time frame 2007. As of 2003, a number of space agencies are considering the use of Linux operating systems along with TCP/IP for the future communication and distributed processing architectures of their satellite missions (space segment and ground segment).

The CubSat UWE-1 (launch Oct. 27, 2005) of the University of Würzburg, Germany, used a micro Linux operating system (μCLinux) in a low—power H8S—2674R microprocessor (Hitachi) to provide the capability of testing the communication protocols and to increase the potential for applications, such as ftp—server, http—server, or mission—specific applications.

On the commercial side, a Linux-compatible OS/COMET Satellite Network Control Software is being provided by Harris Corporation of Melbourne, FLA, as of 2004. OS/COMET is an advanced software tool set featuring commercial off-the-shelf (COTS) design and high levels of flexibility. The software package supports both single-satellite missions and the largest and most complex satellite networks.

Reconfigurable computing systems in space are a relatively new but rapidly evolving technology at the start of the 21st century to cope with vastly increased processing demands and to provide a re-allocation capability of system level functions to maximize the efficient use of mission resources. Reconfigurable computing systems are a combination of hard-
ware/software data processing platforms that implement computationally intensive algorithm elements in **FPGA (Field Programmable Gate Array)** technology, yielding eventually a 10-to-1000 time improvement in processing speed over traditional CPU based “software only” systems. FPGAs use fusible links to provide custom interconnections between standard devices and building block elements already fabricated on an IC. This programming burns in a custom pattern of interconnects and hence circuitry to meet the design need. Although the FPGA manufacturer has predetermined which devices and functional building blocks exist on a chip, it is possible to support a high percentage of custom needs using this technology.  

FPGAs are flexible programmable devices that are used in a wide variety of applications such as network routing, signal processing, digital filtering, pattern recognition and rapid prototyping. As such FPGAs provide an alternative to both functions, general purpose processor and to ASIC implementations. With FPGAs, logic can be configured to realize different applications in hardware. The driving force and technological base of reconfigurable computing are reprogrammable logic chips with gate densities exceeding millions of gates and capable of supporting run-time-reconfiguration. The use of run-time-reconfiguration in space will allow to modify onboard hardware by replacing faulty/outdated designs at different stages of a mission. Hardware reconfigurability and software upgradability are increasingly being viewed by the space community as attributes crucial to the survival of a spacecraft in long-life missions, requiring the availability of flexible onboard avionics architectures.

Reconfigurable computing involves manipulation of the logic within the FPGA at run-time. In other words, the design of the hardware may change in response to the demands placed upon the system while it is running. Here, the FPGA acts as an execution engine for a variety of different hardware functions — some executing in parallel, others in serial — much as a CPU acts as an execution engine for a variety of software threads. We might even go so far as to call the FPGA a reconfigurable processing unit (RPU).

During the past decade, FPGA devices have been used in a number of satellite developments, ranging from breadboards to flight equipments. Some implementations of space-borne reconfigurable systems are:

- The WIRE (Wide Field Infrared Explorer) mission of NASA (launch March 4, 1999) failed soon after launch (detection of a spinning problem on second pass). The WIRE mishap investigation found the root cause of the mission loss to be a digital logic error in the instrument control electronics. The turn-on transient characteristics of the FPGA used in the pyro control circuitry were not adequately considered in the electronics design. WIRE is an example of an early FPGA implementation resulting in the loss of the mission.

- The SNAP-1 nanosatellite mission of SSTL (Surrey Satellite Technology Ltd), UK, with a launch on June 28, 2000, employes Intel’s StrongARM SA-1100 OBC with 4 MByte of 32 bit wide EDAC protected SRAM. The synchronous communications channel is full duplex (configured for 9.6 kbit/s to receive and 38.4 kbit/s to transmit) and is implemented in an FPGA of Xilinx for logical data interfacing and clock multiplexing.

- The Australian FedSat-1 mission (launch Dec. 14, 2002) carries a technology demonstration experiment called AIM (Adaptive Instrument Module), designed and developed at JHU/APL in cooperation with NASA (GSFC, LaRC), Queensland University of Technology (QUT), and CRCSS (see M.13). AIM contains a SRAM-based FPGA technology (Xilinx XQR4062XL of Xilinx Inc., San Jose, CA), providing a system capability to evolve or adapt

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to changing requirements (the functions implemented in the FPGA can be dynamically reconfigured). AIM demonstrates the practicalities of using reconfigurable computing hardware devices by conducting a series of designed experiments. Initial experiments include the demonstration of implementing data compression, data filtering, and communication message processing and inter-experiment data computation.  

- SAFER (Simplified Aid for EVA Rescue) is a NASA propulsive crew self-rescue device (a mini-maneuvering unit), worn by astronauts when conducting an extravehicular activity on ISS. The SAFER device (built by QuickFlex Inc., Austin, TX and Titan Corp., Houston, TX) is an upgradeable system which employs SRAM-based FPGA technology. An early test of SAFER occurred on STS-88 (Dec. 4-15, 1998, first ISS assembly flight). A full rescue simulation was conducted by the astronauts onboard STS-92 (Oct. 11-24, 2000, ISS-05-3A assembly flight) using SAFER.

- BAE Systems (Manassas, VA) has developed (2003) a true reconfigurable spaceborne processing system in the MPN (Multi-Processor Network). Reconfigurability is based on a module that can be reprogrammed on orbit using three Xilinx Virtex FPGAs. A non-volatile C-RAM (Chalcogenide RAM) memory FPGA technology is employed to provide reconfigurability. The general onboard MPN architecture consists of four modules: a) a general purpose processor, b) GM (Global Memory), c) ODI (Other Data I/O), d) RCC (Reconfigurable Computer).

- NPSat1, a student-built microsatellite of NPS (Naval Postgraduate School), Monterey, CA, with a launch in 2008, will demonstrate fault-tolerant onboard operations with CPE (Configurable Processor Experiment), based on an FPGA design to support any application (a Linux distributed processing architecture is used). In one scenario, the board is configured to act as a TMR (Triple-Modular Redundant) computer such that within FPGA, the three core processors operate in-step. In another application, the FPGA will be configured to act as a data compression engine.

- Flying Laptop is a microsatellite of the Institute of Space Systems (Institut für Raumfahrtsysteme, IRS) at the University of Stuttgart, Stuttgart, Germany. A launch is planned for 2008. The Flying Laptop will probably be the first microsatellite using a fully processorless primary OBC (Onboard Computer) consisting of field programmable gate arrays (FPGAs). A user-programmable EEPROM (Electrically Erasable Programmable Read-Only Memory) on board can be reconfigured from the ground station via modem. In case of failure, the original FPGA configuration is restored from a PROM.

- The introduction of the CMOS SOI (Silicon on Insulator) transistor technology represents an advanced manufacturing process for processors and microchips, developed by IBM. SOI differs from CMOS by placing the transistor’s silicon junction area on top of an electrical insulator. The most common insulators employed with this technique are glass and silicon oxide. With the SOI technique, the gate area can be assured of minimal capacitance, which is a measure of ability to store an electrical charge. Any medium that can con-
duct electricity has some degree of capacitance. Technically, a MOS transistor is regarded as a capacitive circuit. This implies that the MOS circuit must completely charge to full capacitance to activate its switching capability. The process of discharging and recharging the transistor requires a relatively long amount of time in contrast to the time it requires to actually switch the voltage state of the transistor’s metal layer. SOI attempts to eliminate this capacitance, as a low capacitance circuit will allow faster transistor operation. As transistor latency drops, the ability to process more instructions in a given time rises.

Background: Over the last three decades, SOI CMOS had been identified as one possible method for increasing the performance of CMOS over that offered by simple scaling. Prior to the 1990s, SOI had not been suitable as a substrate for mainstream applications. The barriers to its widespread use were many, the main ones being SOI material quality, device design, and the steady progress in bulk CMOS performance through scaling. In early 1989, the IBM Research Division initiated activity in SOI CMOS with a program focusing on device design and materials research. Major development progress was made in the early 1990s with a technique called SIMOX (Separation by Implantation of Oxygen) to create an insulating layer of silicon oxide on top of the silicon wafer. By injecting oxygen at high pressure onto the silicon wafer at high temperature, the silicon reacts with the oxygen to form a layer of silicon oxide - bonded to the silicon layer. In 1997, IBM server group designers selected 0.22 μm CMOS SOI for their next-generation microprocessors. That effort resulted in the first mainstream application of SOI CMOS, significant circuit learning, and its fabrication in a CMOS manufacturing line. The first commercial SOI product, a 64-bit IBM PowerPC microprocessor, was shipped in the summer of 1998. In 2002, the SOI technology moves to the 0.13 μm generation, offering an ever-increasing field of implementations/applications, such as in high-end microprocessors, in low-power RF (Radio Frequency) CMOS devices, EDRAMs (Embedded DRAMs), etc. 1066 At the start of the 21st century, the SOI technology is being introduced by many companies. IBM expects SOI to eventually replace bulk CMOS as the most commonly used substrate for advanced CMOS in mainstream microprocessors and other emerging wireless electronic devices requiring low power.

Some SOI technology advantages are:

- A marked advantage of SOI technology is its low-power behavior, opening a number of opportunities in the low-power arena.
- SOI offers the opportunity for the use of very-high-resistivity substrates to achieve low-loss passive elements. This capability, along with SOI n-FETs with an fT of > 150 GHz, opens exciting opportunities for low-power RF circuits.
- A lowering of the time taken to open and close bridges means that a processor built on this technology could be as much as 30% faster clock for clock than traditional MOS/CMOS processors. SOI designed microprocessors offer first order benefits of lower power operation, reduced junction capacitance, and higher device densities (miniaturization); all combining in significant improvements in device performance and faster circuit level speeds.
- Performance gains are averaging 25-35% when SOI is employed.
- SOI offers a reduction in soft error rates (SER). Soft errors refer to data corruption caused by cosmic rays and natural radioactive background signals. SER will be an important issue as CPUs scale to smaller die sizes and lower voltages. SOI chips indicate a significant reduction in SER related issues, even with current large die chips.
- SOI is the technology of choice for radiation-critical applications (immunity to single-event latch-up from high-energy particles).

In 2002, the CMOS SOI (Silicon on Insulator) technology is poised to take over from bulk CMOS special microelectronics market niches like: low power, high-speed digital, radiation hardened, and/or high-temperature analog, and even optoelectronic and microwave ASICs reaching into GHz frequencies. Silicon on insulator technology is becoming the pro-

cess of choice for high performance consumer electronics. First IBM servers with SOI microchip performance came onto the market in 2000. In 2002, Honeywell came out with products of the CMOS SOI RF switch family, a line of highly integrated, low-cost switches with integrated digital, mixed signal (analog and digital circuits on the same chip) and RF functions. 1067)

1.4.8.3 Satellite onboard autonomy

Autonomy refers to the migration of intelligence and decision capability from the ground station to the spacecraft. Autonomous instrument and spacecraft control as well as autonomous processing and understanding of data will add flexibility to future satellite missions. An important objective in satellite onboard autonomy is also seen in the context of unattended operations; the intend is to reduce operating costs, in particular to free resources of routine operations for long-term follow-up missions, with minimum ground involvement. Other key objectives are: a) to take good advantage of science opportunities, and b) to handle uncertainty -- including robust operations in the presence of faults.

The provision of enhanced functional autonomy demonstrations has been a goal of a number of technology missions by various agencies/institutions and satellite integrators. Most solutions require a considerable effort in software development and of course an architecture and infrastructure that supports the basic functions required for intelligent autonomous operations. The emerging spacecraft onboard autonomy turns out to be of strategic importance because it may support such functions as: 1068) 1069)

- Migrate routine functions to the spacecraft level
- Decouple the spacecraft from the ground
- Create a direct link between the PI and his experiment on the spacecraft
- Close planning and control loops onboard.

The nature of “autonomy provision” turns out to be rather complex, in the end it requires nothing less but fault-tolerant systems on all levels. Obviously, various levels of autonomy can be recognized in terms of safety requirements. For instance, the aspect of safety may be 100 times higher for a certain support function of a manned mission than for the same or similar scenario of an unmanned mission. - One aspect of autonomy is the automatic performance of routine operations over a limited period of time, requiring onboard monitoring, analysis and self-correcting measures for each functional aspect on the instrument level, prior to updates from ground control. The other aspect of autonomy is the provision of realistic backup scenarios to handle failure situations. - It has long been realized by all parties involved that so-called “cheap-sats” are not really cheap-sats, if overall costs (all operations + S/C costs + launch) cannot be reduced. And operations happen to be an important and persistent long-term item in the overall bill. The requirement for an autonomous onboard navigation function seems to be on the agenda of many missions (see also autonomy under Navigation in chapter 1.12.5). 1070)

The reason: onboard knowledge of satellite position in ground coordinates is needed for many operational functions such as: activation (start/stop) of Earth observation instruments, data transmission, satellite attitude control (this includes autonomy of all attitude sensing devices such as star trackers, sun sensors, etc.). The latter devices have to solve the “lost-in-space problem,” overcome start-up operations and re-acquisition sequences, be able to handle anomaly detection and isolation and failure

trapping and recovery, be reliable and accurate - to qualify as a fully “autonomous” instrument. Autonomy means to be able to operate safely without any external intervention.

Some examples of partial autonomy demonstrations are being provided. So far, they represent generally small steps in semi-autonomous control provision implemented in an on-board subsystem or in several interrelated subsystems.

At the start of the 21st century, onboard intelligence and autonomy functions and services on a wide front are in fact becoming more and more mandatory, for all types of missions. The reason is to be able of handling the vast information flood and to provide intelligent tools for spacecraft operators in particular in the fields of: a) bus instrumentation, in particular AOCS, TM/TC and onboard data handling, and amongst these, a significant interest has been in highly autonomous and accurate star sensors, and b) instrument observation coordination (scheduling) and resource planning. Planning and scheduling spacecraft operations involves generating a sequence of low-level spacecraft commands from a set of high-level science and engineering goals. It is a safe prediction that further potential applications of autonomy will eventually lead to onboard processing of science data (including the interpretation of all types of imagery) to achieve a real-time analysis capability for rapid response systems, associated with a reduction in data volumes along with the provision of many new services (change detection will be a major field of applications in this scenario). The challenge is in the development and introduction of suitable hardware and software technology and concepts. 1071) 1072)

- Redundancy design. Satellite reliability is an important consideration for continued provision of operational services. In Transit-3-A (launch in 1960), a US Navy navigation satellite, JHU/APL integrated for the first time a passively redundant battery system that could automatically switch to a backup battery. - Further redundant designs followed for such subsystems as RF and telecommand.

- Enhancements on the various generations of GPS satellites. The block I S/C series (with launches from Feb. 1978 to Oct. 1985) was able to sustain unattended operations for up to 3.5 days between navigation message uploads from the ground. The latest block IIR S/C series features autonomous satellite operations for a period of up to six months without ground control corrections (first launch of a block IIR S/C on July 23, 1997).

- The PoSAT-1 microsatellite mission of SSTL (launch, Sept. 26, 1993) reached a certain degree of operational autonomy through its onboard orbit determination capability (first orbital elements).

- For NASA's Clark satellite (launch in 1998), a GPS receiver with the name of GADFLY was used to demonstrate autonomous orbit determination and to use GADFLY also for coarse attitude knowledge. Note: At the end of Feb. 1998, NASA cancelled the Clark mission due to severe cost overruns and launch delays.

- The DS1 (Deep Space 1) technology mission of NASA/JPL (launch Oct. 24, 1998) introduced the concept of a single autonomous Remote Agent Experiment (RAX), a technology demonstration package which includes an onboard mission manager with a mission plan expressed in terms of high-level goals [RAX is also referred to as ARAX (Autonomous Remote Agent Experiment), see M.9]. A planning and scheduling engine uses the goals, along with a comprehensive knowledge of the S/C status, and constraints on S/C operations - to generate a set of time-based or event-based activities. The autonomous Remote Agent concept was successfully tested on May 17, 1999 when the primary S/C com-


mand was given over to Remote Agent for three days of S/C operations. In this period, Remote Agent successfully planned DS1 activities onboard and then carried out the plan without ground intervention. The software detected, diagnosed and fixed simulated problems, showing that it can make decisions to keep the mission on track. RAX on DS1 represented the first time that an artificially intelligent agent controlled a NASA spacecraft.  

- The ARGOS technology mission (M.3, launch Feb. 23, 1999) of DoD employs an onboard automated mission planning system to optimize onboard data handling and power.  

- The UoSAT-12 minisatellite of SSTL (launch April 21, 1999) in Surrey, UK, carries a closed-loop autonomous control system that enables orbit operations to be performed without the need of any ground segment. The autonomous control system consists of a GPS receiver, an onboard propulsion system EPS (Electric Propulsion System), and an orbit maintenance software package of Microcosm Inc., El Segundo, CA, referred to as OCK (Orbit Control Kit). The objective of the control part of the software is to ensure that the orbital altitude of the satellite never falls outside of a prescribed window due to drag. The orbit is described using a set of epicycle parameters which provide an analytic model of LEO orbits. The parameters in this model are estimated onboard the satellite using a Kalman filter. In addition, the software provides control, and an estimation of the orbit parameters by including drag in the model. The satellite was maneuvered into an exact 7-day repeat (ground track) pass orbit for the technology demonstration. The new orbit maintenance software then maintained the satellite mean radius in its resonant orbit for a test period of 27 days within an error band of ±5 m (3 sigma), and slowly maneuvered the S/C into a frozen orbit.  

- Autonomous navigation on DS1 (Deep Space 1, launch Oct. 24, 1998, see M.9.1). This onboard system enables a S/C to determine its location in the Solar System as well as its flight path without help from controllers on Earth. With the knowledge of onboard time, AutoNav computes the position of the asteroids. By measuring where the asteroids appear relative to the stars, it computes where the S/C must be. It then can project its path to its destination and use its propulsion system to make any course changes that are required. On July 29, 1999, DS1 successfully performed a close flyby of asteroid 9969 Braille using the AutoNav system. The AutoNav system was also flown on the DI (Deep Impact) mission of NASA/JPL (launch Jan. 12, 2005). The DS1 and DI AutoNav systems used nearly identical file—based data management systems.  

- The first-ever NASA autonomous orbit navigational maneuver by a satellite was conducted in December 1998 by JPL engineers. The experiment involved an orbit adjustment maneuver of the TOPEX/Poseidon satellite. The technology validation required flight controllers to uplink software to the spacecraft that subsequently autonomously planned the satellite’s actions and generated a series of commands to steer it. The software required minimal input from ground controllers, consisting only of changes in velocity and the time to execute the maneuver. The software then computed the changes in satellite orientation and the amount and timing of satellite thruster burns with no further input from ground controllers.  

- The EO-1 mission of NASA/GSFC (launch Nov. 21, 2000, see M.10.2) demonstrated autonomous navigation/instrument operation with an onboard software package referred

1077) http://www.jpl.nasa.gov/releases/98/topexnav.html
to as AutoCon™ (GSFC teamed with a.i.-solutions Inc.). AutoCon is capable of autonomously planning, executing, and calibrating routine spacecraft maneuvers to maintain satellites in their respective constellations and formations. The AutoCon features include an innovative use of fuzzy logic decision making capabilities and natural language to resolve multiple conflicting constraints. The EO-1 formation flying experiment validated a fully non-linear autonomous system for formation flying. The AutoCon system is also being considered to fly on follow-up missions such as GPM (Global Precipitation Mission).\textsuperscript{1078} 1079)\textsuperscript{1079)

- NASA’s TIMED mission (launch Dec. 7, 2001), designed and operated by JHU/APL, introduces operational autonomy by separating payload/instrument operations from all S/C system operations activities. In this way, the instrument teams are able to control all of the instrument modes, operations and science data return at their own choice without explicit interactions or approvals by the S/C project team. A combination of onboard GPS processing and the use of the Internet move the data from the APL ground station to each investigator’s home site. In addition, the Internet is used by each investigator to control his instrument directly (the packetized messages are integrated into the uplink command structure in an automated fashion). The ultimate goal for TIMED is to develop a “lights-out” concept of operations as the missions progresses.

- ESA’s PROBA minisatellite mission (launch Oct. 22, 2001, M.30).\textsuperscript{1080) The attitude control and avionics subsystems accommodate the core technologies for S/C autonomy. Demonstration of autonomous operations for orbit and attitude determination with a GPS receiver (SGR-20). The other autonomous subsystem is ASC (Advanced Stellar Compass) of DTU, Denmark. ASC is capable to reconstruct autonomously the S/C inertial attitude starting from the condition “lost in space.” The mission operations concept provides considerable flexibility in the allocation of onboard resources and in scheduling of operations.

- The Block IIR satellites of the GPS constellation [launch of SVN 43 (Block IIR-2 first of series) on July 23, 1997] feature the AutoNav concept, providing the ability of the constellation to self-navigate and to maintain overall accuracy by optimally filtering ranging data and ensembling the clock data from all the GPS satellites. The filters are processed and updated using the crosslink measured range to each viewable satellite along with that remote satellite’s crosslinked filter parameters. At the end of 2003, there are 9 Block IIR satellites in orbit. With AutoNav, the specification for the GPS IIR system requires a rms URE (User Range Error) of < 6 m in the survivable mode at the end of 180 days without Ground Segment corrections.

- A NASA/GSFC technology initiative is developing (1998) a concept referred to as IA/GNC (Image-Aided/Guidance, Navigation and Control) to support S/C autonomy and to reduce operating costs.\textsuperscript{1081) The IA/GNC scheme uses 2-D images from the S/C science instrument or a secondary low-cost camera and generates attitude control and image stabilization information that enhances pointing performance and ultimately permits autonomous onboard geo-referencing and geometric rendering of data. IA/GNC relies heavily on image correlation tracking (ICT) techniques which compute the translational offset between an instantaneous image and a stored reference image derived from a previous image or a model.

\textsuperscript{1080) Note: SGR-20 (Space GNSS Receiver-20) was developed under ESA’s ARTES-5 program in the UK (SSTL). First use of SGR-20 on UoSat-12 (launch Apr. 21, 1999). The receiver has 24 L1 C/A code channels and can operate with four antennas simultaneously. In addition, the SGR-20 features 1 MByte of memory, a 20 MHz processor, EDAC (Error Detection and Correction) and a noncoherent architecture, i.e. the Delay Lock Loop and Phase Lock Loop are decoupled.
\textsuperscript{1081) http://gnctech.gsfc.nasa.gov/gto/library/stafi/stafi171.html
• The MSG (METEOSAT Second Generation) spacecraft series of EUMETSAT (launch of MSG-1 on Aug. 28, 2002) provide an onboard software design called FDIR (Failure Detection, Isolation and Recovery), allowing to detect any malfunction and to perform the necessary recovery/reconfiguration action autonomously. This implies recovery after a single onboard failure during 24 hours without ground intervention.

• The SMART-1 moon mission of ESA (launch Sept. 27, 2003, M.35) introduces a software package by the name of OBAN (On-Board Autonomous Navigation). OBAN validates navigation algorithms by planetary body tracking. It makes use of the S/C star trackers and of AMIE images. The overall objective is to test navigation algorithms with respect to their workability in a real-mission environment. The OBAN experiment is designed to function in what is termed an ‘open loop’, obtaining all the data an autonomous navigation system would require, but instead of being processed onboard, this information is downlinked to be processed on Earth.

• The STEREO (Solar Terrestrial Relations Observatory) mission of NASA (launch Oct. 26, 2006, K.28) will demonstrate the feasibility of autonomous solar navigation (the sun is used as a reference). The technique employs a dual-mode imaging system (2 S/C designed by JHU/APL) for measuring the direction of the sun using a CCD camera which captures the image of the sun against a star background (the stars serve as a direction reference). The two-mode design, based on the JHU/APL DSAD (Digital Solar Attitude Detector) imaging system, permits the control of the vast brightness contrast differences. The S/C state vector is determined by onboard processing the solar observation data. 1082)

• Autonomous station keeping of S/C. Up to the late 1990s, the station keeping of satellites (in GEO and LEO) has primarily been ground-based, involving the Control Center personnel in all phases of operations, including orbit maintenance and station keeping. Current GEO satellite operations have evolved so as to take advantage of the stationary nature of the satellite position relative to the ground stations. The favorable geometry provides a continuous window for ranging, tracking, and commanding, thereby minimizing the computational burden on the onboard processors. The LEO satellites (with intermittent ground contacts), on the other hand, always required an onboard processing capability to provide some limited autonomy in navigation. Functional capabilities in the direction of autonomy improved considerably with the availability of onboard GPS systems and advanced feedback control techniques. New orbit control designs are based on the concept of continually minimizing the position and velocity error between a satellite and its target orbital position.

• NASA/JPL developed ASE (Autonomous Sciencecraft Experiment), 1083) an onboard software package within NMP. The main science objective of ASE is to demonstrate that process-related change and feature identification can be made during space flight. ASE is a software suite providing onboard science analysis and replanning to radically increase science return by enabling intelligent downlink selection and autonomous retargeting. The onboard processing package consists of three autonomy software components: 1084)
  - Onboard science algorithms to analyze the image data, generate derived science products, and detect trigger conditions such as terrain boundaries and change relative to previous observations
  - Execution management software using the SCL (Spacecraft Command Language) package to enable event-driven processing and low-level autonomy
  - A low-latency continuous planner, CASPER (Continuous Activity Scheduling Planning Execution and Replanning), to replan activities, including downlink, based on science

CASPER is a critical subset of the ASE software package. It uses iterative repair to support **continuous modification and updating of a current working plan** from goals in light of a changing operating context. The ASE software package of JPL was uplinked to the EO-1 spacecraft in the summer and fall of 2003 to realize an autonomy demonstration and validation experiment on the extended EO-1 mission (the spacecraft is in its extended mission phase). The ASE Science Team has developed scene classifiers to detect thermal emission in both day and nighttime Hyperion data. The objective is to extract static features of the imagery and to detect changes relative to previous observations. Also, automatic identification of regions of interest including regions of change (such as flooding, ice melt, and lava flows). - While RAX (Remote Agent Experiment) on DS1 demonstrated a batch onboard planning capability, CASPER on EO-1 verifies a continuous planning capability along with onboard science processing and feature recognition (monitoring of surface change, etc.).

The objective of ASE is to demonstrate several integrated autonomy technologies to enable autonomous science applications. Several science algorithms including: onboard event detection, feature detection, change detection, and unusualness detection are being used to analyze science data, in particular those of Hyperion. The instrument images a 7.5 km by 42 km land area per image and provides detailed spectral mapping across all 220 channels with high radiometric accuracy.

On May 7, 2004, the ASE package of EO-1 observed/analyzed an eruption of the Mount Erebus volcano in Antarctica autonomously (without human interaction). The software detected an unusual area of heat within an image of Hyperion, it then directed EO-1 to capture more imagery on a pass about 7 hours later. The satellite was able to repeat the experiment on May 14, 2004.

ASE on EO-1 is demonstrating an integrated autonomous mission using onboard science analysis, replanning, and robust execution. The ASE performs intelligent science data selection that leads to a reduction in data downlink. In addition, the ASE increases the science return through autonomous retargeting.

The ASE feature recognition package (i.e. event monitoring) is also being planned for a number of future NASA missions such as GEC (Geospace Electrodynamic Connections) and MMS (Magnetospheric MultiScale).

- The Livingstone software package version 2 (LV2) is being used in EO-1 on-orbit testbed demonstrations. The AI (Artificial Intelligence) software package “Livingstone” was developed by a team at NASA/Ames Research Center (S. Hayden) and uplinked to...
EO-1 in the summer of 2004. The LV2 automatically detects and diagnoses simulated failures in the EO-1 payload instruments. The software package has the ability to find and analyze errors in the spacecraft’s systems. A key feature of the software is its “reasoner” function, which enables it to compare the predicted performance of a system based on readings from onboard monitors. Contradictions between the predicted and actual performance are used to identify the failures. The autonomous diagnostic tool of LV2 can help controllers in identifying and detecting a potential problem in sufficient time to make repairs or to find a work-around solution. (1093) (1094) (1095)

- Autonomous onboard control offers several operational capabilities not available to missions without this feature (according to reference 1075):
  - The position of the spacecraft at all future times is known as far in advance as desirable
  - The ground track (or inertial track) of the spacecraft can be made to follow a predefined pattern which may be changed at user request
  - The process for computing future positions is simple and can be included in any ground-based equipment that uses a general-purpose microprocessor
  - There is a longer planning horizon dealing with the potential problems of RF or physical interference with other spacecraft or debris
  - Disturbance torques are much lower than with more traditional orbit control processes, such that the size and responsiveness of control actuators can be lessened and restrictions on the timing of stationkeeping maneuvers can be reduced or eliminated.

In summary, autonomous onboard orbit control can fundamentally change the way space missions operate. It is a key component in extending the philosophy of “faster, better, cheaper” to 21st century ground operations.

Today’s requirements of future space-system functionality call for nothing less but system intelligence (error-tolerant systems) with the following characteristics: (see reference 18)
  - Autonomy to think for themselves
  - Self-reliance to identify, diagnose, and correct internal problems and failures
  - Self-repair to overcome damage
  - Self-assembly and evolvability to adapt to and explore new and unknown environments
  - Extreme efficiency to operate with very limited resources and without input from mission control.

1.4.8.4 Autonomous ground stations and systems

- The first ground stations that could be operated autonomously were probably the APT (Automatic Picture Transmission) stations for NOAA satellite data reception. The APT broadcast service was first introduced with TIROS-8 (launch Dec. 21, 1963). Simple APT ground stations could soon be purchased to support autonomous data acquisition.


- Autonomy is also invading the mission control room. Traditionally, satellite operations have been preformed from a fixed set-up of computers in a dedicated control room at the space agency’s or satellite owner’s premises. The control room was staffed around the clock in order to continuously monitor and operate the spacecraft. This 24 hour staffing approach, however, was very expensive. For small scientific satellites on a constrained budget, this type of support may only be justified during the initial commissioning phase (typically a few weeks) and in case of contingencies or special campaigns. - Future missions of satellites

1095) http://ic.arc.nasa.gov/story.php?sid=193
will increasingly rely on autonomy for routine operations and automatic downlinking of housekeeping and instrument data. Both the onboard computer and computers at the ground station or a dedicated control facility will continuously monitor the health of the spacecraft and alert the operator-on-call in case of anomalies.

- Increased use of Internet services in S/C (or mission) operations, in particular for small S/C to save costs over the conventional leased-line communications approach. Furthermore, with the first LEO commercial telephone networks in operation, S/C operators (in particular student developed satellites) are designing their prime communications needs for uplink and downlink data transmissions entirely on the service provision of these distributed cellular telephone networks. This eliminates the conventional dedicated ground segment to space segment communication links for a space mission.

- Munin (N.16), a Swedish nanosatellite of IRF (Swedish Institute of Space Physics), students at Umeå University (RYP), and students at Luth (Luleå University of Technology) with a launch as a secondary payload on NASA's EO-1 mission (launch Nov. 21, 2000), feeds its science data (space weather parameters) directly into the Internet at reception, available to anyone.

- The ION-F (Ionospheric Observation Nanosatellite-Formation, three satellite constellation of USU (Utah State University), UW (University of Washington, and VT (Virginia Polytechnic Institute) with a launch in 2004, employs also commercial cellular phone communications in all links.

### 1.4.8.5 Spaceborne data collection systems (DCS)

Satellite data collection, in particular of environmental data from autonomous remote stations in the ground segment, is an established long-term service provision which started operationally in the 1970s with the introduction of ARGOS (see C.2) on NOAA weather satellites. An overview of DCS (Data Collection Systems) can be found in Table 213 (Part C).

- True and continuous autonomous ground station operations has probably first been realized with the introduction of systematic spaceborne data collection services (DCS) from the ground segment. Each remote ground station (on land, on water, or in the air) had to be operationally autonomous to participate in such a venture. The first such system in LEO (polar orbit) was IRLS (Interrogation, Recording, and Location System), employing a range-only platform location technique and flown on Nimbus-3 (launch April 14, 1969, see M.26.3). The French-US Eole experiment measured ambient air temperature and pressure and determined 200 mb winds over the Southern Hemisphere by tracking constant-density balloons, employing a range and range-rate location technique (launch Aug. 16, 1971). A simplified approach, using only random-access range-rate data, was employed in the TWERLE (Tropical Wind Energy conversion and Reference Level Experiment) flown on Nimbus-6 (launch June 12, 1975, see M.26.6). These systems led eventually to the French-developed Argos Data Collection and Location System, first flown on TIROS-N (launch Oct. 13, 1978, see C.2). The Argos system is being managed and operated by CLS (Collecte Localisation Satellites), a CNES subsidiary based in Toulouse, France.

- A similar system to Argos, namely COSPAS, was developed by the Soviet Union and first launched on June 29, 1982 (the name of the satellite was Cosmos-1383 or COSPAS-1).

- In 1982, the USA, Canada, France, and the Soviet Union banded together to form COSPAS-S&RSAT (Search and Rescue Satellite Aided Tracking System), an international humanitarian search and rescue system that became fully operational in 1984 (see I.8). As of 2002, over 13,000 persons have been rescued by COSPAS-S&RSAT services since its inception in 1982. For example, in the year 2000, 1520 people were rescued after COSPAS-S&RSAT distress signals were sent out from aircraft, ships, and land vehicles. Since 1982, the four founding countries of COSPAS-S&RSAT have been joined by 32 further countries - a humanitarian program on a global scale.
• The first DCS (Data Collection System) in GEO orbit was flown on SMS-1 (Synchronous Meteorological Satellite-1, launch May 17, 1974). See chapter 1.13.

• INPE of Brazil launched its SCD-1 satellite in 1993 and its SCD-2 spacecraft in 1998 to perform data collection services in the southern hemisphere.

• There are also commercial data collection services available such as: FAISAT (FAISAT-1 launch Jan. 24, 1995, see C.3); Orbcomm satellite constellation (see C.5) initial service started in 1995; the SAFIR system of OHB-System (see C.6) started services with SAFIR-1 in Nov. 1994, and with SAFIR-2 in 1998; TEMISAT of Telespazio (Rome) was launched in 1993 to provide data collection services.

• Starting with NOAA-15 (launch May 13, 1998), the NOAA POES series satellites are equipped with the Argos-2 instrument system featuring a number of improvements such as: a) updated Argos receiver with better sensitivity [an increase of 3 dBm, higher number of Data Processing Units (8 vs. 4 for Argos-1) and larger receiver bandwidth (80 kHz instead of 24)], and b) capability of increased reception in the number of messages with better quality.

• The first Argos-Next instrument [a third-generation system also referred to as ADCS (Argos Data Collection System)] is being flown on ADEOS-II of JAXA (launch Dec. 14, 2002) providing two-way messaging services [demonstration and checkout for ADCS until April 2003, then full operation] in the framework of a French-Japanese cooperative project. This service allows users to send messages to fixed and mobile terminals anywhere in the ground segment. The two-way messaging capability paves also the way for more sophisticated terminals, called PPTs (Platform Transmitter Terminal) in the ground segment. The Argos-Next downlink gives users the possibility of sending short messages (up to 128 bit) to their PPTs. - Argos-Next instruments are also being planned to fly on the MetOp series satellites of EUMETSAT (launch of MetOp-A, Oct. 19, 2006) and on the NOAA POES series starting with NOAA-N (planned launch in 2008) as well as on the NPOESS series.

• A new DCS by the name of ADAM (Advanced Data Acquisition and Messaging System) was developed for FedSat-1 (Australia, launch Dec. 4, 2002, see M.13) and STSat-1 (Science and Technology Satellite-1) of KAIST/SaTReC, Korea (launch Sept. 27, 2003, see M.39). ADAM has been developed in a cooperative effort between SaTReC and ITR (Institute for Telecommunications Research) of the University of South Australia in Adelaide and CRCSS. ADAM provides bi-directional communication between the on-board DCS and the ground segment, consisting of many DCPs (Data Collection Platforms). The DCPs are also referred to as MTs (Mobile Terminals). A TDMA (Time Division Multiple Access) protocol is being used in the uplink to collect the data from various DCPs simultaneously. ADAM, providing the functionality of two-way packet communications for remote environmental monitoring and forward messaging, is primarily used to collect data from Argo. The X-Sat (Minisatellite Technology Mission) of NTU (Nanyang Technological University), Singapore (launch 2008, see M.51), employs also ADAM. The UHF communication system stores its collected data in the S/C mass memory system until they are forwarded to a ground station (in S-band), where they are processed and distributed to end users.

• Argo (Data Collection in the Global Oceans). Argo (see C.1) is an internationally coordinated program directed at deploying a global array of temperature/salinity profiling floats. By 2004/5, the deployed Argo network will consist of an array of about 3,000 free-drifting (Lagrangian) profiling floats, capable of surveying the upper 2000 m of the world’s oceans. The Argo international ocean program is part of GCOS/GOOS (Global Climate Observing System/Global Ocean Ocean Observing System), part of CLIVAR (Climate Variability and Predictability Experiment), and part of GODAE (Global Ocean Data Assimilation Experiment - 2003-2005). Status at the end of 2003: a total of about 1000 Argo
floats were deployed. - Argo data collection is being conducted via a network of existing data collection satellites.

1.4.8.6 Hibernation modes in spacecraft operations

- Spacecraft operation system designs may be implemented in various ways to suit a particular operations support scheme. While most observation satellites employ continuous operation schemes of the spacecraft (with intermittent periods of data gathering), there has also been a trend toward event-driven spacecraft operations schemes. In general, the event-driven schemes are of the hibernation/activity type; they react to preset stimuli, come out of hibernation, observe an event for a certain period, and return to hibernation again. Other spacecraft are simply put into a hibernation mode (i.e. standby mode) during particular mission phases of inactivity. In any case, hibernation always implies that resources are being conserved for other planned periods of activity. Hibernation thus extends the general life time of a mission - by reducing cycle times of vital instruments, to safe energy, etc. The hibernation periods help also to reduce mission operation costs [ground support of manpower and resources (like antennas, etc.)]. Most hibernation recovery schemes rely to a considerable degree on onboard autonomy systems and capabilities. The following missions are examples of hibernation mode experiments or operations:

- GEOS-2 (GEOstationary Satellite) of ESA (launch July 14, 1978). GEOS-2 provided two years of data, was placed in hibernation for eight months, then revived for eight months in 1981 to support the EISCAT program of upper atmosphere motion measurements. GEOS-2 remained in use until the end of 1983. Periodic monitoring support (1984) of the chemical releases of the AMPTE mission.

- ERS-1 mission of ESA (launch July 17, 1991). The satellite was in hibernation since June 1996. Operations were limited to the monitoring of the platform vital elements, the battery maintenance and the periodic checkout of the entire system every 70 days. - To maintain the ERS-1 batteries performance, the SAR image mode was activated once or twice a day. This was used to perform limited ERS-1/2 SAR interferometry acquisitions. The ERS-1 mission ended on March 10, 2000 by a failure of the onboard attitude control system.

- The GOES-10 spacecraft of NOAA (launch April 25, 1997) was put in standby mode (hibernation) after launch to await its turn of active operations support. GOES-10 was activated on July 21, 1998 to replace the GOES-9 spacecraft.

- The SNOE (Student Nitric Oxide Explorer) mission of the University of Colorado at Boulder, CO (launch Feb. 26, 1998) employed a hibernation mode on a GPS receiver, BGSR, provided by JPL. The GPS orbit is determined about three times per orbit for short time intervals, otherwise the receiver is in hibernation. The information is used for post-factum ground orbit determination.

- The TUBSAT (Technical University of Berlin Satellite) series satellites introduced hibernation mode operations with DLR-TUBSAT (launch May 26, 1999) and the subsequent S/C, MAROC-TUBSAT (launch Dec. 10, 2001, see N.30.5). The ACS (Attitude Control Subsystem) design supports hibernation mode operations as a way of life in regular S/C operations. Most of the time (certainly over 95%) the satellite is orbiting in standby mode, slowly tumbling (a few rotations per orbit); all onboard systems are in hibernation (including ACS) to save power; only the UHF receiver is listening for potential commands. In case of an event, the S/C attitude may be restituted within a few minutes. Event recognition or a command from a ground station cause the spacecraft to return to observation mode.

- Hibernation modes are of particular interest in deep space missions with long periods of low activity between major event periods (long-term cruise phases). The Giotto extended

mission of ESA is an example. In its extended mission, Giotto hibernated twice - the first hibernation began in March 1986 and lasted for 1,402 days. The second hibernation period began in July 1990 and lasted for 670 days (however, the Giotto S/C was not specifically designed for hibernation). The Giotto hibernation recovery scheme relied on a directional antenna strategy. The NASA CONTOUR (Comet Nucleus Tour) Discovery mission (launch July 3, 2002) is using hibernation modes for the in-between periods of comet encounters. Objective: visit and study of at least two comets. Note: mission failure on Aug. 15, 2002 - An objective of the long-duration deep space mission Rosetta of ESA (launch March 2, 2004) is to rendezvous with comet 67P/Churyumov-Gerasimenko (10 year journey to the comet, reaching it in 2014). To reduce mission operation costs - and also because of trajectory constraints - a good portion of the cruise phase is allocated into unattended hibernations.

**Disaster monitoring.** Although a spaceborne (LEO) service of disaster monitoring is of great interest to a global community of civil protection authorities, there has been no satellite so far dedicated to the task of service provision during periods of natural disasters (volcano eruptions, floods, etc.). However, there have been imagery services, in particular for flood events, from a number of instruments on various satellites of existing space missions. Examples are: ERS-1/2 (AMI), JERS-1 (SAR, OPS), RADARSAT-1 (SAR), IRS-1C and -1D (LISS-3, PAN), Landsat-5 (TM), NOAA (AVHRR) series, and the SPOT (HRV) series, BIRD a demonstration mission of DLR (launch Oct. 22, 2001).

As of 2003, the **DMC (Disaster Monitoring Constellation)** of microsatellites (SSTL, Surrey, UK) is in the build-up phase; the following launches took place: AlSat-1 (Nov. 28, 2002), while a common launch was provided on Sept. 27, 2003 for BilSat-1 (Turkey), NigeriaSat-1 and UK-DMC. – As of March 2004, AlSAT-1, BILSAT-1, NigeriaSat-1 and UK-DMC achieved their target orbits in the constellation with nominal phase slots of 0º, 90º, 180º, and 270º around the DMC orbit (altitude =686 km, inclination = 98.8º). *With the coordinated constellation systems tested and commissioned, this enables the DMC consortium to provide imaging coverage anywhere on the surface of the Earth with a 24-hour revisit period.* Another microsatellite, China-DMC+, is scheduled to join the DMC constellation in 2005. A future mission is: **FOC/FUEGO** (Fire Observation Constellation), in the definition phase by ESA and the EU, is planned to deal in particular with forest fire observations.

### 1.4.8.7 Special S/C maneuvers and/or rescue/repair operations

On-orbit equipment malfunctions or failures are a fact of life for all space missions. This section lists some examples of special spacecraft maneuvers and deals in particular with significant repair and/or maintenance accomplishments performed on malfunctioning spacecraft subsystems to salvage/extend the mission. Reported are some in-flight success stories. It should be pointed out, however, that most malfunctions in spaceflight are attributed to the critical launch and deployment phases of a spacecraft. To become “spaceborne in the intended orbit and fully functional” after launch and deployment is certainly a prerequisite of high quality, all further spacecraft operations depend on this requirement.

Some examples of rescue or repair missions are:

- On the night of April 13, 1970, an oxygen tank of the command module of Apollo 13 exploded (after nearly 56 hours into the flight) – with a crew of three astronauts (James A. Lovell, Fred W. Haise and John L. Swigert) onboard on the way to the moon. This mishap crippled the command/service module engines of Apollo 13 some 321,860 km from Earth. Naturally, the scheduled lunar landing was aborted. The crew circled the moon in a dramatic rescue plan devised by Mission Control in Houston. The most immediate problem of the crew was the loss of the oxygen supply to the command module (fortunately, the environ-

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mental control system of the lunar module functioned as a backup). A four-day rescue mission followed in which Mission Control in Houston tried to devise a plan for a safe return to Earth. The firing of the lunar module engine provided the means to steer the powerless spacecraft safely back home. Reentry required the unusual step of undocking the lunar module, which had been retained for the flight back to Earth, in addition to the separation of the damaged service module. The lunar module had remained attached to the spacecraft to preserve the maximum electrical power in the command module for entry. All three men returned safely in this breathtaking rescue mission. 1099)

- HST (Hubble Space Telescope). See the Hubble repair missions in chapter 1.11 (on-orbit servicing).

- S/C rotation maneuver of RADARSAT-1 (see D.35.2). During AMM (Antarctic Mapping Mission), in the time period of September to November 1997, the RADARSAT-1 spacecraft underwent a successful maneuver to rotate its normally right-looking radar array into a left-looking attitude. The shift involved rotating the satellite by 180° in yaw. Although other missions do regular yaw maneuvers to reorient S/C, RADARSAT-1 was the first satellite in remote sensing history to perform this maneuver twice (back to nominal right-looking configuration at the end of AMM). The left-looking configuration allowed to map the entire Antarctic continent for the first time (24 day exact repeat observations for interferometric studies). A complete high-resolution mosaic of Antarctica was created, it is available for use by the science community.

- Recovery of momentum wheel (MW) failure in the ACS (Attitude Control Subsystem) of RADARSAT-1 (launch Nov. 4, 1995). The S/C encountered twice the problem in satellite pitch stabilization accuracy degradation: the first occurrence in August 1999 and the second in November 2002. 1100) Both events were caused by a gradual deterioration (wear) of “pitch momentum wheel” bearings resulting in an increase and destabilization of their friction torque. The first failure was resolved simply by swapping the prime wheel to the redundant one. The second failure, however, required the development of an appropriate ACS configuration to maintain the satellite attitude within the required pointing accuracy. The solution developed involves a switch of attitude control in the pitch channel from the MW to the MTR (Magnetic Torque Rod) actuators by uploading to the satellite ACS processor a new set of control tables. The new ACS configuration developed (an asymmetric control scheme provided by two MW and three MTR) allows the satellite to continue its mission, practically without any performance degradation. The problem solution (and extended mission life) was made possible due to the double-string cold redundancy architecture of the ACS and the upload capability to the onboard ACS processor.

- S/C rescue operations - GOES-10. In May 1997, the solar array mechanism of NOAA’s newly launched GOES-10 (launch April 25, 1997 as an orbit backup) satellite, designed to rotate once each day to keep itself pointed normally at the sun, slowed down and shortly thereafter stopped working entirely. 1101) The subsequent rescue work by NOAA and NASA engineers led to an unusual solution by turning the spacecraft into an upside down orientation (a yaw-flip maneuver). This maneuver turned out to be highly successful in saving the spacecraft for regular operations, because it permitted the solar array to work in a backwards-rotating orientation. As a consequence, the onboard software was changed so that data from the instruments are provided to users as if the spacecraft were in the normal upright position. GOES-10 was activated on July 21, 1998 to replace the GOES-9 spacecraft.

1099) http://nssdc.gsfc.nasa.gov/planetary/lunar/ap13acc.html
• MIR station accident. In the summer 1997 (June), an emergency occurred that had considerable impact on MIR’s fate. While docking with the MIR space station, an automated Progress cargo ship, filled with garbage, failed to respond to commands and rammed the Spektr module of MIR. As a result of this first collision between operating spacecraft, the Spektr module was punctured and leaked oxygen (causing a loss of air pressure in the Spektr module). The international crew aboard MIR (two Russian cosmonauts and a US astronaut) retreated to a docked Soyuz spacecraft to prepare for emergency evacuation. However, the situation was brought under control. The punctured module’s hatch was closed and the oxygen leak was stopped. The crash also damaged one of MIR’s solar panels, shutting off much of its electrical power system. The station drifted, starved for power, until the crew could bring the it back to life.  

1102) For the next two years, MIR crews did extensive maintenance and brought the space station back into full working order. By the time MIR was abandoned in the summer of 1999 -- after more than 13 years of operations -- the Russians had shown that humans could face daunting, even terrifying problems in space, and succeed.

• Rescue operations of the ESA/NASA spacecraft SOHO (Solar and Heliospheric Observatory), with a launch of SOHO on Dec. 2, 1995. Operational control of the SOHO S/C was lost on June 25, 1998 (when SOHO spun out of control and communication was lost). Subsequent investigations by a joint NASA/ESA/MMS team showed that the loss of contact with SOHO had been preceded by a routine calibration of the spacecraft’s three roll-control gyros. On July 23, first S/C recovery operations were performed with the Arecibo radio telescope in Puerto Rico.  

1103) The 305 m diameter dish antenna was used to transmit S-band signals to SOHO, while NASA’s DSN at Goldstone functioned as receiver, thereby locating the spacecraft’s echo. On Aug. 3, contact with SOHO was re-established and reception of the carrier signal by DSN. Attitude recovery was established on Sept. 16, 1998, resulting in a SOHO lock to the sun. SOHO was finally brought back to normal operating mode on Sept. 25. The only equipment failures at S/C level were in two of the three gyros. Instrument re-commissioning started on Oct. 5 with SUMER and ended with CELIAS on Oct. 24, 1998. On Dec. 21, 1998, the last onboard gyro failed during the preparation of a routine orbit-correction and wheel management maneuver.

In January 1999, a gyroless mode of operation was devised and installed with a new software patch for a modification of the AOCS (Attitude and Orbit Control Subsystem), making SOHO the first three-axis-stabilized S/C of ESA to be operated without a gyro.  

1104) The software patch was developed by MMS (Matra Marconi Space), now EADS Astrium SAS of France (an ESA patent is pending). The software allows to determine SOHO’s drift by measuring the changes in the speed of the spacecraft’s momentum wheels (the software triggers the momentum wheels instead of the faulty gyrosopes). Final recovery from ESR (Emergency Sun Re-acquisition mode) and full S/C operation of SOHO was regained Feb. 1, 1999. A joint ESA/NASA investigation board came to the conclusion that the loss of the SOHO S/C was a direct result of operational errors, a failure to adequately monitor S/C status, and an erroneous decision which disabled part of the onboard autonomous failure detection.

• The ERS-2 satellite of ESA started its mission on April 21, 1995 with six operational gyroscopes (S/C design life of 2 years), three of which were required for its three-axis pointing control, and a further gyro for the back-up safe mode. In 1997, the S/C lost gyro #2 and in 1998 a pointing anomaly on gyro #3 made it unreliable. The measures implemented in Feb. 2000 to protect the satellite against further gyroscope failures have allowed the continuation of the ERS-2 operations, despite two major anomalies that took place in Jan. 2001. Under normal conditions these would have meant the end of the ERS-2 mission, but the

measures implemented meant that the effects were limited to the interruption of service for about one month and temporary degradation of data quality. 1105) 1106) 1107)

Close collaboration between ESA and EADS Astrium has resulted in the successful implementation of a gyroless or ZGM (Zero-Gyro Mode) of operation. The ZGM software was loaded on June 6, 2001 and activated onboard. The first period of recommissioning lasted until the end of July 2001. In Nov. 2001, the tuning was improved to cover all data products. The ZGM represents a re-design of AOCS, making extended use of the platform’s sensors and actuators to compensate for the lack of gyroscopes. The goal is to extend the ERS-2 mission until MetOp-A becomes operational in 2006. - However, one consequence of renewed ERS-2 operations is that ATSR-2 high-rate operations are suspended since the Wind/Wave mode is used for S/C attitude control (only within narrow limits can the ATSR-2 HR mode be operated).

- PseudoGyro - is a software package of The Aerospace Corporation (El Segundo, CA) to save satellites from failure (US patent as of Feb. 1, 2000). The PseudoGyro package emulates a hardware gyro through software processes. 1108) The technique was successfully demonstrated in 1999 on a classified satellite of NRO (National Reconnaissance Office) which had experienced failures of its primary and secondary hardware gyros. PseudoGyro works in conjunction with orbital-attitude-estimation filtering techniques and takes advantage of all available sensors, including the vehicle itself, in determining attitude. It uses the principle of conservation of momentum to accurately determine the angular velocity of a spacecraft. It can be applied to virtually all types of space vehicles that are controlled by any type of momentum storage device. The technology can be integrated before or after a satellite is in orbit. In general, gyroscope-mimicking software might not replace the real thing, but it can reduce the workload on gyros, thereby extending their lives. PseudoGyro addresses also the need to reduce the risks and costs associated with new technology gyros.

- S/C rescue operations - DS1 extended mission. In November 1999, two months after the end of its extremely successful primary mission and early in its extended bonus mission, the star tracker of DS1, responsible for the spacecraft’s orientation, ceased operating. Rather than abandon the project, NASA engineers managed a deep-space rescue. They sent new software to DS1 (at a distance of 321 million km from Earth), turning an onboard camera (MICAS) into a navigation instrument. The challenging task was completed in June 2000 to resume thrusting in time to give DS1 a chance to encounter comet Borrelly in September 2001 (the encounter took place on Sept. 22, 2001).

- The Italian-Dutch X-ray orbiting observatory, BeppoSAX, was launched Apr. 30, 1996. The original AOCS software design, relying on three gyroscopes, has been changed in flight following failures of several of these units (up to 4 out of 6 rate integrating gyros). 1109) 1110) In Feb. 1997, the original safe mode was replaced by a totally gyroless one, referred to as GSM (Gyroless Safe Mode). Then a fine pointing mode, relying on a single gyroscope, was developed/uploaded in Aug. 1997, allowing the continuation of the scientific mission. In 1999, a fully gyroless scientific pointing mode (ESM2) was designed and developed as a precautionary measure; this software package was uploaded in Oct. 2001, allowing continuation of the SAX observations until April 30, 2002, when the S/C was deactivated on ASI decision.

1105) Project News, ERS, ESA Earth Observation Quarterly No 69, p.4, June 2001
1106) Project News, ERS, ESA Earth Observation Quarterly No 70, p.4, January 2002
A most unusual salvage of a so-called lost commercial communication satellite has been achieved with the HGS-1 (Hughes Global Services-1) S/C. Hughes Global Services Inc. of HSC (Hughes Space Communication Company) of El Segundo, CA, rescued a stranded communications satellite (intended to be AsiaSat-3) by sending it on a sequence of lunar passes. HGS-1 was launched Dec. 25, 1997. Because of a malfunctioning launch vehicle, it was left in an unusable, highly elliptical orbit. Hughes orbital engineers devised a novel mission to salvage the satellite, using lunar gravity to improve the resulting orbit once the satellite returned to Earth. That flyby, in mid-May 1998, was the first commercial mission to the moon. In a second lunar flyby, the satellite controllers fired the onboard motor for 12 minutes, which slowed the spacecraft enough to enter a circular orbit 36,000 km above the equator. As of June 17, 1998 HGS-1 is in GEO (Geostationary Earth Orbit). 1111)

The ARTEMIS (Advanced Relay and Technology Mission) rescue mission of ESA (launch July 12, 2001) experienced an extensive reprogramming of its onboard software when it was realized that the launch failure had left ARTEMIS in an elliptical orbit much lower than intended. Before the orbit-raising operations could get underway, a huge reprogramming effort was required. 1113) In all, about 20% of the original spacecraft control software had to be modified in order to accomplish the new mission scenario. Thanks, however, to the re-programmable onboard control concept, these modifications could be made by uplinking “software patches” to the satellite. These software patches amounted to a total of 15,000 words, making it the largest reprogramming of flight software ever attempted for a telecommunications satellite. In fact, the new attitude-control strategy developed for the satellite’s recovery has been retained as the best option for normal-mode operation in an inclined orbit. Moreover, an extension of this mode has been devised for station-keeping operations, which could be of great value for future telecommunications missions, as it provides for smooth attitude control during stationkeeping without mode transitions, and with minimal operator involvement.

The unusual route taken by ARTEMIS to get to geostationary orbit was long and hard, and beset with unfamiliar problems. But the mission was saved by the skills of a dedicated team of engineers and other specialists from ESA and its contractor companies (Alenia Spazio, Telespazio, Astrium, etc.). See also chapter 1.4.10.1 on ARTEMIS orbit raising.

The solar array onboard EchoStar-4, a commercial communications satellite in GEO of EchoStar, that had remained stuck in its stowed position since its launch (May 7, 1998), suddenly opened (i.e. deployed) the weekend of Sept. 4, 2004, according to EchoStar (the owner and operator of EchoStar-4). This is a most unusual event in deployment history — after six years! The solar array simply deployed without any warning during routine operations (it probably deployed on its own due to a long-term exposure to the sun). 1114)

The Landsat-7 project de-powered one of its gyroscopes on May 5, 2004, due to indications of anomalous behavior. The spacecraft has three two—degrees—of—freedom gyroscopes and needs two at any time to maintain attitude control. A risk assessment reported a 40% likelihood of another gyro failure by July 2005. A team was assembled to modify the software on board the spacecraft to operate in what is being termed Virtual Gyro (V—Gyro) mode. In this mode, if another gyro fails, the attitude control system would use the remaining gyro, along with existing onboard instrumentation and new control logic, to maintain attitude control.

As of February 1, 2006, the Landsat-7 team developed and uploaded flight software that can act like a “virtual” gyro — ready to use if another gyro fails. The enhanced capability was
designed, developed, tested, and implemented with no interference to ongoing Landsat-7 operations. 1115)

- Switch maneuver of the GRACE satellites in Dec. 2005 (joint US-German mission). Since launch (March 17, 2002), the trailing satellite (GRACE—2) of the co-orbiting twin GRACE spacecraft (separated by nominally by 200 km in along-track) has been flying “forward” with its K-band antenna horn exposed to the impacting atomic oxygen. There is some risk that overexposure to atomic oxygen could lead to a loss of thermal control over the K-band horn, which would affect the accuracy of the KBR (K-band Ranging system) signal. To ensure uniform aging and exposure for the K-band antennas on each of the satellites, the GRACE team performed a switch maneuver to exchange the leading and trailing spacecraft of the GRACE formation. For this purpose, an inclination/eccentricity separation has be used for a fuel and operational effort optimized switch maneuver. The switch was accomplished with only three OTMs (Orbit Thrust Maneuvers). OTM—1 took place on December 3, 2005, and the two subsequent maneuvers (OTM—2 and OTM—3) occurred respectively on December 12, 2005, and January 11, 2006. The maneuver was a success and GRACE—2 is now the leading satellite (Jan. 2006). 1116) 1117) 1118)

1116)“Switch Maneuver Of GRACE Satellites,” URL: http://www.csr.utexas.edu/grace/operations/switch_maneuver.html
1.4.9 Cooperative Distributed Space Systems – Satellite Formations

Distributed space systems (DSS) are multi-satellite systems that work together to perform a unified mission. Such systems are an alternative to monolithic satellite missions in which all on-orbit activities are performed on a single platform. Distributed space systems can range from global constellations offering extended service coverage to clusters of highly coordinated vehicles in formation flight (FF) that perform distributed sensing (FF is a subset of DSS).

Flying several spacecraft in formation enables spaceborne interferometry at a very high angular resolution, distributing the sensor over a collection of optical elements on individual spacecraft, and eliminating the restrictions imposed by the use of physical structures to establish, maintain, and control instrument separation and stability. Global constellations of communication and navigation satellites are considered “loosely coupled” systems, they are in existence for many years. On the other hand, the use of spacecraft formations for remote-sensing applications represents a new and rather unexplored type of constellation, namely “tightly coupled” systems with a new quality of service and support capabilities. 1119)1120)1121)1122)1123)

In general, the presence of multiple satellites leads to multi-point observations at different times and/or locations. This is the key to resolving the spatial-temporal ambiguity, which in turn enables a significant step forward in our understanding of the large-scale system dynamics (such as Earth’s magnetosphere). 1124)1125)

The logical sequence toward full FF implementations requires a number of technological steps from autonomous navigation and constellation control to one and two-way formation flying, and finally to virtual platforms, defined as collective, coordinated operations of multiple spacecraft oriented and positioned to achieve a set of predefined mission objectives. The entire concept of DSS, leading eventually toward virtual payloads and/or virtual satellites [referring to a collective guidance, navigation & control (GN&C) function for multiple spacecraft], represents in fact a new paradigm for remote sensing in general.

Formation Flying (FF) is critical to enable an order of magnitude (and greater) improvements in resolution and coverage achievable from scientific remote sensing platforms. Size limitations on launch vehicle fairings leave formation flying as the only option to assimilate coherent large apertures or large sample collection areas in space. The FF concept opens a completely new chapter in all observations from space. 1126)

DSS spacecraft architectures offer the following basic benefits and capabilities. 1127)

1) Multiple spacecraft can be separated to large baselines thereby improving angular resolution for such missions as Earth imaging, astrometry, and planet detection.

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2) Each spacecraft in a formation can be smaller than a single spacecraft designed to perform the same mission and thereby provide easier packaging, launch, and deployment.

3) Since interspacecraft interfaces are soft (e.g., communications, optics, control, metrology), if a spacecraft fails, it can easily be removed from the formation and replaced with a functioning spacecraft.

4) As technology improves, replacement spacecraft can be launched and integrated into the array thereby evolving the formation’s capabilities without the costly “block changes” typical of past programs.

The drawbacks of these architectures are on-orbit FF geometry maintenance requiring energy (a consumable, normally a propellant) as well as a considerable amount of FF control.

The idea of the FF mission concept demonstrations is to use clustered small spacecraft (minisatellites, microsatellites and/or nanosatellites) missions, capable to cooperate and to share resources and functions (processing, communications, payload, and/or observation/mission functions) with each other, in order to perform the functions of a large single satellite. Sensors on satellites, flying in formation, may function as a single large sensor (large aperture), offering entirely new observation capabilities such as:

- More frequent coverage through wider swaths, stereoscopic observations of imaging instruments (multifold coverage of common target regions), parallel provision of similar measurements at higher time-and-space sample rates (altimetry applications), virtual large aperture radar, etc.
- The entire field of spaceborne interferometry is offering new dimensions and observation capabilities with the introduction of DSS.
- An FF configuration offers very large baselines to synthesize a large sparsely distributed aperture that cannot be achieved by monolithic apertures. This feature is beneficial for such missions as spaceborne SAR or large apertures for the detection of ground-based moving targets in the cluster, the latter is also referred to as MTI (Moving Target Indication).
- Flexibility of FF architectures: The ability to reconfigure a cluster’s geometry for instance allows modifying the revisit time requirement. This is one particular instance of flexibility -- an ability to respond to changes in the requirements occurring after the system has been fielded -- it is characteristic of FF and is not feasible with a monolithic design. Furthermore, the ability to modify the revisit time on-orbit implies that it needn’t be specified prior to launch or further up front in the development phase of the system. - The idea that critical system requirements need not be narrowly specified prior to launch, because changes can be accommodated afterwards, is one particular advantage of the property of flexibility in design.

An FF experimental testbed by the name of SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) is being developed and installed at the Space Systems Laboratory of MIT (Massachusetts Institute of Technology) to provide the USAF and NASA with long-term, replenishable, and upgradable test capabilities for the validation of high risk metrology, control, and autonomy technologies [support of TechSat-21, TPF (Terrestrial Planet Finder) programs, etc.]. Some flight test experiments, evaluating both testbed and control algorithm performance, have already been con-

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1131) http://ssl.mit.edu/spheres/index.html

1132) http://cism.jpl.nasa.gov/events/workshop/SPHERES.pdf
ducted (in 2000) onboard NASA’s KC-135 aircraft. DARPA (Defense Advanced Research Projects Agency) is a major sponsor of the SPHERES program.

Another aspect of the SPHERES program is to take a SPHERES payload, an ISS-internal testbed in the US Laboratory, to ISS [Note: a launch of SPHERES took place on April 24, 2006 on a Soyuz–U launch vehicle with the Progress M–56 payload (ISS service flight) from Baikonur, Kazakhstan]. The system consists of: 1133)

- Three experimental self-contained 20 cm diameter free-floating nanosatellites (each of 3.56 kg) which perform the various algorithms
- A laptop computer
- Five small beacons (metrology beacon system).

The objective is to achieve a mature autonomous satellite formation flight capability (allow for the interchange of control algorithms; demonstrate key close proximity formation flight and docking maneuvers; test autonomous fault diagnosis and recovery; ensure the adaptability of control algorithms). The nanosatellites were designed by MIT students (under a program funded by MIT, DARPA and NASA), and built by Payload Systems Inc. of Cambridge, MA. The ISS testbed provides a risk-tolerant environment capable of testing unknown algorithms and recovering from failures at low costs compared to that of a full mission. The program provides human observability and manipulation by both, the guest scientists in a ground station, and operators in the ISS. 1134)

The ESA FAMOS (Formation Flying Analysis and Missions Operations Simulator) was developed by GMV S. A. of Madrid. 1135) 1136) FAMOS provides detailed analysis of satellite formations using highly coupled GNC algorithms, which integrate attitude, navigation and maneuvers. FAMOS is a generic, six degrees-of-freedom simulator for 2 satellites flying in LEO formation. It is a powerful tool implementing a wide range of sensors which are integrated into highly coupled GNC.

Distributed S/C control architectures are characterized by interactions between S/C, cooperation between S/C, and collective behavior among S/C within a constellation or formation. The introduction of concepts such as decision making, hierarchical control, decentralized control, etc., within the management of the formation enables spacecraft to cooperate with one another. Autonomy is a critical technology in this scenario that impacts every level of the design, from the subsystem, to the instrument, the platform, as well as the entire formation. If a cooperative formation includes a variety of basic, versatile instruments, for example UV, VIS and IR spectrometers, then “virtual platforms” for different applications can be formed in space, on the fly, and “disassembled” (or reconfigured) later for other uses - flexibility to adapt to the evolving science needs and to implement the newest technologies during the course of an on-going mission are the basic requirements. In this new observation concept of formation flying, GPS navigation, i.e. orbit and attitude sensing and vehicle orbit (relative and absolute positioning) and attitude control, plays a key role as a navigation instrument in the maintenance and control of the formation (measurement of formation states, i.e., the relative orientations, positions and velocities of the vehicles).

- **Definition of general DSS (Distributed Space System) characteristics:** 1137) A collection of spacecraft may be categorized as a constellation, a cluster, or a formation, depending on how closely the spacecraft are coupled in time and space.

1133) “Mini Satellites Rocketing To Space Station,” http://www.spacedaily.com/reports/Mini_Satellites_Rocketing_To_Space_Station.html
1) A constellation of spacecraft, such as the 24 GPS satellites orbiting in six orbital planes around Earth, are discrete spacecraft that are partially organized in time and space and controlled separately from Earth.

2) Another type of DSS is the concept of a local cluster, where satellites are intentionally placed close together in the same orbit to train on a common target. Optionally, this cluster of satellites may have a more complex instantiation, namely a formation.

3) **Definition of FF (Formation Flying) architecture.** There are four elements that are unique to the formation flying problem: formation design, relative navigation, intersatellite communication, and formation control. — The new technology of spacecraft formation-flying includes a set of more than one spacecraft in a tightly-controlled spatial configuration (formation), whose operations are closely synchronized, with a collective control system distributed among the spacecraft so that the individual spacecraft are not controlled from Earth (active, real-time, closed-loop control is involved). The relative location (distance) between the satellites in the formation is of prime concern for operational control/maintenance to achieve the distributed observation configuration.

![Figure 24: Various views of DSS (Distributed Satellite Systems)](image)

Flying two or more spacecraft in a precise formation for **cooperative observations** (i.e., to obtain **contemporaneous spatial sampling** by a group of separated spacecraft) presents a number of complex challenges:

- Each spacecraft must have a sensory and control system enabling it to attain and maintain a precise relative position.
- Each spacecraft must have a sensory and control system enabling it to attain a specified attitude, with all spacecraft targeting the desired object.
- Each spacecraft must be able to communicate with each other in the formation.

A number of critical FF technologies \(^{1138}\) are required to enable and maintain separated spacecraft FF-based mission architectures. These include:

- Robust, fault tolerant and scalable formation architectures for distributed spacecraft communication, control, and sensing. A key feature in this scenario is the ability to dynamically reconfigure the sensing, information flow and control connectivity across each space-

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\(^{1137}\)http://starlight.jpl.nasa.gov/formfly/special.html

craft in the formation. Also provision of graceful degradation of performance and functionality within the given onboard hardware redundancy. The formation flying architecture must allow for stand-alone operation in case of inter-spacecraft communication and/or formation sensor faults.

- Formation autonomy. The onboard software needs to autonomously provide formation as well as individual spacecraft guidance, estimation, and control functions within the framework of high level reasoning and commanding to achieve the desired science goals in a resource-efficient manner.

- A new class of formation guidance, estimation and control algorithms. This includes such functions as:
  - The capability of robust lost-in-space acquisition, i.e. the ability to obtain lock of the relative sensors to initialize the formation after initial deployment or after reset/recovery events
  - Collision-free operation
  - Consumable resource balancing across all spacecraft
  - Path planning in both attitude and translation under multiple constraints (e.g. solar, thermal, glint, H/W capability)
  - Precision hierarchical control coordinated across multiple spacecraft
  - Observation-on-the-fly capability to enable continuous science measurements during formation maneuvers.

- Relative sensor technology to provide the inter-spacecraft range and bearing measurement. The knowledge of range and bearing (range vector) between each pair of spacecraft is essential in configuring the overall formation to achieve a desired baseline, and maintaining the baseline within a prescribed tolerance during the course of the science observation. Collision avoidance is another key formation flying requirement enabled by formation sensor based relative range vector knowledge.

- Precision actuator technology to enable fine motion (both inertial and relative) control of each spacecraft in the formation (in particular for interferometry missions). Most missions will require coarse actuation (for retargeting maneuvers) and precision actuation to enable stable and accurate science pointing and tracking.

- Ground and flight demonstration testbeds to integrate and bring these technology elements to a level of maturity for infusion into future missions. See SPHERES above in this chapter.

- The implementation, maintenance and operation of formation flying poses further challenges: ¹³³⁹)
  - The performance requirements and disturbance/operating environments vary substantially between Earth-orbiting and deep space missions. For EO missions, orbital and environmental dynamics (J₂, drag, ground track coverage requirements, etc.) affect each spacecraft in a formation differently. These variations affect the formation stability. Solar radiation pressure is the chief disturbance source for deep space formation flying missions which typically require much tighter formation capabilities (TPF, DARWIN, LISA).
  - There are several major formation flying maneuver types: a) formation acquisition and initialization, b) formation maintenance, c) formation resizing (change of interferometer baselines), d) formation rotation (move to new baseline orientations around the line of sight), e) formation retargeting slews, f) stationkeeping, g) rendezvous and docking, and other close proximity maneuvers.

ber’s relative state tracking control law. This FFG definition includes open-loop control design (i.e., an optimal control profile that only depends on time and initial conditions). In general there are two regions of FFG: POE (Planetary Orbital Environment) and DS (Deep Space). - The POE FFG is of particular interest in the context of Earth observation, where spacecraft in a formation have significant orbital dynamics (LEO missions). General POE FFG mission requirements consider reconfigurations of the formation and on finding passive apertures. - The most common linear passive apertures are thrust-free, periodic solutions to the Hill-Clohessy-Wiltshire (HCW) equations, referred to as FETs (Free Elliptical Trajectories). Example: The ICW (Interferometric Cartwheel) FET is useful for synthetic aperture radar (CNES mission). The FETs rotate with the local-vertical, local-horizontal frame and are useful for looking at the Earth. 1140) 1141) 1142) 1143)

The observation concept from any formation-flying cluster is regarded as multistatic where two or more platforms, each furnished with an active instrument, can be used with different views of the same observed area, permitting such applications as stereoscopy and interferometry.

- **DSS as seen from the perspective of mission resolution requirements.** Distributed spaceborne observing systems offer an attractive architecture for achieving high spatial and temporal resolution. However, multiple architectural configurations and system sizes should be considered for an optimal observing system design to suit best all functional requirements. Various phenomena which may be observed from space have different temporal and spatial scale requirements. For example, severe storms evolve quickly, and observations every 15 minutes or less may be required. On the other hand, ice sheets evolve slowly and thus may be observed less continuously. Similar arguments can be made for spatial requirements. Thus it is important to consider various vantage points — ice sheet observations could be made from LEO (Low Earth Orbit) while severe storm observations should probably be made from GEO (Geostationary Orbit) or HEO (Highly Elliptical Orbit) to meet the revisit requirement. Surface deformation occurs on a variety of temporal scales ranging from long-term volcanic inflation to seasonal hydrologic variations to earthquakes. 1144) 1145) 1146)

Within this context four major classes of distributed spacecraft systems can be identified where each successive class represents an evolutionary step in DSS formations:

1) Virtual observing systems: Refer to multiple space platforms with limited-to-no inter-spacecraft communication. Currently meteorological observations from a variety of sources are brought together as part of the data assimilation process. The platforms that are making the observations are not coordinated nor commanded to alter their observing strategy. The data is simply gathered from wherever it is supplied. Nonetheless, when considered as a whole, the current meteorological observing system constitutes a virtual single observing system with multiple components.

2) Simple formations (a degree of coordination is required): The observing assets are distributed across several spacecraft, replacing the functions of very large spacecraft. The

1143) Note: In this context, the term “guidance” refers to path planning (i.e., reference trajectory generation) and optimal, open loop control design.
advantage of the formation compared to a single large spacecraft is flexibility, redundancy and louver systems engineering costs. The “A-train” of several spacecraft can be regarded a simple formation, taking advantage of existing assets.

3) Virtual instruments: This refers to a multiple satellite configuration which together provide a single observation configuration. Example missions in this category are: The GRACE mission of two minisatellites, ST5, etc.

4) SensorWeb: Refers to future systems/architectures (a networked collection of heterogeneous space and surface assets organized into a ”SensorWeb”) in which every element of the deployed system has awareness of all other elements and can coordinate and share duties on a real-time basis with neighboring elements. A SensorWeb may include virtual instruments and simple formations. 1147) 1148)

1.4.9.1 Survey of early formation-flying (EO) demonstrations
The problems yet to be solved associated with formation flying are numerous and each very challenging. Examples of S/C formation-flying demonstration missions (with correlated measurements) or early proximity operations missions (rendezvous and docking applications) are:

- The first ever rendezvous and FF took place with Gemini-6 and -7 spacecraft on Dec. 15, 1965 (5 hours of close FF). The rendezvous of two spacecraft was an important step in preparation for a future moon landing mission.

- The first automatic docking of Kosmos 186 & 188 (USSR) took place on Oct. 28, 1967.

- In 1969, data from various US, USSR, and of ESRO (European Space Research Organization) satellites 1149) were correlated to study how large solar flares interacted with the Earth’s magnetosphere and ionosphere — thereby achieving the first contemporaneous spatial sampling by a group of separated spacecraft (although, this was no formation flight configuration). The S/C involved in the measurement campaign were: 1150) 1151)
  - ESRO spacecraft: ESRO-1/Aurorae (launch Oct. 3, 1968), ESRO-IIB (launch May 17, 1968) also referred to as IRIS (International Radiation Investigation Satellite), and HEOS-A1 (Highly Eccentric Orbit Satellite), also referred to as HEOS-1, launch Dec. 5, 1968. The objectives of HEOS-1A were to study interplanetary magnetic fields, cosmic rays, the solar wind, and the magnetosheath.

- ASTP (Apollo-Soyuz Test Project), launch of both S/C on July 15, 1975. This flight marked the culmination of the Apollo-Soyuz Test Project, a post-moon race ‘goodwill’ flight to test a common docking system for space rescue (also near-proximity operations).

- The ORFEUS-SPAS-2 Shuttle mission of NASA/ESA/DLR on STS-80 (Nov. 19 - Dec. 7, 1996), a free-flyer platform, demonstrated for the first time relative navigation using a


1148) http://sensorwebs.jpl.nasa.gov/

1149) Note: ESRO (created in 1962) was one of the predecessor organizations of ESA (since 1975), the other was ELDO (European Launcher Development Organization)


1151) Information was kindly provided by Daniel P. Scharf of NASA/JPL, Pasadena, CA
code-based DGPS system, ARP (ATV Rendezvous Predevelopment) of ESA, consisting of a GPS receiver on ORFEUS/SPAS deployed from the Shuttle, and a second GPS receiver on the Shuttle (see J.1.3). Raw GPS phase measurements were collected by the two receivers, providing 10-50 m relative positioning accuracy and m/s level relative velocity data in post-processing. 1152)

- The SNAP-1 and Tsinghua-1 missions of SSTL, UK (launch June 28, 2000). Each S/C carried a GPS receiver (SGR-05), demonstrating meter-level positioning capabilities using pseudoranging (see D.52.17 and D.52.18). However, the two S/C computed their absolute positions independently, the relative positioning capability using DGPS was not demonstrated.

- The ETS-VII (Engineering Test Satellite VII) of NASDA with a launch on Nov. 27, 1997 conducted an autonomous rendezvous and docking experiment using a code-based DGPS navigation receiver. The instrument RGR (Relative GPS Receiver) was used successfully in the docking demonstrations (see M.12.1). Relative position and velocity errors of <10 m and <1 cm/s were achieved. However, the GPS receiver was only used in the coarse approach phase due to its relatively poor accuracy. A laser radar and a proximity image sensor were used in the final approach and docking phase.

- GRACE (Gravity Recovery and Climate Recovery), a cooperative US-German dual-minisatellite mission with a launch March 17, 2002 (see E.13). The mission concept makes use of measurements of the inter-satellite range and its derivatives between two co-planar satellites (in low-altitude and polar orbits), using a K-band microwave tracking system (using ultrastable quartz oscillators) and a GPS receiver system (BlackJack) for precision orbit determination to enable accurate orbit determination. The oscillators’ precise and stable signals continuously measure satellite-to-satellite distance, and thus their relative velocity, with unprecedented accuracy. In addition, each S/C carries a high-accuracy accelerometer (SuperSTAR) and a star camera (SCA) for attitude sensing. It should be noted, however, that the GRACE tandem mission is not a tightly controlled system with regard to relative distance between the two spacecraft. The inter-satellite range variations of the freely drifting tandem orbits is in fact the prime observation parameter — inferring variations in the Earth’s gravity field. Note: The varying gravity field is mostly due to variations in water content as it cycles between the atmosphere, oceans, continents, glaciers, and polar ice caps. 1153)

- The Orion - Emerald (Electromagnetic Radiation and Lightning Detection) mission, a two-satellite project of Stanford University, Santa Clara University, and NASA). A launch on a Shuttle mission was planned for 2003. The objective was to demonstrate the use of CDGPS as a sensing system for precise relative navigation and formation flying control in real-time. Somehow, the mission Orion—Emerald concept was cancelled after the tragic Columbia accident (Feb. 1. 2003) due to other priorities of the Shuttle program.

- A program initiative, TechSat-21 (Technology Satellite of the 21st Century), was started in 1998 by various US DoD departments/directorates, namely AFRL (Air Force Research Laboratory), AFOSR (Air Force Office of Scientific Research), and DARPA (Defense Advanced Research Projects), with the objective to exploit the new paradigm and enabling technologies, such as MEMS (Micro-Electro-Mechanical Systems) and overall component miniaturization and function integration - that “involves satellites flying in tight formation that operate cooperatively to perform a surveillance mission.” Under this effort, a variety of application missions are being considered including surveillance, passive radiometry, terrain mapping, and communications. Launch of TechSat-21 is planned for 2006 with one year of on-orbit operations. Note: The TechSat-21 program was cancelled in early


In spite of this unfortunate mission end, the concept studies have amply highlighted the extreme system-level challenges involved in FF.

- In addition, a University Nanosatellite Program (UNP)\(^{1154}\)\(^{1155}\) was set up for this purpose by AFSOR/DARPA/NASA to fund ten university research projects centered on the design and demonstration of nanosatellites. The partially funded projects within Tech-Sat-21 / UNP are:

- 3CSat (3 Corner Sat), a constellation of three microsatellites in formation. 3CSat is a joint project of the University of Colorado at Boulder, ASU (Arizona State University), and NMSU (New Mexico State University). A multiple launch took place on Dec. 21, 2004; however, the two microsatellites that were launched did not reach the proper orbit.

- ION-F (Ionospheric Observation Nanosatellite-Formation), a three-satellite project of USU (Utah State University), Logan, UT; UW (University of Washington), Seattle, WA; and VT (Virginia Polytechnic Institute), Blacksburg, VA. Formation flying is a primary objective. Introduction of new technologies including micro-thrusters, magnetic gimbaled attitude control, and an Internet-based operations center. A Shuttle launch is proposed for 2004.

- Constellation Pathfinder, a one to three satellite mission of Boston University.

- Solar Blade Heliogyro Nanosatellite, a mission of CMU (Carnegie Mellon University), Pittsburgh, PA to demonstrate the solar sail concept.

**Further projects of flown/planned cluster missions and formation flying are:**

- ST5 (Space Technology 5), formerly called Trailblazer, is a NASA demonstration mission in the NMP (New Millennium Program) of three microsatellites (each < 25 kg, orbit = GTO), flying in formation, a launch took place on March 22, 2006. The objective is to validate new technologies in space associated with microsatellite design and demonstration of functional capabilities (provision of autonomy and virtual control). Also use of an autonomous network scheduling tool to manage ground contacts with multiple satellites. The science objective is the collection of the magnetic field data from a constellation.\(^{1156}\)\(^{1157}\)\(^{1158}\) – Note: The ST5 mission team concluded all mission operations on June 30, 2006, completing all major demonstration objectives within the planned mission life of three months

- The TanDEM-X mission concept of DLR (launch 2010) is based on an extension the TerraSAR-X mission (launch June 15, 2007) by a second TerraSAR-X-like satellite, namely TanDEM-X. A close orbit formation flight is planned for both satellites — thereby providing a flexible single-pass SAR interferometer configuration, where the baseline can be selected according to the specific needs of the application. In the TanDEM-X and TerraSAR-X space mission design, the SAR (Synthetic Aperture Radar) instruments of each spacecraft are fully compatible, both offer transmit and receive capabilities along with polarimetry. Availability of the following support modes: a) monostatic, b) bistatic, and c) alternating bistatic mode.

- The PRISMA mission is a Swedish-led technology mission to demonstrate formation flying and rendezvous technologies (in-orbit servicing). The mission consists of two spacecraft, one advanced and highly maneuverable one, called **MAIN**, and a smaller S/C without a maneuvering capability, called **TARGET**. A launch of PRISMA is planned for early 2009.

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\(^{1155}\)http://www.vs.afrl.af.mil/vsd/techsat21/


\(^{1157}\)http://nmp.jpl.nasa.gov/st5/

The experiments encompass a) autonomous formation flying, b) homing and rendezvous experiment, and c) proximity operations.

- NASA/GSFC is defining MagCon (Magnetospheric Constellation), a mission of about 100 nanosatellites (deployed from a single mother ship) to acquire vector images of the magnetic and plasma flow fields in highly elliptical orbits (from 3 to 50 RE). Simultaneous, multi-point observations of the Earth’s magnetospheric environment. The overall science objectives are to a) determine the equilibria of the magnetotail, b) understand the responses of the magnetotail to the solar wind, c) reveal the instabilities of the magnetotail. A launch of MagCon is planned for 2006.

Examples of constellations are:

- GPS (Global Positioning System) constellation of the USAF (United States Air Force). The constellation is composed of 24 satellites in semi-synchronous orbits, placed evenly in six planes designed to provide position and timing information to users on land, sea, air, and in space.
- The GLONASS constellation of Russia (nominally of 24 S/C) is utilizing 12–14 satellites in two orbital planes.
- The Iridium LEO constellation of nominally 66 communications satellites is an example of an early commercial communication constellation (provision of global mobile phone communications). The launches took place in the timeframe 1997–2000/2. Iridium is the only commercial system to date that employs RF crosslinks. Iridium is also one of the first constellations with some degree of autonomy.
- The Cluster mission (Cluster–II) of ESA is a four spacecraft constellation which was launched on July 16, 2000 and on Aug. 9, 2000 (each launch of two identical S/C). The objective of Cluster is to gather scientific data on the magnetosphere in three dimensions (highly elliptical orbits). Cluster has the ability to take simultaneous measurements of phenomena over a large volume. Cluster does not employ controlled formation flight, but rather falls into the free flying category, where only stationkeeping propulsion is required.
- DMC (Disaster Monitoring Constellation), a five-microsatellite constellation (international partners), has been developed and built at SSTL (Surrey Satellite Technology Ltd), Surrey, UK. The overall objective is to provide global daily imagery at 32 - 36 m spatial resolution (swath of 600 km) for the monitoring and mitigation of natural and man-made disasters and dynamic Earth observation. The successful launch of AlSat-1, the first S/C in the series, occurred on Nov. 28, 2002. Another multiple launch occurred Sept. 27, 2003 with the following DMC spacecraft: BilSat-1 (Turkey), NigeriaSat-1 (Nigeria), and UK-DMC (UK). The Beijing – 1 S/C was launched on Oct. 27, 2005. **DMC is in fact the first operational Earth imaging constellation.** All DMC spacecraft are flown in a single orbital plane providing a cumulative swath.
- FormoSat–3/ROCSat–3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate), is a collaborative US/Taiwanese (led by UCAR and NSPO) microsatellite constellation, a launch took place on April 14, 2006. In the scenario, a LEO constellation of six spacecraft in three orbital planes collects atmospheric remote sensing data for operational weather prediction, climate, ionospheric (space weather monitoring), and gravity research (refractive GPS radio occultation measurements).
- RapidEye is a commercial Earth imaging mission of RapidEye AG of Brandenburg, Germany, that includes a constellation of five minisatellites (launch in 2007). Multispectral imagery of 6.5 m spatial resolution will be obtained. The constellation approach in a single orbital plane permits a cumulative swath to be built up (the spacecraft view adjacent regions of the ground, with image capture times separated by only a few minutes). A revisit time of one day can be obtained anywhere in the world (± 70° latitude) with body pointing techniques.
– The COSMO-SkyMed mission of ASI and the Italian Ministry of Defense, Rome, Italy, is a 4-spacecraft constellation (launch of first S/C on June 8, 2007). Each satellite is equipped with a SAR (Synthetic Aperture Radar) instrument and is capable of operating in all visibility conditions at high resolution and in real time. All spacecraft of the SAR constellation will be positioned in the same orbital plane.

– Swarm is a minisatellite constellation mission of ESA with a planned launch in 2010. The overall objective is to provide the best ever survey of the geomagnetic field (multipoint measurements) and its temporal evolution (accurate determination and separation of the large-scale magnetospheric field). The three satellites of the constellation are being flown in 3 orbital planes with 2 different near-polar inclinations to provide a mutual orbital drift over time.

– The MMS (Magnetospheric MultiScale) mission is part of NASA’s Solar Terrestrial Physics Probe line. Its goal is to understand the fundamental physics which underlies the solar terrestrial environment and which drives space weather. MMS is composed of four identical spacecraft, each having a complete set of particles and fields instruments to study the ambient plasma. A launch of the constellation is planned for 2013. The spacecraft fly in a tetrahedral array with inter-spacecraft separations ranging for 10 to 1000’s of km in four distinct highly eccentric orbital phases. Note: In this formation flying mission, it is only important to control the geometry of the formation (in this case to form a tetrahedron) at the apogee point of the orbit. 1159)

1.4.9.2 Intersatellite communication and navigation

A prerequisite to formation flying is intersatellite communication (also referred to as cross-communication or simply crosslink) for the control and monitoring functions of the spacecraft cluster. Such a service may be provided by the GPS constellation offering a range of sensing options for a formation including such functions as: absolute positioning, relative vehicle positioning, attitude estimation, and precise timing. This approach is based on a combination of CDGPS (Carrier-phase Differential GPS) and GPS-like transceivers (the challenge of using CDGPS is in estimating the cycle ambiguity to sufficient accuracy). The transceivers are RF-based cross-communication devices that can also be used as local ranging systems. In CDGPS, the measured phase of the GPS carrier is compared to the carrier phase measured on the other spacecraft.

**Relative navigation:** 1160) 1161) 1162) 1163) Within a constellation or formation of satellites, the relative position between the spacecraft in the formation is often needed with a higher accuracy than the absolute position of the satellites. - Relative navigation of two or more spacecraft in a formation is done by differencing the measured pseudoranges and carrier-phase measurements of the GPS constellation. In the differencing process, errors common to all spacecraft, such as GPS ephemeris errors or ionospheric delay errors, can practically be eliminated (since all S/C in the formation are affected in the same measure). In addition, the carrier phase measurements require to resolve the ambiguity (integer number of whole wavelengths) to obtain utilizable data. Two solutions are available for relative navigation.

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processing: a) an onboard software/hardware package to perform these functions in real-time along with the crosslink communication service. In this setup, requirements for autonomous onboard control of the formation (in position and/or attitude) are becoming a must (essential technology); and b) a ground processing option by a control station or center. However, for the general LEO formation, the latter option does generally not offer a continuous link between the formation and the ground to exercise the control function (actuation).

Examples of GPS-like transceivers for relative navigation include:

- CLT (Cross Link Transceiver) of NASA designed and developed by JHU/APL.\(^{1164}\) CLT is an integrated navigation and communication system for multiple distributed spacecraft flying in formation. The design of CLT provides three core functions: processing/memory, GPS reception, and crosslink communications. The processor supports signal acquisition and tracking, navigation, communications, and distributed command and control for space assets.\(^{1165}\) The CLT provides both an absolute and relative navigation solution (position and velocity) as well as precision time recovery and a steered one pulse-per-second output. Autonomous orbit determination is provided by the reception of GPS signals and processing by an extended Kalman filter. The crosslink communications module consists of a crosslink transmitter and a multi-channel crosslink receiver. In addition, crosslink signals support relative navigation, with the potential for both, direct solutions as well as relative GPS solutions which rely upon the computation of double differences of GPS data in a paired manner among spacecraft. The mass of the CLT device is 0.86 kg, its size is a cube of 10 cm side length.

- SPTC (Stanford Pseudolite Transceiver), a relative navigation and crosslink system for formation-flying spacecraft. SPTC uses COTS devices: modems, L1 pseudolites, and an attitude-capable GPS receiver. CDGPS measurements provide precise relative positioning and an attitude determination to within 0.25°.

- Star Ranger of AeroAstro Inc. of Herndon, VA. The system combines CDGPS and an inter-satellite communications link between clustered co-orbiting satellites. Star Ranger is considered for AFRL's TechSat-21 formation-flying mission.

- LPT (Low Power Transceiver) of NASA/GSFC in cooperation with ITT Industries [ITT-AES (Advanced Engineering and Sciences Division) in Reston, VA].\(^{1166}\)\(^{1167}\)\(^{1168}\) The LPT is a compact, flexible device consisting of multiple PC-104 modules that can be configured to perform custom communications and navigation functions in terrestrial, airborne, and space applications; in addition, rLPT (radiation-tolerant LPT) can withstand radiation environments. The LPT performs signal-processing functions with reprogrammable FPGA and DSP devices. Additionally, the industry standard modules used in the LPT allow it to host application-specific and COTS modules that contain processors and interfaces. The device integrates TDRSS S-band two-way communications and Ground Networks (STDN) for TT&C and science data relay, and GPS navigation in a compact package. LPT employs GEONS (GPS Enhanced Orbit and Navigation System) a software package of GSFC. The first demonstration flight of LPT has been conducted aboard Shuttle flightSTS-107 (Jan. 16 - Feb. 1, 2003, see J.6) in the experiment CANDOS (Communications and

Network Demonstrations on Shuttle, see also CANDOS under 1.4.7.4). The LPT navigation software provides several integrated functions, including the absolute navigation, relative navigation, and attitude determination. The most recent generation of the LPT includes a “Dial-a-Channel” feature that dynamically optimizes the LPT’s signal processing capability by allowing the user to increase the nominal maximum data rate when the total number of receive channels is reduced.

The vision of NASA’s Earth Science Enterprise (ESE) involves the interconnection of future space instruments into a vast network, with each space instrument working individually yet in a collaborative way to achieve new levels of performance. This future network, referred to as the SensorWeb, allows multiple vantage points (e.g., LEO, MEO, and GEO) to provide data diversity. Within the Sensorweb, formations of micro- and nanosatellites perform autonomously while achieving reliability through redundancy. In addition, reconfigurable payloads reduce risk by allowing for context switching and instrument/algorith upgrades and adaptions after deployment.

- NCLT (Nanosatellite Cross Link Transceiver) of CLT heritage is under development at APL. The UNP University Nanosatellite Program satellites (of DoD/ NASA) employ this device and NASA's ST5 (Space Technology 5, launch March 22, 2006) constellation. NCLT is a multicard, stand-alone system that implements three fundamental functions: onboard processing, GPS receiver, and crosslink communications. NCLT supports multiple-access communications architectures (FDMA/CDMA/TDMA). 1169) 1170)

- CCNT (Constellation Communication & Navigation Transceiver), developed at JPL. CCNT was flown on the ST5 (Space Technology 5), a three spacecraft microsatellite mission (launch March 22, 2006). CCNT was used for inter-constellation ranging, communications, and GPS-based absolute positioning. Additional requirements called for transfer of event messages between the spacecraft.

- Other distributed observation strategies of constellation flying. This category considers so-called “trains of satellites performing similar observation objectives with their payloads in closely spaced sequences.” Their orbits are optimized to coincide (within a few minutes) with those of other satellites. Examples are:

- The Landsat-7, EO-1, SAC-C and Terra “morning constellation” train (in formation as of March 2001). 1171) There is 1 minute separation between Landsat-7 and EO-1, a 15 minute separation between EO-1 and SAC-C, and a 1 minute separation between SAC-C and Terra. The objective is to compare coincident imagery from the ETM+ and ALI instruments. The “paired scene” images are used to evaluate the performance of ALI. – Note: The morning train represents the loosest, and least collaborative form of formation flying, implemented through the ground (not through a crosslink); the S/C separations are being controlled.

- As of Jan. 2002, the TOPEX/Poseidon and Jason-1 spacecraft are flying as a tandem mission (Jason was launched Dec. 7, 2001) on the same ground track with a one minute separation time. 1172) This orbital configuration permits cross-calibration to be performed. It also provides ocean topography data with unprecedented accuracy (better than either S/C could attain by itself). After the checkout/verification phase (Sept. 2002), the tandem mission is flying in an interleaved orbit (i.e., the TOPEX/Poseidon orbit has been moved to an orbit that produces interleaved groundtracks with a 1.4º longitude spacing from the Jason-1

tracks). The intent is to address the following topics: a) double the spatial sampling to enhance the resolution of the Rossby waves and eddies; b) quadruple the crossover points for the estimation of the current velocity vector; c) enhanced coastal tide models; and d) obtain improved global change detection. \(^{1173}\) \(^{1174}\)

- The Aqua, CloudSat, CALIPSO, PARASOL, and Aura spacecraft will successively form the so-called “A-train” (Aqua in the lead and Aura at the tail, the nominal separation between Aqua and Aura is about 15 minutes) or “afternoon constellation” (formation flight starting sometime after the Aura launch July 15, 2004). \(^{1175}\) The objective is to coordinate observations and to provide a coincident set of data on aerosol and cloud properties, radiative fluxes and atmospheric state essential for accurate quantification of aerosol and cloud radiative effects. The orbits of Aqua and CALIPSO are tied to WRS (Worldwide Reference System) and have error boxes associated with their orbits. The overall mission requirements are written such that CALIPSO is required to be no greater than 2 minutes behind Aqua. The OCO mission of NASA is a late entry into the A-train sequence. The satellites are required to control their along-track motions and remain within designated “control boxes.” Member satellites will exchange orbital position information to maintain their orbital separations. \(^{1176}\) \(^{1177}\) \(^{1178}\)

<table>
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<tr>
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</tbody>
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Table 55: Overview of the A-train science mission chronological build-up

1.4.9.3 Operational architecture concepts of DSS networks

Background: The very nature of “conventional” space mission operation concepts is that of a point-to-point architecture, also referred to as stove-pipe operation (i.e., there are only islands of joint situational relations and awareness - maintaining an intermittent operational support). Stove-pipe solutions are built such that different technology parts are bolted on as needed with whatever tools are available. There is generally not a high level of coordination and conceptualization; however, such systems become more difficult to manage with increasing complexity.

Most traditional LEO missions employ direct station communications (to one or several stations) in the ground segment requiring scheduling and some coordination. This support concept requires an onboard S&F (Store & Forward) technique to collect the observational

data during the non-contact periods of the orbit. Long spacecraft isolation periods lead of course to greater storage volumes and in turn to higher downlink rates for the relatively short acquisition periods. In a number of early SAR missions (SEASAT, ERS-1, ERS-2, JERS-1, RADARSAT, Envisat), the science source data were simply not recorded onboard (or only very small portions of it), leaving instrument observational support modes only to regions of a direct-downlink contact (see 1.4.7.1 for onboard storage history). Eventually, this lead ESA and others to the installation of SAR receiving ground stations into remote regions of our globe [O’Higgins Station (DLR), and Syowa Station (Japan), both located in Antarctica; Libreville, Gabon (DLR); Ulan Bator, Mongolia (DLR); etc.] to be able to obtain repetitive observational data of the region of interest. The hyperspectral imaging instruments of today represent another class of very high-volume science source data.

The notion of networks in space (i.e., formation-flying satellites acting as a unit) is a drastic shift in thinking and requires entirely new architectures, radio systems (antennas, modems, and media access) and possibly new protocols. Interoperability is the nature and trademark of DSS (Distributed Space Systems) to provide a flexible service architecture.

Conceptually, a number of standards will be needed for the support of the communication infrastructure. The key issues that need to be addressed regarding communications in a formation-flying constellation include: 1179)

- The overall architecture and distribution of processing
- The type of communication that needs to take place among the sensor spacecraft
- Timing and synchronization issues

1.4.10 On-orbit Propulsion

On-orbit (or in-space) propulsion has been a basic need and challenge of spaceborne missions from the early days of space flight - offering an extended application range and enhanced mission capabilities. However, it took a while to develop the concepts of maneuvering capabilities of such actuators/dispensers as apogee kick motors and AVCS (Attitude and Velocity Control System) with the available and evolving technologies. Some typical on-orbit propulsion functions are:

- Insertion into a higher operational orbit. Example: from GTO (Geosynchronous Transfer Orbit) into GEO (Geostationary Earth Orbit).
- Other kick stages to non-GEO orbits (including Earth escape trajectories). Some of the more recent upper-stage systems provide multiple restart capabilities for precise LEO or MEO injection and flexible deployment maneuvers.
- Spacecraft onboard control propulsion (such as station keeping, orbit corrections, reboost services, relocation/station changes, survivability/evasive maneuvers, attitude control, acceleration for deployed appendices, autonomous teleoperations, retrieval/rescue operations, repair/resupply, etc.)
- Demonstrations of alternative propulsion means. The evolution of on-orbit electric propulsion and the demand for low-cost space missions have raised interest in small satellites and in their potential use as parts of satellite formations as well as building units of satellite constellations. Formation flying of small satellites can be used to bring in-orbit spares for failed payloads on larger satellites as well as to replace large satellites by flying the mission on more small satellites, each carrying a single payload. The complexity of formation flying requires also a considerable degree of spacecraft autonomy.

- On-orbit chemical propulsion systems. Traditionally, low-thrust propulsion tasks are accomplished with cold gas or hot gas thrusters (bi-propellant technology). These thrusters, which are quite simple in principle, are perfectly suited to most of the applications (attitude control, etc.). There are some drawbacks to the system. Of course, all gases need to be stored in pressurized tanks. This means that extra weight is added to the spacecraft due to the heavy structure, hermetic seals, piping etc. The specific impulse (Isp) of cold gas thrusters is very low (in the order of two orders of magnitude lower than in electric propulsion systems). Low specific impulse means a relatively large amount of propellant to deliver a given total impulse. The total amount of propellant that can be carried poses a limit to the mission lifetime. - Note: The scope of this text does not consider the history of the numerous on-orbit or Earth-to-orbit chemical propulsion systems.

- Some chemical thruster types are: cold gas thrusters, monopropellant thrusters, bipropellant thrusters, solid propellant thrusters.

1.4.10.1 On-orbit solar electric propulsion (SEP) systems

These systems use electrical power provided by the spacecraft’s solar panels to accelerate a propellant to high velocity creating a reaction which causes the movement of the spacecraft. Electric systems generate thrust by using electric and magnetic processes to heat and/or accelerate a propellant or plasma (charged particles). Electric thrusters have an exhaust velocity normally 2 to 10 times higher than chemical thrusters, which means their efficiency with respect to propellant usage is greater.

Although the trust generated in this fashion is rather small, electric propulsion systems nonetheless provide the capability of raising a satellite’s orbit and/or to maintain platform attitude - thereby offering the potential for considerably extended mission life times. Of course, the operational response of an electric propulsion system is constrained by the available electrical power provided the spacecraft’s solar panels (a typical microsatellite might only be able to provide electrical power of < 100 W). The high specific impulse of an electric propulsion system allows a much higher total \( \Delta v \) than a chemical propulsion sys-
A further advantage of electric propulsion is spacecraft mass reduction: the fuel load on conventional propulsion systems is considerable for long-term missions; the consumable “fuel” of an electric propulsion system is rather small in comparison. The electric propulsion technology can also be used for missions requiring drag compensation. Several thruster technologies have been demonstrated or are being developed for demonstration.

A new era in space (secondary and/or primary) propulsion is evolving, gaining momentum in the late 1990s. Particular interest in electric propulsion comes from formation flight projects as well as from conventional satellite projects covering the entire breadth of satellite classes for enhanced support services. Only the very high specific impulse of electric propulsion will allow future commercial satellites to use more than 50% of their launch mass for payload, to put meaningful scientific payloads into orbit around distant planets like Mercury or the outer planets beyond the asteroid belt, and enable humans to remain in space for long periods of time and ultimately fly to our neighboring planet Mars.

In general, solar electric propulsion (SEP) involves the conversion of electrical energy into kinetic energy of the exhaust gases. The various thruster technologies are classified into three categories based on the method of accelerating the propellant — electrothermal, electrostatic, and electromagnetic. Of these, the electrostatic and electromagnetic concepts have the potential of being very propellant efficient, expressed by a high value of specific impulse (Isp).

1) Electrothermal propulsion systems: arcjets, resistojets (simplest form of electric propulsion). The propellant gas is heated to a higher temperature than can be obtained through combustion processes resulting in higher exhaust velocities and better propellant efficiency (acceleration is provided by electric propellant heating and thermodynamic gas expansion through a nozzle). Typical arcjet propellants are hydrazine (Isp = 5000 - 7000 m/s), hydrogen (Isp = 10,000 - 20,000 m/s), or ammonia. Resistojets operate by direct ohmic heating of the propellant. In arcjet systems, the methods of propellant heating are: DC current heating, AC current heating, RF heating, as well as laser-thermal heating. Arcjets have also been designed using either alternating or direct current. Pulsed arcjets, or PETs (Pulsed Electrothermal Trusters), are similar to DC arcjets, except that instead of a steady current, it pulses resulting from charge and discharge of the input capacitance.

2) EIP (Electrostatic ion propulsion), (electron bombardment ion, radiofrequency ion, field emission electric propulsion/colloid ion, and electron cyclotron resonance/microwave discharge ion thrusters) — the EIP concept uses a high voltage electrostatic field to accelerate positively charged particles (or ions) to large exhaust velocities (acceleration is created by the force on charged particles in the electric field). Many electrostatic systems rely on a gridded system at the exhaust port for containing and producing the high electric field needed to accelerate the ions. Several types of ion thrusters have been developed.

- Ion engine or IPS (Ion Propulsion System). Positive ions are produced by bombarding neutral propellant atoms in a discharge chamber with thermonically excited electrons. Traditional ion engines use three closely separated perforated grids containing thousands of millimeter-sized holes attached to a chamber containing a reservoir of the charged particles. The first grid has thousands of volts applied, and the second grid operates at low voltage. The voltage difference over the gap between the two grids creates an electric field that...
acts to simultaneously extract and accelerate the ions out of the chamber and into space in a single step. The higher the voltage difference, the faster the ions are expelled and the greater the fuel efficiency of the thruster.

- **RIT** (Radiofrequency Ion Thruster) — or **gridded ion engine** (a metallic coil around the outside of the vessel is used to induce a radio frequency field inside the chamber). The RIT technique relies on ion creation by pumping a cavity with radio frequency radiation, usually in an insulated discharge chamber. The ions are then extracted through the exhaust port by an accelerator grid. Thrust levels in the range of tens of mN (milli Newton) have been demonstrated with the RIT-10, developed by the Institute of Physics at the University of Giessen and at EADS Astrium GmbH (Germany, formerly MBB). 1185)

The RF-ion thruster research started at Giessen University in 1962, focusing on a 10 cm diameter ionizer model technology. This RIT-10 type model went into industry (MBB at the time) in 1970. It’s first flight occurred in 1992 on the EURECA mission of ESA. This was followed by scaled-up versions of thrusters with ionizer diameters of: 15, 20, 22, 26, and 35 cm. — RIT advantages: Within the class of gas-discharge electric thrusters, the RF-type seems to be the most suitable for variable thrust levels (scaling-down), because it works without any discharge electrodes, magnetic pole shoes, etc. inside the ionizer. Newer RIT versions provide thrust levels of << 1 mN for minute thrust-level applications. The complete absence of discharge electrodes guarantees in effect a long life time of the thruster. 1186) 1187) 1188)

- Electrostatic colloid thruster. With an electrostatic colloid thruster, droplets of a conductive liquid such as glycerol or sodium iodine are pumped through a needle at a high potential (~ 5-10 kV).

- **FEEP** (Field Emission Electric Propulsion). The FEEP technique relies on a strong electric field, typically 8-15 kV, to directly ionize the surface of a working fluid, typically a liquid metal. The FEEP technology is the only existing thruster capable of accurate thrust modulation in the 1 μN - 1 mN thrust level range. Typical thrust ranges from 1-100 μN are used for drag-free control while thrust levels up to 1 mN are used for small spacecraft AOCS, respectively.

3) **Electromagnetic propulsion systems** (Hall effect, pulsed plasma, and magnetoplasma-dynamic thrusters) — the propellant is ionized and accelerated by the combined interaction of electric and magnetic field forces on the resultant propellant plasma. — All electromagnetic techniques rely upon the production of plasma which is then accelerated to its exhaust velocity by an electromagnetic field to generate the desired thrust. A principle advantage of electromagnetic techniques over electrostatic ones is that plasmas with higher temperature and density (typically by several orders of magnitude) can be confined and directed. This results in higher exhaust velocities and therefore more efficient use of propellant mass. Major thruster types are:

- **HET** (Hall-Effect Thruster). 1189) The so-called **Hall effect** was discovered by the American physicist **Edwin H. Hall** in 1879 (1855-1938), then a graduate student at Johns Hopkins University in Baltimore, MD. In Hall effect thrusters, an axial electrical field and a radial magnetic field are established in the discharge chamber. All Hall thrusters are gridded accelerators which use the body forces on charges in crossed electric and magnetic fields. The most common configurations in use have an axisymmetric cavity in which a radial

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1185) [http://nathanderweise.physik.uni-giessen.de/~dhasselk/Diverses/Loeb~Tab.html](http://nathanderweise.physik.uni-giessen.de/~dhasselk/Diverses/Loeb~Tab.html)
1189) Hall discovered that a magnetic field would skew equipotential lines in a current-carrying conductor. This effect is observed as a voltage (Hall voltage) perpendicular to the direction of current in the conductor.
magnetic field is generated by electromagnets with the field pointing to (or from) the surrounding coil/chamber body from (or to) an inner magnetic pole. Russia has been a long-time leader in the field of Hall thrusters. Typical usage is for orbit raising and station keeping maneuvers. Two types of HETs are in use: SPT (Stationary Plasma Thruster), the technique was mainly developed at the Design Bureau Fakel, and TAL (Thruster with Anode Layer), developed mainly at the Central Research Institute for Machine Building (TsNIIMASH).

In an SPT device, an electric field is established along the axis of the device with the anode located at the non-exhaust end of the ionization chamber and with the cathode located externally or at the exhaust end of the chamber. The applied electrostatic field accelerates the ions into the exhaust flow.

In a TAL thruster the ion production region is positioned more externally than in SPT units. Russia has been using SPT and TAL thrusters for decades (SPT-50, SPT-70, SPT-100, etc.) in such applications as NNSK (North South Stationkeeping), EWSK (East West Stationkeeping), attitude control, orbit injection, and repositioning of spacecraft.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resistojet</th>
<th>Arcjet</th>
<th>SPT (Stationary Plasma Thruster)</th>
<th>Ion Thruster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>N₂H₄</td>
<td>N₂H₄</td>
<td>Xenon</td>
<td>Xenon</td>
</tr>
<tr>
<td>Input electric power (kW)</td>
<td>0.2 - 0.8</td>
<td>0.5 - 2.0</td>
<td>0.15 - 1.5</td>
<td>0.4 - 2.0</td>
</tr>
<tr>
<td>Thrust (mN)</td>
<td>200 - 800</td>
<td>200 - 250</td>
<td>40 - 200</td>
<td>15 - 40</td>
</tr>
<tr>
<td>Specific Impulse, Isp (m/s)</td>
<td>2,700 - 3,000</td>
<td>4,500 - 6,000</td>
<td>16,000</td>
<td>28,000 - 35,000</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.9</td>
<td>0.33</td>
<td>0.48</td>
<td>0.75</td>
</tr>
<tr>
<td>Mission life (hours)</td>
<td>&gt;390</td>
<td>&gt;830</td>
<td>&gt;4000</td>
<td>&gt;8000</td>
</tr>
</tbody>
</table>

Table 56: Typical performance values of some electric propulsion systems

- **PPT** (Pulsed Plasma Thruster). The plasma is created by an arc discharge from a capacitor across a pair of electrodes. The ions in the plasma are then accelerated by the Lorentz force in the induced magnetic field. The PPT technique generates plasma by ablating a solid block of spring-fed Teflon. PPTs are of particular interest for space exploration and exploitation since they essentially combine the advantage of continuously operated high-power MPD (Magneto Plasma Dynamic) thrusters with low average electric power consumption and manageable heat generation. Example: NASA's EO-1 mission uses the PPT technique.

PPTs are considered an attractive propulsion option for stationkeeping and drag makeup purposes for mass- and power-limited satellites that require an impulse in the range of micro-Newton second (μNs) to milli-Newton second (mNs). The μPPT can deliver an impulse bit in the 10 μNs range to provide attitude control and stationkeeping for microsatellites. ¹¹⁹⁰

- **MPD** (Magneto Plasma Dynamic) thrusters. The MPD arcjet evolved from electrothermal arcs and magnetogasdynamic technology and is sometimes referred to as a Lorentz Force Accelerator. The potential difference between electrodes ionizes the inflowing neutral gas. Once ionized, the plasma is accelerated by both Joule heating and electrodynamic forces. The current carrying plasma interacts with a magnetic field resulting in a Lorentz acceleration which expels the plasma. The Lorentz force provides the dominant acceleration mechanism.

- **ECR** (Electron Cyclotron Resonance) thruster. ECR is an electrode-less technique using a microwave waveguide to deliver the energy for ionizing a gas. Circularly polarized transverse-electric mode radiation is absorbed by the small population of free electrons constrained to move in cyclotronic paths within the plasma chamber in a magnetic field produced by an external surrounding solenoid.

Some remarks on the units of the specific impulse:
In the International System of Units [SI], the unit of specific impulse (Isp) is newton-seconds per kilogram or Ns/kg. Hence, Isp is the impulse (a force applied for a second) exerted with 1 kg of propellant. It follows that the higher the specific impulse, the greater the performance of the engine and the less propellant required. The numerical value of the specific impulse also corresponds to the effective exhaust velocity (m/s) of the gas exiting the thruster in a vacuum. However, in the literature the Isp is widely expressed in units of pound-thrust per pound-weight per second, with a remaining unit of “seconds” for Isp. When comparing these “Isp second” values with those of the SI system, then the “Isp second” values have to be multiplied by the factor 9.81 m/s² to account for the pound-force to pound-mass ratio and to obtain the unit m/s of the SI system. In this documentation all Isp values are given in the SI system.

<table>
<thead>
<tr>
<th>Type of electric engine</th>
<th>Input Power (W)</th>
<th>Isp (m/s)</th>
<th>Thrust (mN)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arcjet</td>
<td>750</td>
<td>4,700</td>
<td>115</td>
<td>IRS, University of Stuttgart, Germany</td>
</tr>
<tr>
<td>Resistojet</td>
<td>500</td>
<td>2,900</td>
<td>372</td>
<td>Primex, USA</td>
</tr>
<tr>
<td>Resistojet</td>
<td>600</td>
<td>2,150</td>
<td>270</td>
<td>SSTL, UK</td>
</tr>
<tr>
<td>Ion</td>
<td>740</td>
<td>29,000</td>
<td>28</td>
<td>MELCO, Japan</td>
</tr>
<tr>
<td>Ion</td>
<td>600</td>
<td>31,500</td>
<td>18</td>
<td>MMS, France</td>
</tr>
<tr>
<td>Hall</td>
<td>100</td>
<td>8,700</td>
<td>5.7</td>
<td>KeRC (Keldysh Research Center) Russia</td>
</tr>
<tr>
<td>Hall</td>
<td>200</td>
<td>13,700</td>
<td>11.7</td>
<td>KeRC, Russia</td>
</tr>
<tr>
<td>Hall</td>
<td>300</td>
<td>15,600</td>
<td>18.5</td>
<td>KeRC, Russia</td>
</tr>
<tr>
<td>Hall</td>
<td>600</td>
<td>14,500</td>
<td>36</td>
<td>Busek, USA</td>
</tr>
<tr>
<td>Hall</td>
<td>207</td>
<td>12,600</td>
<td>12.4</td>
<td>Busek, USA</td>
</tr>
</tbody>
</table>

Table 57: Performance parameters of some low-power electric propulsion systems

Background / applications: The Russian engineer Valentin P. Glushko (1908-1989) was a pioneer of electric propulsion. While attending the St. Petersburg State University (1925-1929) he had the idea of designing an interplanetary spacecraft powered with electric engines. However, in 1929 he started his career at the St. Petersburg GDL (Gas Dynamics Laboratory), who were the builders of the earliest Russian liquid rocket engines. From 1974-1989, Glushko was the chief designer of NPO Energia.

Research on HET (Hall-effect Thruster) technology started in the early 1960s notably in the Soviet Union. Research and development of the PPT (Pulsed Plasma Thruster) technology has been started in the 1950s. The first spaceborne PPT system was flown on the Soviet satellite Zond-2 (launch Nov. 30, 1964). The Zond-2 S/C, on its way to Mars, was equipped with secondary electric thrusters. The Yantar-1 satellite (launch Oct. 1, 1966 from Kapustin Yar into a 400 km orbit), a Soviet military surveillance S/C built by TsKB, flew the first argon ion engine. In Feb. 1972, the Soviet Meteor-1-10 S/C (launch Dec. 29, 1971) was the first satellite to correct its orbit with an SPT engine. Since 1971, Soviet/Russian spacecraft (more than 20 missions) have been using low-power xenon plasma thrusters, referred to as SPT (Stationary Plasma Thrusters), for station-keeping and on-orbit maneuvering functions on the Express communication satellite series. The early SPT family engines (SPT-60 and SPT-70) were manufactured by EDB (Experimental Design Bureau) Fakel Company of Kaliningrad, Russia.

EDB is also a partner in the International Space Technology, Inc. (ISTI) joint venture (formed in 1993) that includes the Aerojet division of GenCorp of Sacramento, CA, SS/L (Space Systems/Loral) of Palo Alto, CA, and the SEP division of SNECMA, France.

1192) http://www.astronautix.com/astros/glushko.htm
objective of ISTI is to adapt Fakel thruster to Western-built satellites, in particular communication satellites. Fakel-based technology is even finding its way aboard US military satellites. LMSS (Lockheed Martin Space Systems) Co. of Sunnyvale, CA, has selected Fakel electric thrusters, provided by Aerojet, for use on the USAF AEHF (Advanced Extremely High Frequency) communication satellites.  

A list of early Russian electric propulsion systems, used for NNSS stationkeeping, is given in Table 58. The design lifetime of M-70 (or SPT-70) is no less than 5,000 hours. So far, no thruster failure was reported. Since 1994 the SPT–100 are exploited in space with a nominal power of 83 mN and a specific impulse 1600 s.

Further SPT-100 thrusters are being used on the following GEO spacecraft: Telstar-8 (launch June 23, 2005), Intelsat-10-2 (launch June 17, 2004), Inmarsat-4 (launch June 25, 2001), GE Americom, iPSTAR-1 (launch Aug. 11, 2005), and MBSAT (launch March 12, 2004) of Japan’s Mobile Broadcasting Corporation.

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Orbit</th>
<th>Thruster type (quantity)</th>
<th>Launch date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kosmos-1366 (Potok-1)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>18.05.1982</td>
</tr>
<tr>
<td>Kosmos-1540 (Potok-2)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>02.03.1984</td>
</tr>
<tr>
<td>Kosmos-1700 (Luch-1)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>25.10.1985</td>
</tr>
<tr>
<td>Kosmos-1738 (Potok-3)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>04.04.1986</td>
</tr>
<tr>
<td>Kosmos-1888 (Potok-5)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>01.10.1987</td>
</tr>
<tr>
<td>Kosmos-1897 (Luch-2)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>26.11.1987</td>
</tr>
<tr>
<td>Kosmos-1961 (Potok-6)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>02.08.1988</td>
</tr>
<tr>
<td>Kosmos-2054 (Luch-4)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>27.12.1989</td>
</tr>
<tr>
<td>Kosmos2085 (Potok-7)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>19.07.1990</td>
</tr>
<tr>
<td>Kosmos-2172 (Potok-8)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>22.11.1991</td>
</tr>
<tr>
<td>GALS-1</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>20.01.1994</td>
</tr>
<tr>
<td>Kosmos-2291 (Potok-9)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>21.09.1994</td>
</tr>
<tr>
<td>Express-1</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>13.10.1994</td>
</tr>
<tr>
<td>Luch-3</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>16.12.1994</td>
</tr>
<tr>
<td>GALS-2</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>17.11.1995</td>
</tr>
<tr>
<td>Kosmos-2319 (Potok-10)</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>30.08.1995</td>
</tr>
<tr>
<td>Luch-1</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>11.10.1995</td>
</tr>
<tr>
<td>Express-2</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>26.09.1996</td>
</tr>
<tr>
<td>Express-A-2</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>12.03.2000</td>
</tr>
<tr>
<td>SESAT (Eutelsat consortium)</td>
<td>GEO</td>
<td>SPT-100 (8)</td>
<td>18.04.2000</td>
</tr>
<tr>
<td>Potok-11</td>
<td>GEO</td>
<td>M-70 (4)</td>
<td>05.07.2000</td>
</tr>
<tr>
<td>Express-A-3</td>
<td>GEO</td>
<td>M-100 (8)</td>
<td>24.06.2000</td>
</tr>
<tr>
<td>Express-A-4</td>
<td>GEO</td>
<td>M-100 (8), T-120 (1)</td>
<td>10.06.2002</td>
</tr>
</tbody>
</table>

Table 58: Communication S/C of NPO PM, Russia, with SPT electric propulsion systems

At the start of the 21st century, electric propulsion is being considered/introduced in ever more space applications (mission types: EO, science, defense, commercial, etc.), and in all

1197) Note: The original thruster series designation of Fakel Company was M-70, M-100, etc. The SPT (Stationary Plasma Thruster) designation came about in the 1990s to make the name and technology more understandable for western engineers involved in electric propulsion thrusters. While the M-70 and SPT-70 are the same product, the SPT-100 represents a modification of the M-100 thruster.
types of orbits from LEO, MEO, GEO, HEO, to deep space missions. Still, there is plenty of
room left for new technology introduction. The goal is also to use electric propulsion sys-
tems in formation flight applications of constellations [a most demanding application is
sparse aperture interferometry as used for the JWST (James Webb Space Telescope) space-
craft of NASA with ESA and CSA cooperation; and the LISA (Laser Interferometry Space
Antenna) mission of ESA/NASA] requiring a considerable degree of position control.
Furthermore, micropropulsion systems are being needed for a variety of applications from drag
control to microsatellites. 1199) - The increasing use of EP on modern S/C introduces differ-
ent operational requirements on the launcher than for conventional spacecraft. These re-
quirements involve issues such as:
- Injection strategies
- Ground operation and control
- Relaxation of launch windows

Some examples of electric propulsion system introduction on spacecraft:

- Electrothermal propulsion systems (arcjets, resistojets):
  - ARGOS of DoD (SMC/TE at Kirtland AFB, NM), launch Feb. 23, 1999. The space-
craft uses arcjet propulsion technology for orbit transfer, maneuvering capability, and atti-
dude adjustment. The electric propulsion system is ESEX (Electric Propulsion Space Ex-
periment), built by TRW. Demonstration of the largest electric propulsion system (26 kW of
power input) so far (orbit raising). The ESEX system employs an ammonia arcjet.
  - UoSAT-12, the first minisatellite of Surrey (launch April 21, 1999), employs a resistojet
electric propulsion system. The thruster can impart velocity changes of up to 10 m/s to the
spacecraft.
  - SNAP-1 (launch Jun. 28, 2000), an SSTL nanosatellite of 8.3 kg total mass using a mi-
crothruster of 30 μN with a Δv capacity of 3 m/s. The SNAP-1 micro-propulsion system, the
size of a pencil, is also using butane as a cold gas system (note: butane and xenon are consid-
ered “green” propellants). The propulsion system is used to maneuver SNAP-1 to rendez-
uvous with Tsinghua-1 of the University of Beijing (see D.52.17 and D.52.18). 1200) 1201)
  - The AMSAT-P-3D [Amateur Satellite-Phase-3D, now called AMSAT-Oscar 40
(AO-40), launch Nov. 15, 2000 from Kourou into HEO (Molniya-type orbit)] spacecraft
employs a low-power arcjet thruster by the name of ATOS (Arcjet Thruster on OSCAR Sat-
ellite) for on-orbit fine control of the S/C (also for orbit-raising and inclination control).
ATOS was developed at IRS (Institut für Raumfahrtsysteme) of the University of Stuttgart,
Germany and funded by DLR. ATOS is a 750 W ammonia arcjet with a specific impulse Isp
of 4600 m/s. Orbit maneuvers are achieved by a separate 400 N chemical thruster.
- Alsat-1 (Algeria Satellite-1) is a microsatellite of CNTS (Centre National des Tech-
niques Spatiales), Arzew, Algeria. 1202) 1203) The S/C was developed and built at SSTL
(launch Nov. 28, 2002) and is the first S/C in the DMC (Disaster Monitoring Constellation)
of SSTL, Surrey, UK. AlSat-1 carries a resistojet microthruster using 15 W redundant heat-
ers and using butane as propellant. Naturally, the follow-up S/C of DMC, namely BilSat-1
(Turkey), NigeriaSat-1 (Nigeria), and UK-DMC (UK), with a common launch Sept. 27,
2003, feature also resistojet propulsion. In addition, there is a resistojet on Beijing—1 (China DMC+4) with a launch on Oct. 27, 2005.

- The DRTS (Data Relay Test Satellite) of JAXA, Japan, was launched on Sept. 12, 2002 into GTO. A hydrazine AKE (Apogee Kick Engine) brought the S/C into GEO. The dual-mode UPS (Unified Propulsion Subsystem) of DRTS consists of the AKE (20 N thrusters, 1 N thrusters) and a pair of DC arcjet thruster systems for north-south stationkeeping tasks. The DC arcjet system (GenCorp/Aerojet, USA; model: MR-509A/509B) consists of thrusters, PPUs (Power Processing Unit), and power cables. Electric power (1.88 kW) is supplied by solar panels through the NiH₂ battery. The system has a specific impulse of 5,000 m/s (4,500 m/s average). The DC arcjet system has a mass of 30.7 kg (see Ref. 1225). The Japanese name of DRTS is “Kodama” (“echo”).

- PPT (Pulsed Plasma Thruster) systems:
  - The LES-6 (Lincoln Experimental Satellite-6), designed and built by MIT/LL in Lexington, MA, was launched from Cape Canaveral on Sept. 26, 1968. The DoD spacecraft with a mass of 163 kg flew a PPT propulsion system (positioned in GEO). A further demonstration of PPT technology took place on LES-9 with a launch on March 15, 1976.
  - The navigation satellites of the US Navy (designed and built by JHU/APL), namely Triad-2 (also referred to as TIP-2, launched Oct. 11, 1975) and Triad-3 (TIP-3, launched Sept. 1, 1976), were each equipped with a redundant pulsed-plasma thruster (PPT) electric propulsion system, used for drag compensation (drag-free satellite). Three more NOVA satellites, nearly identical to the TIP design, used a PPT propulsion system to compensate for drag. NOVA-1 launch May 15, 1981; NOVA-3 launch Oct. 12, 1984; NOVA-2 launch June 16, 1988.
  - EO-1 (Earth Observing-1) of NASA/GSFC (launch Nov. 21, 2000). A PPT (Pulsed Plasma Thruster) from Aerojet of General Dynamics/OTS (Ordnance and Tactical Systems) Aerospace Operations [formerly Primex Aerospace (formerly Olin (formerly Rocket))] is used to demonstrate on-orbit electromagnetic propulsion technology and to provide a spacecraft precision-pointing capability (complete pitch axis control of the S/C). This is the first flight demonstration of an operations support with PPT throttling capability (see M.10.2).

- Initial demonstrations of the FEEP (Field Emission Electric Propulsion) technology [indium ion emitter type referred to as LMIS (Liquid Metal Ion Source), provided by ARCS (Austrian Research Centers Seibersdorf) for ESA] have been conducted in space on several occasions: the Russian MIR station in 1991; the GEOTAIL mission with a launch on July 24, 1992; on Equator-S with a launch Dec. 2, 1997, and on the Cluster-2 mission in July/Aug. 2000. However, in all of these missions the FEEP technology was utilized for spacecraft potential control or as a mass spectrometer experiment and not for thruster functions. 1206) 1207) 1208)

The FEEP thruster technology offers the advantage of a highly controllable μN thrust level (1-100 μN range/thruster) as well as a very low thrust noise. The technology is being considered/introduced by a number of missions in planning/preparation such as:

- GOCE (Gravity Field and Steady-State Ocean Circulation Experiment) of ESA (launch 2007). Electric propulsion in GOCE is being used for drag force compensation in a LEO (240-270 km altitude) gravity mission configuration. FEEP technology is used for drag compensation. Propulsion requirements call for a total impulse of 6045 Ns, a total operating time of 14,000 hours, a max. thrust level of 650 μN. 1209)

- Microscope (MICROSatellite à trainée Compensée pour l’Observation du Principe d’Equivalence) is an approved CNES/ESA physics research microsatellite mission for a test of the weak Equivalence Principle (launch 2008). 1210) 1211) FEEP propulsion is being used for drag compensation and for high-accuracy attitude control. Four clusters of thrusters are being implemented on Microscope. The instrument performance requirements call for a max. thrust level of 0-150 μN for each thruster, power needs of 80 W (8 thrusters on) and 120 W (12 thrusters on), and a total mass limit of 40 kg.

- ST7 (Space Technology 7) mission of NASA within NMP. The objective is the on-orbit system-level validation of the DRS (Disturbance Reduction System) technology. DRS incorporates a set of μN colloid thrusters, provided by Busek Company. The DRS instrument package consists of two sets of 4 μN thrusters each for position and attitude control, DFACS (Drag—Free and Attitude Control System), and a microprocessor. The descoped DRS will now use the LTP (LISA Test Package) inertial sensors as its drag—free sensors. The ST7 DRS, scheduled to fly on the LISA Pathfinder mission (formerly SMART-2) of ESA in 2009, is designed to maintain the S/C position with respect to GRS (Gravity Reference Sensor) to < 10 nm/(Hz1/2) over the measurement range of 1-30 mHz. 1212) 1213) 1214)

- LISA (Laser Interferometry Space Antenna) mission of ESA/NASA with a planned launch in 2013. 1215) 1216) 1217) The LISA formation will consist of three satellites (265 kg minisatellite) each containing two optical benches. They will be deployed with one launch vehicle at each of the vertices of a slowly rotating equilateral triangle (the LISA arm lengths are 5 x 10^6 km) in a heliocentric orbit. Thus the satellites will form a giant Michelson interferometer. The orbital deployment is designed to maintain the triangular formation, with the triangle appearing to rotate about the center once per year. The center of the triangular formation will be located in the ecliptic plane 1 AU (150 x 10^6 km) from the sun and about 20° behind the Earth (Earth trailing orbit). The objective is to detect gravitational waves from binary galactic systems through very long baseline laser interferometry. The control system for LISA is DRS (Disturbance Reduction System) providing five control functions: a) attitude control, b) DFC (Drag Free Control), c) proof mass suspension control, d) telescope articulation control, and e) point ahead and acquisition control.

1210) Information kindly provided by Olivier Vandermarcq of CNES (project manager of Microscope)
- TPF (Terrestrial Planet Finder) of NASA (launch 2014)
- DARWIN (Detection and Analysis of Remote Worlds by Interferometric Nulling) of ESA (launch 2015)

- The HET (Hall-effect Thruster) technology has been under intensive [governmental and industrial (TsNIIMASH)] investigation in Russia since the early 1990s (see Table 58).

- The first US spacecraft with a Hall thruster is the STEX (Space Technology Experiment) mission of NRO (launch Oct. 3, 1998, end of mission in June 2000). STEX was flying EPDM (Electric Propulsion Demonstrator Module), developed by NASA/GRC, to provide orbit-raising and station-keeping functions (see O.12.2). The TAL-D55 (Thrust with Anode Layer) Hall-effect thruster used in EPDM was developed by the Russian Central Research Institute of Machine Building (TsNIIMASH).

- The ESA mission SMART-1 (Small Mission for Advanced Research in Technology) to the moon with a launch Sept. 27, 2003, employs the HET/STS (Hall-Effect Thruster/Stationary Plasma Thruster) concept, referred to as PPS-1350-G, to use electric propulsion as the primary engine of the S/C on an interplanetary mission. The thruster assembly can be throttled for variable thrust generation: input power of 462-1190 W; variable thrust range of 30-90 mN, Isp of 10,000-16,000 m/s. The PPS-1350-G constitutes the primary propulsion of SMART-1 (370 kg minisatellite) to escape Earth’s gravity for its 16-month cruise to the moon and to stay in lunar orbit for six months. As of Sept. 17, 2005, the PPS-1350-G was shut down (in moon orbit) thus ending all electric propulsion operations of the mission. It had accumulated 4958.3 hours of active firing using a total of 82.5 kg of Xenon fuel.

- The PPS-1350 electric propulsion engine (a model with a lower thrust than the PPS-1350-G version) of SNECMA Moteurs (Paris, France) along with a SPT-100 thruster of Fakel, Kaliningrad, Russia, had also been installed on France’s Stentor communication technology demonstration satellite. Unfortunately, a launch failure of Ariane-5ECA occurred on Dec. 11, 2002 with Stentor as payload (fault of Vulcain 2 exhaust nozzle). 1218) 1219) 1220) 1221)

- The history of EIP (Electrostatic Ion Propulsion) development began in the 1950s at NASA/LeRC (now GRC) and the first ion engine was built in 1959 by Harold Kaufman. First demonstrations in this thruster class were flown on early NASA missions: SERT-1 (Space Electric Rocket Test-1) from Wallops Island on a Scout rocket (launch of SERT-1 July 20, 1964, a suborbital flight); and with SERT-2 (launch Feb. 4, 1970) from VAFB, CA on a Thor Agena vehicle. SERT 2 carried two ion thrusters, one operating for more than five months and the other for nearly three months. Extended ion thruster restarts from 1973 to 1981 were conducted, in addition to cross-neutralization tests. SERT 1 carried one mercury and one cesium engine, while SERT 2 had two mercury engines. 1222) 1223) The EIP technology only reached full operational status in the 1990s. The NSTAR development for the DS1 mission (see below) is a prominent example of the use of EIP techniques in space.

- SCATHA (Spacecraft Charging at High Altitude) S/C of the USAF (launch Jan. 30, 1979) flew the first xenon ion engine, built by Hughes Research Laboratories, Malibu, CA. Hughes started development work on ion engines already in the 1960s.

The ETS-III (Engineering Test Satellite-III; also referred to as Kiku-4) of NASDA demonstrated the first on-orbit operation of a Japanese-developed IES (Ion Engine System) in 1983 (launch of ETS-III on Sept. 3, 1982 from Tanegashima Space Center, Japan). IES, with two electron bombardment mercury ion thrusters of 5 cm anode diameter, was flight tested during the extended mission period from Sept. 1983 to March 1985.\(^{1224}\)

ETS-VI (Engineering Test Satellite -VI; launch Aug. 24, 1994)\(^{1225}\) and COMETS (Communications and Broadcasting Engineering Test Satellite; launch 1998) of NASDA, Japan. Both S/C carried an IES (Ion Engine System) for north-south stationkeeping tasks. However, both satellites failed to reach a geostationary orbit because of a malfunctioning apogee kick engine and/or launch vehicle failure. Therefore, both ion engine systems were operated as an experiment.

![Schematic illustration of the NSTAR/IPS engine on DS1 (image credit: NASA)](image)

Figure 25: Schematic illustration of the NSTAR/IPS engine on DS1 (image credit: NASA)

- DS1 (Deep Space 1) mission of NASA/JPL (launch Oct. 24, 1998) employs IPS (Ion Propulsion System), designed and built by the NSTAR team [the IPS is also referred to as NSTAR(NASA SEP Technology Application Readiness)]. NSTAR was built by Being ETI (Electron Technologies Inc.) for NASA/GRC and NASA/JPL. It is the first time that IPS technology was demonstrated as the spacecraft’s primary engine (smooth and continuous IPS operation from Nov. 24, 1998 for over 200 days) throughout the prime mission which ended in Sept. 1999 (total IPS operation time of about 3000 hours). This was followed by the Extended Mission in which IPS accumulated a total of 16,265 hours of operation and processed approximately 72 kg of xenon. At the end of the Extended Mission for DS1, which successfully flew by the comet Borrelly (flyby on Sept. 22, 2001), NASA executed the Hyper-Extended Mission that was designed to evaluate the wear on the ion engine after extended operation in space.

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The NEXT (NASA’s Evolutionary Xenon Thruster) is an evolutionary design/development program of an ion propulsion system (based on NSTAR) by NASA/GRC which started in 2001. The NEXT system is targeted for robotic exploration of the outer planets using a 25 kW-class solar-powered electric propulsion.\(^{1226}\)

- The ARTEMIS data relay satellite of ESA in GEO \(^{1227}\) (launch July 12, 2001, see M.4), built by Alenia Spazio of Rome, Italy, includes also a xenon electric propulsion thruster system (redundant systems: RITA (Radio-frequency Ion Thruster Assembly) built by EADS Astrium GmbH, Ottobrunn, Germany, and EITA (Electron-bombardment Ion Thruster Assembly) built by QinetiQ, UK. The RIT-10 system, a predecessor of RITA, was already test-flown on the EURECA-1 mission (launch July 31, 1992 - retrieval of EURECA, July 1, 1993). \(^{1228}\)

ARTEMIS rescue mission: ARTEMIS is the first spacecraft in history whose mission was salvaged by the availability of electric propulsion (flexible propulsion architecture using bi-propellant and ion propulsion). \(^{1229}\)\(^{1230}\) An upper stage malfunction of Ariane-5 resulted in a useless orbit with a perigee of 592 km, an apogee of 17,518 km, and an inclination close to 3° (the nominal GTO called for a perigee of 857 km, an apogee of 35,837 km, and an inclination of about 2°). The failure orbit represented a shortfall of about 500 m/s in injection velocity. -- The liquid apogee kick motor then raised the orbit into a 31,000 km circular parking orbit (5 near-perigee and 3 apogee maneuvers were performed, with sufficient fuel left for S/C east-west stationkeeping and attitude control using a 10 N RCS over the design life), and still about 5000 km short in altitude to GEO. The parking orbit was achieved on Aug. 24, 2001. -- The final orbit raising maneuver employed an IPP (Ion Propulsion Package), carried on board for north-south stationkeeping and maintenance functions and not for any orbit boost functions of the S/C. In stationkeeping configuration, the thrust direction of the ion engines is perpendicular to the orbital plane. The rescue operation, however, required thrust to be generated in the orbital plane. This could only be realized by rotating the satellite in the orbital plane by 90° with respect to its nominal orientation. The actual ion-propulsion phase started on April 4, 2002 using a single functional ion thruster (RITA) and gaining between 12-14 km of altitude every day; the final geostationary orbit at about 36 000 km was reached by the end of January, 2003. This is a remarkable accomplishment of ion propulsion considering the S/C launch mass of 3,100 kg (550 kg payload, and 1,538 kg of bi-propellant). All orbit raising maneuvers were performed by a dedicated team of ESA, Alenia Spazio S. p. A., and EADS Astrium GmbH at the Telespazio center in Fucino, Italy. The deorbiting maneuvers of the S/C after mission end (a design life time of 10 operational years) will make use of the ion propulsion thruster with the remaining 25 kg of xenon. Since April 2003, ARTEMIS has been routinely providing high-data-rate links to France’s SPOT-4 and ESA’s Envisat missions. Both the optical and Ka-band links are providing very-high-quality image transmission.


- MUSES-C (Mu Space Engineering Satellite; launch May 9, 2003), a deep space asteroid sample return mission of JAXA (formerly ISAS), Japan (Note: MUSES-C is also referred to as Hayabusa). The target asteroid is Itokawa (1998SF36). MUSES-C carries an IES (Ion Engine System) in combination with a microwave ECR (Electron Cyclotron Reso-

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nance) discharge system. ECR generates plasma which is introduced into a discharge chamber with permanent magnets to take advantage of electrode-less plasma production. In this design, a single microwave source feeds power to a neutralizer which features a small microwave antenna as well as an ion source. The new IES [system thrust of 5.2 - 23.6 mN; system input power of 0.31 - 1.1 kW; specific impulse of about 30,000 m/s; system mass = 61.8 kg; lifetime >16,000 hours; xenon mass of <73 kg; the 4 ion thrusters provide a Δv of about 3.7 km/s] is being used as the primary propulsion system to propel MUSES-C from a sun-synchronous orbit into a deep space orbit, asteroid orbiting, sample gathering, and return flight to Earth (see Ref. 1225). The overall mission scenario calls for an Earth swing-by one year after launch (the gravity assist maneuver took place May 19, 2004), spacecraft arrival at the target in Oct. 2005, two months of close target observations and sampling after landing. The rover MINERVA (MIcro/Nano Experimental Robot Vehicle for Asteroid) was intended to be deployed onto the surface when the spacecraft touches the asteroid. 1231) 1232)

In Nov. 2005, the spacecraft performed five descents, among which two touch-down flights were included. Actually Hayabusa made three touching-downs and one long landing on the surface of Itokawa during those two flights. 1233)

In the aftermath of the various touch-downs, JAXA was not able to reconstructed the events any more. In early March 2006, JAXA officials said they had re-established communications with the Hayabusa spacecraft, and they managed to estimate the probe’s trajectory for the first time in three months. Hayabusa veered off-course on Dec. 8, 2005 due to some unknown event that JAXA described as a ”strong attitude disturbance.” The operations team continues its efforts to have Hayabusa back to Earth by June 2010. – Originally, a S/C landing on Earth was planned for 2007.

• **On the commercial side** (communications satellites), on-orbit electric propulsion makes great inroads. The US Telstar 401 communications satellite of AT&T (launch Dec. 16, 1993 into GEO) employed the first arcjet system flown (also first use of S7000 bus platform of Martin Marietta Astro Space). Later, the Lockheed Martin S7000 platform series communication satellites, such as Intelsat-8, TelStar-IV, and Echostar, continued to use hydrazine arcjets for NSSK functions. Hughes is supplying xenon ion engines as an option on high-powered versions of the HS-601 platform.

PanAmSat-5 (PAS-5) of PanAmSat Corp., a telecommunications satellite launched July 30, 1997 (and launch of PanAmSat-1R launch Nov. 15, 2000), use XIPS (Xenon Ion Propulsion System), built by HSC of Hughes Electronics Corp., Los Angeles, CA) on the HS-702 platform for station keeping and attitude maintenance. In the latter case, XIPS is the spacecraft’s sole means of station keeping. By the end of 2000, 12 communication satellites were using XIPS and variations thereof. On the 702 platform, XIPS has an active grid diameter of 25 cm, Isp = 37,000 m/s (3,800 s), thrust = 165 mN (max), input power of 4.5 kW. The mass of XIPS is 55 kg.

Note: As of Oct. 2000, BSS (Boeing Satellite Systems) acquired three units within Hughes Electronics Corporation. XIPS is now being manufactured by Boeing Electron Dynamic Devices, Inc. – More recent launches of the BSS 702 platform, like the Anik-F2 communications satellite of Telesat (launch July 17, 2004), Canada, employ the XIPS also to augment final orbit insertion, thus conserving even more mass as compared to using only an onboard liquid apogee engine. – SSL (Space Systems/Loral) and ASI (Alcatel Space Industries) are manufacturing communication satellites (Telstar-8 and Astra-1K, respective-
ly) which use SPT (Stationary Plasma Thrusters) type electric propulsion systems to support such functions as stationkeeping. (1234) (1235) (1236) (1237)

The Russian company Fakel Design Bureau in Kaliningrad produces the SPT-100 electric propulsion system for many applications in the commercial satellite market. SNECMA of Paris, adapting technology developed by Fakel Design Bureau, has provided the SPT-100 system for Astra-1K, owned by SES of Luxembourg (provision of NSSK for Astra-1k). EADS Astrium SAS is using the SPT-100 system of SNECMA on three Inmarsat-4 mobile communication satellites, owned by Inmarsat Ventures, London (operational availability in 2005, Inmarsat-4F2 was launched on Nov. 8, 2005). - The function of electric orbit raising is also being considered for large communication satellites. An arcjet electric propulsion system of General Dynamics (Primex) had its first flight in 1994.

As of January 2001, there were over 100 Primex arcjets in orbit (160 as of 20006). As of 2002, General Dynamics Space Propulsion Division (Aerojet) in Redmond, WA, and Lockheed Martin Space Systems of Sunnyvale, CA, are jointly developing an electric propulsion system called BPT-4000 (Busek Primex Thruster) - a xenon Hall effect thruster with 4.5 kW power input (max). The qualification of HTPS (Hall Thruster Propulsion System), as it is referred to at Aerojet, was completed in 2006. The first flight of the BPT-4000 system is scheduled for mid-2008. The HTPS consists of the following Aerojet—supplied products: a) the 4.5 kW BPT-4000 Hall thruster; b) the PPU (Power Processing Unit); c) and the XFC (Xenon Flow Controller). The BPT-4000 will be used for orbit insertion, orbit maintenance, and repositioning of geosynchronous satellites. (1238)

<table>
<thead>
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<th>Parameter</th>
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<th>4.5 kW version</th>
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</thead>
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<td>290 mN</td>
</tr>
<tr>
<td>Thrust (400 V)</td>
<td>170 mN</td>
<td>254 mN</td>
</tr>
<tr>
<td>Specific impulse, Isp (300 V)</td>
<td>1750 s (17,000 m/s)</td>
<td>1850 s (18,000 m/s)</td>
</tr>
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<td>1920 s (18,800 m/s)</td>
<td>2020 s 19,800 m/s)</td>
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<tr>
<td>Life capability</td>
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</tr>
<tr>
<td>Total impulse</td>
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</tr>
<tr>
<td>On-off cycles</td>
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<tr>
<td>Input power, input voltage</td>
<td>1 to 4.5 kW, 200 or 400 V</td>
<td></td>
</tr>
</tbody>
</table>

Table 59: Characteristics of the BPT-4000 thruster performance

Figure 26: Illustration of the BPT-4000 thruster

1234) http://www.hughespace.com/factsheets/xips/xips.html
For large telecommunication satellites (EuroStar-3000 of Astrium and Spacebus-4000 platforms of Alcatel) a new version of the Hall-effect thruster, called PPS-1350-G, has been designed and developed by SNECMA Moteurs (Paris) with the objective for GEO NSSK (North-South Stationkeeping) and to reduce the manufacturing cost of the thruster. The lifetime of this thruster is about 11000 hours [thrust of 85 mN, Isp = 16,000 m/s, power input of 1.5 kW]. PPS-1350-G is an upgrade of the standard model PPS-1350. The PPS-1350-G is foreseen for late 2004. 1239)

1.4.10.2 Solar sails

Solar sailing is an alternate form of spacecraft propulsion. Rather than carrying propellant, solar sails refer to spacecraft propulsion concepts, which utilize the momentum transfer of photons (solar radiation pressure) on very large, highly reflecting sails in space for passive propulsion and orbit transfer functions. The combination of ultra-light weight solar sail structures with micro/nano technologies opens a wide field of space applications. Since solar sails are not limited by a reaction mass, they can provide continual acceleration, limited only by the lifetime of the sail film in the space environment. On a long-term perspective, the solar sail technology offers the potential, to expand the envelope of possible missions (within the solar system), enabling new high-energy mission concepts that couldn’t be done with conventional reaction propulsion. The design of a solar sail assembly poses a number of technology challenges, some are listed: 1240) 1241) 1242)

- Rather large surface areas of solar sail are needed to intercept a large flux of photons (the solar radiation pressure is very small - yielding only a small momentum)
- The fabric of solar sails must be extremely light (<20 g/m²) to be able to generate as high an acceleration as possible from the momentum transported
- The mass per unit area of the entire S/C, the so-called sail loading, may be of the order of 20-30 g/m²
- The sail assembly loading is a key measure of technology, in addition to the sail loading. The sail assembly loading is defined as the ratio between the mass of the sail structure plus reflective film (excluding the payload and the bus), and the sail area.
- Solar sails must be near-perfect reflectors to maximize the momentum. By adding the forces due to incident and reflected photons, the total force exerted on the sail is directed almost normal to its surface.
- By controlling the orientation of the sail relative to the sun-line, the sail can gain or lose orbital angular momentum. - Achieving a useful characteristic acceleration in the order of 0.1-1 mm/s² (at 1 au) from solar radiation pressure poses great challenges in terms of innovative technology demonstration of low-mass deployable structures, thin-film sails, and also of payload miniaturization.
- In-orbit deployment. The successful functioning of the solar sail structure deployment procedure and mechanism (after orbit attainment of the solar S/C) represents currently the greatest technical challenge in the solar sailing concept.

The solutions to these challenges must be demonstrated in space before solar sail propulsion is considered to be viable for any mission.

A systematic study of solar sail material (fabric) characteristics was conducted by NASA/MSFC evaluating the thermo-optical and mechanical properties after exposure to a simu-

lated GTO radiation environment. Testing of four materials: aluminized Mylar (DuPont), aluminized Mylar with chromium backing, aluminized Kapton (DuPont), and aluminized CP1 (Colorless Polyamide 1) of SRS Technologies. As of 2003, the thinnest commercially available Kapton films are 7.6 μm in thickness with an area density of 11 g/m². 1243)

**Background:** The concept of solar sailing appears to have been first conceived by Russian space enthusiasts Konstantin Tsiolkovsky (1857-1935) and Friedrich Zander (Fridrikh Tsander, 1887-1933) in the early 1920s. A solar sail works by photon pressure from sunlight, a radial force from the sun into the direction of the universe (Note: the amount of pressure from the solar wind is negligible in comparison to the photon pressure). When light reflects from the surface of a body, the momentum of the light is reversed in direction. As a result, the body experiences a force proportional to the power in the light divided by the speed of light: \( F = \frac{2P}{c} \)

where the factor 2 assumes normal incidence for the light on the reflective surface. 1244)

Since the solar energy, arriving at the top of the atmosphere, amounts to about 1.366 kW/m², the solar force per unit area is about 9.3 N/km² or \( F = 9.3 \times 10^{-6} \) N/m² (the force or solar radiation pressure on 1 m² of sail surface normal to the sun). A solar sail can be steered by tilting the sail to vary the direction of the force vector (see also solar sail in Glossary).

Although the basic idea behind solar sailing is simple, challenging engineering problems have to be solved. Hence, practical experience with “solar sail missions” is rather limited so far. The following list provides an overview of some solar sailing attempts (demonstrations) by various organizations. In spite of the meager progress made so far in solar sail technology development (the deployment problem must be conquered), it can safely be stated that there is a definite future (beyond 2010) for a great variety of solar sail applications in space.

- The first spaceborne application of solar radiation pressure has been used for passive attitude control of spacecraft. The Mariner-10 interplanetary mission of NASA/JPL (launch March 11, 1973) was the first spacecraft using the sun-sail concept for maneuvering by using the pressure of sunlight reflecting off of the solar panels for attitude control. This technique permitted the project to extend the mission life. 1245) Since then, many spacecraft in Earth orbit have employed some form of small sun-sail attitude control.

- Interest in solar sailing was first generated, when a NASA/JPL study proposed a rendezvous mission with Comet Halley, employing the solar sailing concept, in the mid-1970s. Unfortunately, the project could not attain flight readiness for an encounter in 1986.

- In 1990 RSC Energia of Korolev (Moscow region), Russia, as the lead sponsor, formed SRC (Space Regatta Consortium - an association of 15 enterprises) with the objective to promote, develop and demonstrate satellite-based solar sails, so-called solarcraft (large deployable structures based on thin-film sails). The first practical step toward this end was Znamya-2 (Banner), a demonstration experiment conducted on Feb. 4, 1993, when a segmented spinning disk sail (20 m in diameter, about 22 g/m² area density) was deployed by centrifugal forces from the Progress M-15 spacecraft, docked at the MIR space station (the experiment included verification of the system concept, stability and control of the structure, etc.). The Znamya-2 experiment represents the first solar sail deployment experiment in space. It consisted of eight pie-shaped panels fabricated from 5 mm thick aluminized PETF film (a Russian version of Mylar) with no supporting structure.

- In parallel to the Znamya-2 deployment, a further experiment, “Novey Svet” (New Light) was conducted on the same solar sail structure with the objective to illuminate Earth

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1244) L. R. Forward: http://www.transorbital.net/Library/D001_S03.html
from space. The first illumination from space took place in the early morning hours before sunrise over Western Europe. A reflected spot of light of about 5 km in diameter travelled from southern France through Switzerland, Germany, Czech Republic, and Poland, it then disappeared in the early sunlight of Belarus.

- A second Znamya experiment, called Znamya-2.5, from MIR (actually the departing service vehicle Progress M-40) took place on Feb. 4, 1999 with a 25 m diameter sail (solar reflector) structure. The objective of Znamya-2.5 was to demonstrate beaming of solar power (reflected sunlight) from space to Earth for artificial target illumination (spot light of 5-7 km in diameter) under controlled conditions; also test of film structure and test of prolonged illumination. However, a problem in the deployment mechanism resulted in an abort of the demonstration.

- The Cosmos-1 Solar Sail Project, a privately funded venture of the Planetary Society, Pasadena, CA (sponsor: Cosmos Studios). The objective is to conduct a solar sail demonstration flight. In a first step, a sub-orbital test flight of an inflatable tube sail deployment system (600 m² of Mylar sail) on a Volna launch vehicle (a converted SS-N 18 ICBM) took place on July 23, 2001 (submarine launch from Barents Sea). The Russian Babakin Space Center is the prime contractor and spacecraft integrator for the Planetary Society. The projected sub-orbital flight of the 40 kg S/C was from the Barents Sea to the Kamchatka peninsula (solar sail deployment at 400 km altitude). Initial flight analysis revealed a capsule separation failure (neither the solar sail deployment test nor the re-entry capsule inflation sequence that were planned for this sub-orbital test flight were carried out). The Cosmos-1 test craft was to separate from its capsule and unfurl its two 15 m long, wing-like blades before making a soft landing on Kamchatka.

![Figure 27: Artist's view of the Cosmos-1 spacecraft](image)

In a second attempt, a launch of Cosmos-1 (Solnechny Parus) took place on June 21, 2005 from the submerged Russian Submarine Borisoglebsk in the Barents Sea. However, a launch vehicle failure occurred (Volna rocket) after about 2 minutes into the flight. Hence, flight controllers were unable to confirm any orbit injection of the spacecraft.

This time around, a spacecraft of 103 kg was to be injected into a near circular 800 km orbit with an inclination of 78°. 1246) 1247) The basic deployment and structural technology relied on an inflatable tube system to which the sail material was being attached. The 600 m² sail

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1246) [http://www.planetary.org/solarsail/missions/planetary_solar_sai.html](http://www.planetary.org/solarsail/missions/planetary_solar_sai.html)

was configured in eight roughly triangular blades. The nominal sail material consisted of 5 µm aluminized, reinforced Mylar. Mission success was defined as flying long enough to measurably increase the orbital energy (or period) from sunlight pressure in controlled flight.

As of July 21, 2005, the ‘Volna Failure Review Board’ concluded that the telemetry data from the launch vehicle was sufficient to determine that the launch failed due to a premature shut-down of the first-stage engine caused by a "critical degradation in operational capability of the engine turbo-pump." The engine shut down after firing for 82.86 seconds, instead of the expected burn of approximately 100 seconds. The Failure Review Board concluded also that the first and second stages never separated and, as a result, the spacecraft propulsion system did not fire, and the spacecraft did not separate from the third stage.1248) The review board included members from the Makeev Rocket Design Bureau (manufacturers of the Volna launch vehicle), the Lavochkin Association (which built Cosmos–1) and Tsniimash, a lead engineering center of the Russian Space Agency, Roskosmos.

- As of 2003, a DLR-ESA technology demonstration sailcraft design is based on a previous ODISSEE (Orbital Demonstration on an Innovative Solar Sail driven Expandable structure Experiment) proposal. 1249) 1250) The sailcraft comprises a central deployment module for the sail and four CFRP booms that diagonally support the four sail segments, a microsatellite, and a deployable control mast (connecting the microsatellite to the sail structure via a gimbal mechanism). In this rigging concept, the center of mass can be offset from the center of pressure - thus, using photon pressure as an external force, a torque can be generated to control the attitude of the sailcraft.

In preparation for this mission, a solar sail ground deployment demonstration with a breadboard model (35 kg), conducted by a DLR-ESA-INVENT GmbH project team at DLR Cologne on Dec. 17, 1999, was highly successful. 1251) 1252) During the on-ground solar sail deployment in a time frame of approx. 30 minutes, four CFRP booms as well as four triangular aluminium-coated thin Kapton films were deployed under simulated 0-g and ambient environmental conditions. This deployment experiment finalized the development of a 20 m x 20 m solar sail. In this program, advanced deployable CFRP (Carbon Fiber Reinforced Plastic) booms were developed by DLR. These booms consist of two laminated flexible Ω-shaped sheets which are bonded at the edges to form a tubular shape. Once free of the Solar Sail Boom Deployment Module (BDM), the booms resume their original shape supported by a spontaneous self-deployment. 1253) 1254)

As of 2004, a first ESA mission of a small sailcraft configuration (sail area of 20 m x 20 m) is expected to be launched in 2006 (Kayser-Threde as prime contractor). The mission profile comprises the following mission phases: 1255)

Volna launch (Russia) from submarine and orbit insertion

- Pre-deployment phase including attitude stabilization
- Deployment phase consisting of boom deployment and sail deployment
- Post-deployment phase until reentry into Earth’s atmosphere.

The baseline orbit is defined by an altitude of 400 - 450 km, with an orbital inclination of 78°. The sailcraft is fixed to the fourth stage of the VOLNA rocket which will perform the orbit insertion burn.

- Solar sail deployment experiment with a sounding rocket. On Aug. 9, 2004, JAXA/ISAS (Japan) deployed two types of membrane structures, made of thin polyimide film (7 µm), near apogee (122 km) on a sounding rocket flight. During the ballistic flight, two types of membranes (solar sails) were deployed: a “cloverleaf type sail” and a “fan type sail.” The deployment scenario, using centrifugal force mechanisms, was documented with rocket-mounted cameras and transmitted to ground via telemetry. The cloverleaf sail deployment (10 m diameter) was successful — the first ever successful deployment of a good-sized sail in space, while the fan-type sail deployed only partially. 1256) 1257)

- Team Encounter. The commercial company Team Encounter LLC of Houston, TX, is developing two solar sail missions:
  - A mission called Earthview to demonstrate the deployment and control of a small solar sail, 20 m x 20 m in size. A launch of Earthview on Ariane-5 (as ASAP) in planned for 2005 into GTO (Geosynchronous Transfer Orbit). The spacecraft is being built by MicroSat Systems of Littleton, CO, the sailcraft with the inflatable boom and solar sail (400 m² sail area) are being developed by L’Garde of Tustin, CA. - In Sept. 2003, NASA selected a commercial ride for the demonstration package ISC (Inertial Stellar Compass), namely Team Encounter.
  - A second mission on Ariane-5 with a larger solar sail (4900 m² sail area) 1258) 1259) is planned for 2007. The objective is to transport a 3 kg payload out of the solar system by solar sail propulsion. The spacecraft consists of a rocket-powered ”carrier” to boost the spacecraft out of Earth orbit, and a ”sailcraft.”

- Solar Blade - a mission of CMU (Carnegie Mellon University), Pittsburgh, PA is called “Solar Blade Heliogyro Nanosatellite” (launch in 2005?). The objective is to demonstrate the solar sail concept for attitude precession, spin rate management, and orbital adjustments. The mission is supported within UNP (University Nanosatellite Program) of DoD and NASA. The S/C design concept (total mass of 5 kg) employs four solar reflecting blades, each 30 m x 1 m, constructed from ultrathin polyimide film. The blades are attached to a central spacecraft bus and are pitched along their radial axis. Embedded Kevlar and battens provide added stiffness and resistance to tears.

1.4.10.3 Tether Experiments

Tether experiments in space (see M.46). A space tether is a long cable used to couple a spacecraft with an end mass (conceptually a link between two objects in space). Tethers are usually made of thin strands of high-strength fibers or conducting wires. Although the idea of using space tethers goes back to the 1960s, it was the launch of TSS (Tethered Satellite System) in 1993 on Shuttle mission STS-46, which gave a decisive impetus to tether technology development and projects, by realizing the potential of tethers to meet a broad range of applications in various fields. Tether deployment techniques and stable operations were the

1258) http://www.teamencounter.com/starship/spacecraft_info.asp
dominant themes of the early years including the 1990s. Potential tether applications include: propulsion (orbit changes), payload capture and release, power generation, atmospheric studies [a) reaching otherwise unaccessible flight regions with downward deployed tethers; b) active experimentation with the surrounding plasma], and gravity experiments. First detailed studies of space tether technology were carried out in the 1970s and early 1980s by Giuseppe Colombo (1920-1984) of the University of Padua, Italy. Colombo envisioned that tethers could be used for transferring payloads to higher orbits, building space structures, and generating power for space platforms. This led eventually to the definition of project TSS (Tethered Satellite System). \(^{1260}\) \(^{1261}\)

Since the space tether makes it possible to transfer energy and momentum from one object to another, it can legitimately be called a form of space propulsion. There are two general categories of tethers: \(^{1262}\)

- **Momentum-exchange tethers** (MET, nonconductive tethers representing passive propulsion). These tethers permit momentum and energy to be transferred between objects in space, enabling a tether system to toss spacecraft from one orbit to another.
- **Electrodynamic tethers** (EDT, conductive tethers representing active propulsion and power generation). These tethers interact with the Earth’s magnetosphere to generate power or propulsion without consuming propellant. There are two subclasses:
  - Electrodynamic power or tether drag system.
  - Electrodynamic thrust tether system.

As of the late 1990s spaceborne tethers are indeed an experimental reality (there are numerous projects) and their potential is far from being fully appreciated. The future of tether space technology looks rather bright providing capabilities and low-cost services for many applications. A very active company in this field is TUI (Tethers Unlimited Inc.) of Lynnwood, WA, USA, offering their expertise and a number of solutions such as: \(^{1263}\) \(^{1264}\)

- Terminator, a spacecraft deorbiting system. \(^{1265}\) The Terminator Tether™ is a small device that uses electrodynamic tether drag to deorbit a spacecraft. Because it uses passive electromagnetic interactions with the Earth’s magnetic field to lower the orbit of the spacecraft, it requires neither propellant nor power.
- μPET™ (Microsatellite Propellantless Electrodynamic Tether) propulsion system that will provide propulsive capabilities to microsatellites and other small spacecraft without consuming propellant.
- The so-called Hoytether™ represents a fail—safe tether solution (resistant to impact damage) using synthetic fibers in a weblike arrangement.

<table>
<thead>
<tr>
<th>Mission (Agency)</th>
<th>Launch (Timeframe)</th>
<th>Orbit</th>
<th>Tether Length</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini-11(NASA)</td>
<td>Sep. 11-15,'66</td>
<td>LEO</td>
<td>30 m</td>
<td>Spin-stabilized, 0.15 rpm</td>
</tr>
<tr>
<td>Gemini-12(NASA)</td>
<td>Nov. 11-15,'66</td>
<td>LEO</td>
<td>30 m</td>
<td>Local vertical, stable swing</td>
</tr>
<tr>
<td>H-9M-69</td>
<td>1980</td>
<td>Suborbital</td>
<td>500 m</td>
<td>Partial deployment</td>
</tr>
<tr>
<td>S-520-2</td>
<td>1981</td>
<td>Suborbital</td>
<td>500 m</td>
<td>Partial deployment</td>
</tr>
<tr>
<td>Charge-1</td>
<td>1983</td>
<td>Suborbital</td>
<td>500 m</td>
<td>Full deployment</td>
</tr>
<tr>
<td>Charge-2</td>
<td>1984</td>
<td>Suborbital</td>
<td>500 m</td>
<td>Full deployment</td>
</tr>
</tbody>
</table>

\(^{1260}\)http://infinity.msfc.nasa.gov/Public/ps01/ps02/table1.html

\(^{1261}\)Note: The objective of the Gemini tether missions was to see if tethers could be used for rendezvous and docking in preparation for the future moon missions. A parachute cable was used as the tether, which was attached to the Agena by a spacewalking astronaut. The other mission (Gemini-11) experimented with rotation about the CM (Center of Mass) to see if it was stable - it was. The Gemini missions were not electrodynamic in nature, nor were they performed for scientific purposes - as were the TSS missions.


\(^{1263}\)http://www.tethers.com/index.html

\(^{1264}\)R. P. Hoyt, “The μTorque Momentum-Exchange Tether Experiment,” STAIF 2002 (Space Technology and Applications International Forum), Albuquerque, New Mexico, Feb. 3-7, 2002

<table>
<thead>
<tr>
<th>Mission (Agency)</th>
<th>Launch (Timeframe)</th>
<th>Orbit</th>
<th>Tether Length</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHO-7</td>
<td>1988</td>
<td>Suborbital</td>
<td></td>
<td>Magnetic field aligned</td>
</tr>
<tr>
<td>Oedipus-A (NRC/NASA,CRC, CSA)</td>
<td>Jan. 30, 1989</td>
<td>Suborbital</td>
<td>958 m</td>
<td>Spin-stabilized, 0.7 rpm (Canada/USA)</td>
</tr>
<tr>
<td>Charge-2B</td>
<td>1992</td>
<td>Suborbital</td>
<td>500 m</td>
<td>Full deployment</td>
</tr>
<tr>
<td>TSS-1 (STS-46) (ASI/NASA)</td>
<td>Jul. 31-Aug. 8, 1992,</td>
<td>LEO</td>
<td>&lt; 270 m</td>
<td>Electrodynamic tether, partial upward deployment and retrieval of tether</td>
</tr>
<tr>
<td>SEDS-1 (NASA)</td>
<td>Mar. 29, 1993</td>
<td>LEO</td>
<td>20 km</td>
<td>Nonconducting tether, downward deployment, swing and cut</td>
</tr>
<tr>
<td>PMG (DoD) Plasma Motor Generator</td>
<td>June 26, 1993</td>
<td>LEO</td>
<td>500 m</td>
<td>Electrodynamic tether, upward deployment, tether current in both directions. Demonstration of hollow cathode plasma contactors for current collection and emission</td>
</tr>
<tr>
<td>SEDS-2 (NASA)</td>
<td>Mar. 9, 1994</td>
<td>LEO</td>
<td>20 km</td>
<td>Local vertical stable, downward deployment</td>
</tr>
<tr>
<td>Oedipus-C (NRC/NASA,CRC, CSA)</td>
<td>Nov. 6, 1995</td>
<td>Suborbital</td>
<td>1 km</td>
<td>Spin-stabilized, 0.7 rpm (Canada/USA)</td>
</tr>
<tr>
<td>TSS-1R (STS-75) (ASI/NASA)</td>
<td>Feb. 22-Mar. 9, 1996,</td>
<td>LEO</td>
<td>19.6 km</td>
<td>Electrodynamic tether, severed prior to full deployment</td>
</tr>
<tr>
<td>TiPS (NRO/NRL)</td>
<td>May 12, 1996 Jun. 20, 1996 deployment</td>
<td>LEO</td>
<td>4 km</td>
<td>Long life tether of 2.5 mm diameter (tracking of one year). The tether was still in orbit as of 2000.</td>
</tr>
<tr>
<td>YES (ESA, Delta-Utec, students)</td>
<td>Oct. 30, 1997</td>
<td>GTO</td>
<td>35 km</td>
<td>YES (of TEAMSAT) was deployed; but tether could not be deployed</td>
</tr>
<tr>
<td>STEX/ATEx (NRO/NRL)</td>
<td>Oct. 3, 1998 Jan. 16 1999 deployment</td>
<td>LEO</td>
<td>6 km</td>
<td>Nonconductive tether, planned demonstration of tether system stability and control. However, a deployment malfunction caused an experiment failure</td>
</tr>
<tr>
<td>PICOSAT1.0 (The Aerospace Corpor-</td>
<td>Jan. 27, 2000 on OPAL of Stanford</td>
<td>LEO</td>
<td>30 m</td>
<td>PICOSAT1.0 was ejected OPAL on Feb 6, 2000. The system of two S/C operated for 3 days when battery power decayed.</td>
</tr>
<tr>
<td>ation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PICOSAT1.1 (The Aerospace Corpor-</td>
<td>July 19, 2000 on MightySat II.1 of AFRL</td>
<td>LEO</td>
<td>30 m</td>
<td>PICOSAT1.1 was ejected successfully from MightySat II.1 13 months after launch (Sept. 2001) to test storage effects on the system and to demonstrate ideas on onboard and on-call operations.</td>
</tr>
<tr>
<td>ation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METS (MIR Electrodynamic Tether System)</td>
<td>2001</td>
<td>LEO</td>
<td>5 km</td>
<td>Considered to be the first practical application of non-rocket propulsion in space. However, <strong>METS was never realized but remained in the proposal stage.</strong></td>
</tr>
<tr>
<td>ProSEDS (NASA)</td>
<td>2006</td>
<td>LEO</td>
<td>15 km</td>
<td>Upward deployment (producing drag and electrical power). The tether consists of 5 km bare wire plus 10 km of Spectra tether.</td>
</tr>
<tr>
<td>YES2 (ESA, Delta-Utec, students)</td>
<td>2007</td>
<td>LEO</td>
<td>30 km</td>
<td>Deployment from Foton-M3 satellite of Russia. Demonstration of SpaceMail technology, i.e. delivery of a small payload in a tethered reentry capsule</td>
</tr>
</tbody>
</table>

*Table 60: Chronology of tether missions*
1.4.11 Space Environment Experiments

All spacecraft inevitably interact with their environments. Besides the interactions one immediately thinks of in space (zero-g, solar heating, atmospheric drag, expansion into vacuum conditions, etc.) other interactions are also important. Those of interest to spacecraft designers so far may be grouped under several headings:

- Plasma interactions and spacecraft charging
- Debris and micrometeoroids impact
- Chemical reaction with neutral species
- Radiation degradation

- Satellite surface charging experiments (see also Glossary). The ionizing radiation environment in space represents one of the most severe environment loads to space hardware and can cause a large number of problems such as spurious errors or permanent damage to electronics, erroneous signals in detectors, electrostatic charging of spacecraft or health damage to astronauts. In particular, the electrostatic charge on satellite surfaces can pose a hazard, when differential charging is leading to potential gradients. In some cases this potential build-up causes discharge arcing. Electrostatic charging by the natural space radiation environment is regarded as the most serious source of anomalies of S/C electronics. Hence, in-situ measurement of the space radiation environment is an important prerequisite for the enhancement of the static radiation environment models towards dynamic models which are required for the optimized design of future advanced systems. Examples of missions and experiments are:

- GEOS-1/-2 (Geostationary Satellite) missions of ESA, two reference S/C for IMS (International Magnetosphere Study). Launch of GEOS-1 on April 20, 1977; launch of GEOS-2 on July 14, 1978. The GEOS-1/-2 were the first S/C anywhere to carry a totally conductive coating - even over their solar panels. An electron beam experiment and a pair of probes, 40 m apart, provided independent measurements of the electric field surrounding the S/C. The S/C surface-treatment technology was confirmed.

- SCATHA (Spacecraft Charging at High Altitude), the S/C is also referred to as P78-2. A NASA/JPL mission (launch Jan. 30, 1979; orbit: 28000 km x 42000 km, 8.3° inclination, S/C mass = 360 kg). Experiment SC1 (Engineering+VLF and HF Receivers) measured surface potentials (RF waves between 0-300 kHz and 2-30 MHz) of various S/C materials. SC2 (Spacecraft Sheath Fields + Energetic Ions) measured low energy electrons and ions, energetic protons, and electrons. SC3 (High Energy Particle Spectrometer) measured high energy electrons and protons. SC4 (Satellite Electron and Positive Ion Beam System) used ion and electron beam guns to control spacecraft surface potential. SC5 (Rapid Scan Particle Detector) measured electrons and ions. SC11 (Magnetic Field Monitor) measured DC and ELF magnetic fields. ML12 (Spacecraft Contamination + Thermal Control Materials Monitoring) measured contamination rates and property changes of several thermal control material samples.

- GEOTAIL

- STRV-1a and -1b (Space Technology Research Vehicle, of DERA, UK, see M.41), launch June 17, 1994. Both S/C flew CAE (Charge Alleviation Experiment) to demonstrate an active S/C surface charge alleviation system. Other space environment instruments flown on STRV-1a are: SCDE (Surface Charge Detector Experiment), CID.

1266) http://powerweb.lerc.nasa.gov/prsee/publications/TheBasics.html

1267) Note: Spacecraft surfaces exposed to a charged particle or ultraviolet radiation environment are prone to accumulation of static charge buildup. This set of S/C environment interactions is collectively known as spacecraft charging. Differential surface charging results when charge builds up on a surface dielectric, resulting in a potential that is significantly different from the spacecraft’s frame or other components on the spacecraft’s surface.


1270) http://www.newspace.com/ref/msl/QuickLooks/scathaQL.html
(Cold Ion Detector), LPI (Langmuir Probe Experiment), CREDO-II (Cosmic Radiation Environment and Dosimetry Experiment), and RDRS (Radiation Dose Rate Sensor). Other space environment instruments flown on STRV-1b are: SEE (Space Environmental Effects), and REM (Radiation Environment Monitor). Note: The REM instrument was also flown on the MIR space station starting in Nov. ’94 until Nov. ’96. STRV-1c and -1d (launch Nov. 16, 2000) are follow-up missions of DERA, UK with the environment objectives focused on emerging technology hardware. The ESA device SREM (Standard Radiation Environment Monitor) is flown on STRV-1c. SREM is of REM heritage flown on STRV-1b. - SREM is also being flown on PROBA (launch Oct. 22, 2001, see M.30) and Integral (launch Oct. 17, 2002), both are ESA spacecraft. In addition, SREM is planned to be flown on GSTB (Galileo System Test Bed) scheduled for launch in 2005, and on GOCE of ESA (launch 2007).

- Equator-S (launch Dec. 2, 1997, see K.10) carried PCD (Potential Control Device) to reduce the potential caused by the ambient plasma charging of the outer surfaces.
- SPOT-4 (launch March 24, 1998, see D.46.2) carried SILLAGE to measure electrostatic potentials on the outside of the SPOT satellite which are due to the “wake” effect.
- TSX-5 (Tri-Service Experiments Mission 5) of AFRL (launch June 6, 2000) flies two payloads: a) STRV-2 (Space Technology Research Vehicle) of DERA and AFRL with SAMMES (Space Active Modular Materials Experiment System), and b) CEASE (Compact Environmental Anomaly Sensor) of AFRL.
- Cluster-2 (launch July 16, 2000 of first pair of S/C; on Aug. 9, 2000 the second pair was launched, K.7). The four identical Cluster S/C feature conductive outer surfaces. An extremely low S/C-generated electromagnetic background noise is mandatory for accurate electric field and cold plasma measurements. The solar arrays consist of BSR (Back-Surface-Reflection) cells, arranged in self-compensating formations to minimize the generation of DC magnetic fields. The conductive coating on the cell cover glass minimizes the build-up of differential charge potentials.

- Radiation-hardened components. The adverse effect of the ‘space weather’ (solar wind acting against the Earth’s magnetic field, energetic particle flux, etc.) on space hardware, (in particular electronic components, sensors, power and communication systems) increases with radial distance of the S/C orbit. It implies that the long-term performance and reliability of hardware in GEO is much more subjected to a severe environment than a spacecraft in MEO or LEO orbits. - As a consequence, radiation-hardened components (CMOS chips, solar cells, etc.) were developed to account for the space weather and to improve hardware life times. The introduction of radiation-hardened components was first realized in GEO satellites.

- Space environment experiments - collection of cosmic dust, particles and debris from platforms. Dust is ubiquitous in the solar system, with dust particles abundant in regions as diverse as interplanetary space, the terrestrial and martian atmospheres, comets, asteroids, satellite surfaces, and planetary rings. The dynamics of these short-lived particles are particularly sensitive to their environment, so they serve as probes of a variety of processes and are strongly effected by electromagnetic forces. - Since the early 1980s several programs were initiated with the aim of systematic collection and analysis/curation of cosmic dust. Also study of radiation degradation effects on some types of materials. Initial airborne dust collections (since 1981) were made with instruments mounted underneath a wing using NASA WB-57F aircraft from NASA/JSC. Several space agencies (NASA, ESA, JAXA, CNES, etc.) maintain special laboratories to analyze impact damage, instruments are being developed and flown to measure orbital micro-debris sources. Long-term data on the space environment and its effects on space systems and operations is a constant need of spacecraft and instrument designers. In addition, the study of recovered long-duration space structures like LDEF and EURECA, and other recovered hardware (solar array from Hubble, etc.), is of major interest. In particular, large surface structures such as solar arrays, can serve as passive detectors for the study of debris impacts. The evidence of hardware brought
back from space shows clearly that the risk faced by spacecraft from meteoroids is real. The heavily pitted surfaces of Eureca and the shattered solar cells of the Hubble Space Telescope bear witness to the harsh meteoroid environment in Earth orbit. 1271) 1272) 1273) 1274)

In 1995, NASA started its SEE (Space Environments Effects) program 1275) with the objective to collect, develop and to disseminate the technologies required to design, manufacture and operate more reliable, cost-effective spacecraft for the government and commercial sectors. In partnership with industry, academia, and other government agencies, the SEE program defines the space environments and advocates technology development to accommodate or mitigate these harmful environments on spacecraft. The ESEM (Evaluation of Space Environment and Effects on Materials) payload of STS-85, in cooperation with NASA/DA, is one of many experiments in SEE.

<table>
<thead>
<tr>
<th>Mission or Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAC (Large Area Collector), NASA/JSC</td>
<td>LAC is flown on NASA ER-2 aircraft since 1989, P.110</td>
</tr>
<tr>
<td>EURECA-1 launched on STS-46 July 31, 1992 and retrieved on STS-57 July 1, 1993</td>
<td>ESA mission. The experiment TICCE on EURECA-1 collected debris, meteoroids, and cosmic dust. See J.5.1</td>
</tr>
<tr>
<td>EURECA-1</td>
<td>ESA mission. The experiment TICCE on EURECA-1 collected debris, meteoroids, and cosmic dust. See J.5.1</td>
</tr>
<tr>
<td>LDEF (Long Duration Exposure Facility) see J.9</td>
<td>NASA/LaRC S/C deployed from Shuttle on April 7, 1984 (STS-41-C) and recovered on STS-32 Jan. 12, 1990 Exposure of many systems to cosmic radiation and collection of cosmic dust by Exp. A0138-2 of CERT/ONERA, and by Exp. A0201, S001, etc. of NASA/LaRC</td>
</tr>
<tr>
<td>MIR Space Station</td>
<td>On three occasions (1988, 1995, 1997) dust collection detectors were used on the outside of MIR.</td>
</tr>
<tr>
<td>Ulysses mission (ESA/NASA), launch Oct. 6, 1990</td>
<td>DUST experiment of MPIK (Heidelberg, Germany), see K.30</td>
</tr>
<tr>
<td>APEX (Advanced Photovoltaic &amp; Electronics Experiment), S/C of DoD, launch Aug. 3, 1994 (no particle collection on APEX)</td>
<td>Study of long-term radiation effects in an orbit of 361 km x 2528 km, inclination = 70º. Experiments included: PASP (Photovoltaic Array Space Power Diagnostics), CRUX (Cosmic Ray Upset Experiment), and FERRO (Thin-film Ferro-electric Experiment)</td>
</tr>
<tr>
<td>MEEP (MIR Environmental Effects Payload) deployed on STS-76 (Mar. 22, 96) and retrieved on STS-86 (Oct. 1, 1997)</td>
<td>NASA/LaRC/MSFC conducted a series of experiments such as POSA-I &amp; -II (Passive Optical Sample Assembly), PEC (Passive Experiment Carrier), PPMD (Polished Plate Meteoroid Detector), ODC (Orbital Debris Collector)</td>
</tr>
<tr>
<td>CDCE (Cosmic Dust Collection Experiment) and AOE (Atomic Oxygen Experiment), both on STS-85 (Aug. 7-19, 1997)</td>
<td>NASA/LaRC experiments in ESEM program. CDCE: Use of aerogel to capture cosmic dust. AOE: candidate materials for ISS (lubricants, paints, thermal coatings, etc.)</td>
</tr>
<tr>
<td>MightySat-1 of AFRL, launch Dec. 4, 1998, see M.21.1</td>
<td>MPID (Micro-Particle Impact Detector)</td>
</tr>
<tr>
<td>ARGOS (DoD, launch Feb. 23, 1999)</td>
<td>SPADUS (Space Dust Experiment)</td>
</tr>
<tr>
<td>SUNSAT-1 of Stellenbosch University, South Africa, launch Feb. 23, 1999</td>
<td>MIS (Meteoroid Impact Sensor) of NASA/LaRC</td>
</tr>
<tr>
<td>STRV-1c and -1d, DERA, launch Nov. 16, 2000</td>
<td>CDMS (Compact Debris and Micrometeoroid Sensor) characterizes of the debris and micrometeoroid environment in GTO</td>
</tr>
<tr>
<td>STRV-2 of AFRL and DERA (launch June 6, 2000) on TSX-5 mission of AFRL</td>
<td>MDIM (Meteoroid and Debris Impact Monitor) of NASA/ LaRC</td>
</tr>
</tbody>
</table>

Table 61: Overview of some cosmic dust/particle collection platforms

- Measurement of atomic oxygen (see also Glossary). Atomic oxygen is the most abundant atmospheric species in the altitude range of about 100-600 km; it can affect a space-

1271) http://setas---www.larc.nasa.gov/
1275) http://see.msfc.nasa.gov/
craft’s operational capability. Adverse influences include material degradation (erosion). Of particular concern are the following effects: impact of particulate matter (debris), of high-energy UV radiation and of x-ray radiation, both of which are predominantly of solar origin. Early missions of atomic oxygen measurements started within the NASA program AE (Atmosphere Explorer). In this series, the AE-A mission (also known as Explorer 17, see A.4.1) flew the Neutral Mass Spectrometer (launch April 3, 1963). The AE-B mission (launch May 25, 1966) carried two instruments to measure atomic oxygen. The San Marco D spacecraft of the University of Rome and NASA/GSFC measured airglow which infers atomic oxygen. The NASA DE-2 (Dynamics Explorer) mission (launch Aug. 3, 1981) carried NACS (Neutral Atmosphere Composition Spectrometer) to measure abundances of neutral species over an altitude range of at least 100 km to 300 km, and FPI (Fabry-Perot Interferometer) to measure ionic atomic oxygen. The HRDI (High Resolution Doppler Imager) of UARS (launch Sept. 12, 1991) observes emission lines of neutral and ionized atomic oxygen in the visible and near-infrared regions. In addition, several Shuttle missions (STS-4, STS-46, STS-85) flew mass spectrometers to measure atomic oxygen.
1.4.12 Orbital debris

Like any human activity, the conquest of space has generated its share of waste that must now be managed if we are to ensure a sustainable future. Orbital debris generally refers to material that is on orbit as the result of space activities/initiatives, but is no longer serving any function. The use of outer space presents a number of hazards to S/C owners and operators. Temperature extremes, radiation, solar flares, and micrometeoroids have long been essential elements to consider in spacecraft and mission design. Increasing use of space has brought a new source of risk collisions with manmade objects. The proliferation of debris in space generated by spacecraft and launchers is likely to become a serious issue in the near future. Such debris, originating from S/C, upper stage explosions and from the rising number of non-operational and abandoned satellites, represent a hazard for all operational missions (manned and unmanned). The GEO and LEO orbits are in particular littered with debris. 1276) 1277) 1278) 1279) 1280) 1281) 1282) 1283) 1284)  

Some examples of space debris observations/incidents are:

- During the US Gemini manned space program (March 1965 - Nov. 1966) the TV audience of the world could see as one astronaut “walked” in space while a glove floated up and out of the capsule in full view - a first documented incidence of space debris (Ref. 1293).

- Early satellite experiments, such as those aboard NASA’s Explorer-7 (launch Oct. 13, 1959) and Explorer-16 (launch Dec. 16, 1962), tried to detect the impact of micrometeoroids. In 1964, NASA/JSC developed a project called “Micro-Meteoroid Measurement Capsule” which was renamed the “Pegasus” project. These capsules (Pegasus-A, -B and -C) were intended to determine the level of hazard to which astronauts would be exposed.

- The Explorer-46 mission of NASA (launch Aug. 13, 1972) flew an experiment called the Meteoroid Bumper Experiment for the characterization of the background environment. The objectives were to measure the meteoroid penetration rates in the bumper-protected target, and to obtain data on meteoroid velocity and flux distribution.

- Micro-debris originating from objects launched from Earth were first encountered in 1976 on the US Skylab Space Station, where aluminum oxide exhaust from apogee kick motors was identified.

- In 1986, the spent third stage of the Ariane-4 launcher, used to place SPOT-1 into orbit (launch Feb. 22, 1986), exploded after nine months in orbit (LEO). The explosion generated over 700 fist-sized fragments. In addition, thousands of micro-particles of all sizes were released.

- Meteoroid impact on a satellite. In 1993 a Perseid meteoroid (tiny grains of dust) hit a solar panel on the European Olympus communications satellite. The project management is convinced the hit caused a pulse that sent false signals to the control system of the S/C. As a consequence, the satellite went into the wrong automated sequencing causing the loss of the spacecraft (it took all the remaining propellant to regain control, resulting in the end of the mission).

References:
1277) http://www.aero.org/cords/index.html  
1279) F. Alby, “Regulating orbital debris,” CNES Magazine No 19, May 2003, p. 26  
1283) N. L. Johnson, “Man-Made Debris In And From Lunar Orbit,” Earth Space Review, Vol. 9, No 4, 2000, pp. 57-65
- On July 24, 1996, the French microsatellite CERISE collided with a piece of debris (a suitcase-sized piece of the old Ariane rocket of 1986 - the first official collision between two catalogued objects), cutting in half the 6 m long stabilizing boom of CERISE. Fortunately, the French ground controllers regained control over the satellite following the collision.

- On Oct. 26, 1999 ISS (International Space Station) made a maneuver to avoid a potentially dangerous piece of orbital debris (the US Space Command and NORAD had reported that a spent Pegasus upper stage would pass ISS to within 1.4 km). Hence, thrusters of ISS were fired to increase the stations altitude by about 1.5 km. Another collision-avoidance maneuver of ISS took place on Dec. 15, 2001, when the Shuttle Endeavour increased the altitude of ISS by 1 km to avoid a collision with a Russian SL-8 upper stage launched 1971.

- A major contributor to the orbital debris background have been breakups of rocket upper stages and satellites. More than 150 breakups have been verified, and more are believed to have occurred. Breakups generally are caused by explosions and collisions. Explosions can occur when propellant and oxidizer inadvertently mix, residual propellant becomes overpressurized due to heating, or batteries become overpressurized.

These incidents show that all aspects of debris-related issues, including some regulation standards, have to be dealt with in the future. The SSN (Space Surveillance Network) of the US Space Command and NORAD (North American Aerospace Defense Command) in Colorado Springs, CO, maintains orbital element sets of some 8764 objects (of 10 cm diameter or larger) - still many more are too small or in too eccentric orbits to be cataloged. The estimates of objects in size 1-10 cm is in the order of 200,000; in addition, there are more than 35 million objects below 1 cm. Of the 8764 objects being tracked (as of Oct. 20, 1999), there are 2634 satellites (any payload operational or non-operational currently in Earth orbit - meaning LEO, GEO, GTO, MEO, HEO, or any other Earth orbit), 6040 objects are termed “debris” (meaning all man-made objects in Earth orbit), and 90 objects are termed “space probes” (referring to payloads that are not in Earth orbit - such as deep space missions). The historical catalog status of the US Space Command lists on Oct. 20, 1999: payloads decayed = 2,501, debris decayed = 14,680, total = 17,181 objects.\(^{1285}\) - In this context, it is also of interest to look at the estimated distribution of orbital debris in the following scheme: Operatingsatellites = 6%, spent satellites = 22%, upper stages = 17%, operational debris = 13%, and fragments (of rocket upper stages, etc.) = 42%. Consequently, about 94% of the catalogued objects no longer serve any useful purpose and are collectively referred to as “space debris.”

The debris in orbit totals an estimated 4000 tons in 1999, with 175 tons added every year. Complications will arise from the ever-increasing use of space. The operational networks of major commercial satellite constellations (initial launches started in 1998) increases the crowding of space in LEO very rapidly. The Iridium constellation has 77 in orbit (nominal of 66 operational), Orbcomm has 35 (constellation completed in Dec. 1999), Globalstar 48, and Skybridge 64, when fully deployed. These are only a few of the commercial entries. In Earth observation the picture is pretty much the same. Constellations or clusters of small satellites are planned by a number of agencies to enter a new dimension of formation flight observations.\(^{1286}\)\(^{1287}\)

Debris in the geostationary ring.\(^{1288}\) Since the launch of Syncom-1 in Feb. 1963, more than 800 satellites and rocket upper stages have been inserted into GEO or its vicinity. As of 2000, only about 250-270 of these satellites are used operationally. GEO satellites are therefore increasingly at risk of colliding with uncontrolled objects. Contrary to the situa-
tion with LEO satellites, there are no effective natural removal mechanisms for GEO objects. [In order to preserve the GEO for future satellite operations users have been encouraged over the years to re-orbit their satellites at the end of their lives. This mitigation measure involves boosting the satellite to a graveyard region above the GEO ring (sometimes referred to as “super-geostationary” orbit). Unfortunately, this practice is not fully embraced by all satellite operators.] Routine surveillance with ground-based radars of SSN (Colorado Springs, CO) is able to catalog objects of 1 m in size or larger in GEO. Observations with ESA’s Zeiss telescope at the Teide Observatory in Tenerife, with an optimized debris-detection system, have shown that there is a significant population of about 1600 small-debris objects (10-100 cm size) in the geostationary ring.

Collision risk monitoring. Starting in about 1995, space agencies (CNES, ESA, NASA, etc.) are beginning to monitor close encounters of catalogued objects with their own S/C. For instance, the flight path of ESA’s ERS-2 satellite is being checked for potential close encounters or collisions several times per week. ESA performed two evasive maneuvers with ERS-1 in June 1997 and in March 1998. CNES experienced in this process, for instance, that on average, an object passes within less than 1500 m of a S/C every two weeks. Even closer approaches (under 800 m) were observed on 19 occasions.

An important tool in characterizing a small-size debris population are so-called “beam-park” experiments. In this operating mode, the radar beam is maintained in a fixed direction with respect to the Earth and all objects that traverse the beam are registered. In the course of a day, the Earth’s rotation scans the beam through 360º in inertial space. From the backscattering of the radar signal, the size of the object and some of its orbital parameters can be determined. Example radar systems used in space-debris tracking are:

- US radars are carrying out beam-park experiments from Haystack, MA, Goldstone, CA, and Kwajalein (TRADEX radar) in the Pacific Ocean. Between 1990 and 1994, space debris was observed for more than 3000 hours.
- The first European beam-park campaign was carried out in 1993 at the TIRA (Tracking and Imaging Radar) facility of FGAN (Defense Research Facility for Applied Science, Wachtberg near Bonn, Germany). TIRA consists of a 34 m parabolic antenna, a narrow-band monopulse L-band tracking radar, and a high-resolution Ku-band imaging radar. A second data-collection system was installed by ESA at the 100 m steerable parabolic antenna at Effelsberg in Germany.
- The largest rapid increase in the number of tracked objects occurred starting in March, 2003. This timing correlates to the resumption of full power/full time operation of the AN/FPS-108 Cobra Dane ground-based radar located on Shemya Island, AK, USA (52.7º N latitude, 174.1º E longitude). In contrast to the 1994 debris campaign where the gains were the result of temporary operating procedures, the addition of Cobra Dane to the SSN will provide long-term improvement to the total tracked population. Cobra Dane is an L-band (23 cm wavelength) phased array radar which first became operational in 1977. The radar generates approximately 15.4 MW of peak RF power (0.92 MW average) from 96 TWT (Traveling Wave Tube) amplifiers arranged in 12 groups of 8. This power is radiated through 15,360 active array elements. As a result, approximately 2000 orbiting objects have been added to the “Analyst list” of tracked objects.

Debris, reentering the atmosphere, presents a further problem, in particular to population safety. In 1999, it is estimated that about 17,000 objects of debris have reentered the atmosphere since Sputnik - virtually all of them disintegrated in the reentry process, very few ac-

tually hit Earth, although some particularly large or well-shielded objects have been known to get through. Controlled deorbiting and reentry procedures over oceans or sparsely populated regions are the rule for larger returning S/C that can still be steered. At the Skylab uncontrolled reentry in 1979, with a mass of 82 metric tons (the size of the structure was 36 m x 6.7 m diameter), fragments fell into the Indian Ocean and the western region of Australia. This uncontrolled reentry definitely caused many alerts throughout the world. The MIR space station of Russia (with 140,000 kg of mass) was deorbited in a controlled manner in March 2001 with a final reentry into the Pacific Ocean on March 23, 2001. Many governments had their national control centers working for several weeks. An atmosphere of “we are doing something, and everything is under control” was portrayed publicly to keep the people calm. Fortunately, the Russian Control Center did an excellent job to bring MIR to the intended splashdown region. [Russia had asked NASA (incl. radars of the US Space Surveillance Network) and ESA (incl. the radar facilities of FGAN near Bonn, Germany) for support, which was granted. ESOC was the center of a data exchange network among technical centers [TsUP (Moscow Region), NASA/JSC, FGAN (Germany), and other space centers in Europe)].

<table>
<thead>
<tr>
<th>Particle diameter class</th>
<th>Effects on S/C structure</th>
<th>S/C protection</th>
<th>Estimated Nr. of particles on orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.01 cm</td>
<td>Cumulative effect over long periods of time</td>
<td>Unnecessary</td>
<td>Very large number of micro particles</td>
</tr>
<tr>
<td>0.01 - 1 cm</td>
<td>Serious structural damage, perforations. Consequences depend on element affected</td>
<td>Shielding needed</td>
<td>35,000,000 objects</td>
</tr>
<tr>
<td>1 - 10 cm</td>
<td>Very severe damage</td>
<td>No solution so far</td>
<td>110,000 objects</td>
</tr>
<tr>
<td>&gt;10 cm</td>
<td>Objects are cataloged, catastrophic consequences</td>
<td>Avoidance maneuvers</td>
<td>&gt;8700 objects</td>
</tr>
</tbody>
</table>

Table 62: Overview of space debris classes that may impact on operational S/C

A principal forum for debating orbital debris issues and new practices (including debris mitigation measures) is the “Inter-Agency Space Debris Coordination Committee” (IADC), created in 1993 by government representatives from USA (NASA), Europe (ESA, ASI, BNSC, CNES, DLR), Russia (Rosaviakosmos), Japan (JAXA), India (ISRO), China (CNSA, since 1995), and the Ukraine (NSAU). In 2002, IADC completed a set of debris mitigation guidelines agreed to by the agencies. In Feb. 2003, these guidelines were presented to COPUOS (United Nations Committee on Peaceful Uses of Outer Space) for review and approval.

1.4.12.1 Debris policies and spacecraft removal from orbit at end-of-life

Artificial space debris has been with us since the very first satellites, and concerns about the potential hazards of space debris are equally old. However, in spite of continuing concerns about the increasing population of artificial debris, the space agencies of the world didn’t react to the situation. The humble beginnings of a United States policy on space debris were presented in 1986, with a focus on the space debris situation and its potential hazard to space flight, the urgent need for a space debris classification, and an appeal to avoid further man-made space debris (the military establishment tried to avoid any regulations because these would imply further costs to their programs).

In 1993, NASA adopted a new policy, a “NASA Management Instruction” (NMI 1700.8) with regard to spacecraft development (concerning debris prevention and end-of-life dis-
position). A so-called “debris assessment” is needed to determine if requirements are met for waiving the controlled reentry at the end of mission life. Because of lack of global regulations, waivers are likely to be issued for expensive measures that effect the projects of the own agency. But this is not special for the US: most spacefaring nations behave in the same way. Sometimes the US government insists on the strict application of its standard (NASA Management Instruction) as in the case of the Iridium constellation (condition for obtaining the license). In 1997, NASA issued NPD (NASA Policy Directive 8710.3 with regard to space debris. - The planned NPP (NPOESS Preparatory Project) spacecraft and the follow-up NPOESS series, for instance, are expected to have sufficient debris that survives reentry; hence, they feature the capability of a controlled reentry (propulsive maneuvers) to place the debris in a pre-determined location in the ocean.

The NASA “policy for limiting orbital debris generation” was revised as NPD (NASA Policy Directive) 8710.3A in Jan. 2003. The document introduces for instance the general guideline for limiting the lifetimes of such debris in LEO to 25 years.

ESA came out with an “ESA Space Debris Mitigation Handbook,” Release 1, April 7, 1999, and a draft of the “European Space Debris Safety and Mitigation Standard” in 2000 (Sept. 27, 2000, Issue 1, Rev. 0), which discusses the issues of in-orbit debris and gives various scenarios for end-of-life (EOL) disposal. - The two TerraSAR spacecraft of EADS Astrium (TSX and TSL mission with a planned launch in 2006), within the framework of ESA Earth Watch missions, are planning thruster firings at EOL (using budgeted fuel) to obtain an elliptical orbit with a perigee of about 300 km or lower. This generates sufficient atmospheric drag to bring the S/C eventually into a reentry trajectory.

Further references on space debris are: “Position Paper on Orbital Debris,” of IAA (International Academy of Astronautics), Paris, 2001, and “Technical Report on Space Debris,” UN, New York, 1999. The problem with debris policies is that the standard in its entirety will only be applied when everybody in space will abide by the rules. Since no international regulation concerning space debris exists, this will take some time. Such a regulation must necessarily be issued by the UN, where the deliberations in the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) on debris are ongoing since 1994. All agreements must be reached by unanimity. It took several years to reach agreement to have space debris on the agenda.

The introduction of space traffic management is a logical consequence of ever-increasing spacecraft and space debris populations. The first steps toward management of space traffic have already been taken in an uncoordinated fashion. Space traffic management is defined in reference 1296). “Space traffic management encompasses all the phases of a space object’s life, from launch to disposal. It consists of activities intended to prevent damage in the near term (such as collision avoidance and coordination of reentry), as well as actions that must be taken to reduce the long-term potential for future damage (such as deorbiting or moving satellites into disposal orbits).” So far, only ITU (International Telecommunications Union) administers a form of space traffic regulation for communication satellites in GEO. However, the management deals only with frequencies used by satellites, not physical locations of satellites. As a result, satellites broadcasting in different frequencies can occupy essentially the same physical space (i.e., in GEO).

Among the space agencies there is practically a consensus that S/C and rocket upper stages in Low Earth Orbit (LEO - orbits <2000 km) should be removed from orbit within 25-50 years after mission completion. This is simply to avoid further proliferation and generation

1294) Information provided by Walter Flury of ESA/ESOC, Darmstadt, Germany
of debris (through collision). A regulation is however needed to force everybody, including commercial users/operators to apply the same rules.

In principle two categories of measures to reduce orbital debris growth can be distinguished: 1298)

1) Debris avoidance

2) Debris removal. The natural cleaning of the Earth environment by the trajectory disturbances will no longer be sufficient in the future to keep the Earth environment in an acceptable status for the operation of manned and unmanned spacecraft. The only effective way to limit the growth of the orbiting debris is to systematically remove satellites and rocket upper stages at the end of their mission life from the near Earth space. There is already now international space law, the Liability Agreement, which clearly stipulates the liability of the owner in case of damage on ground or in air-space.

In general, the post-mission disposal options are:

- Option 1 (uncontrolled deorbiting): Maneuver to an orbit (by propulsion or other means, tether) in which atmospheric drag will eventually remove the structure within a given time frame, e.g. 25 years. With relatively small spacecraft masses (destruction and burn-up in the atmosphere), this will probably be the option favored by most satellite operators in the future.

- Option 2 (controlled deorbiting); 1299) Direct retrieval and deorbiting. Examples are: 1) MIR Space Station of Rosaviakosmos (March 2001), 2) Compton Gamma Ray Observatory of NASA (June 2000); 3) The Astra-1K (launch Nov. 25, 2002) commercial communications satellite of SES (Societe Europeenne des Satellites) Luxembourg, built by ASI (Alcatel Space Industries) of France, experienced a launch failure due an upper stage malfunction (Proton K/DM3 launch vehicle from Baikonur) leaving Astra-1K in a useless orbit (very low GTO). CNES and ASI put the satellite into a controlled atmospheric reentry trajectory. As a consequence, Astra-1K was safely de-orbited on Dec. 10, 2002.

- Options 3: Maneuver to one of a set of disposal regions in which the structures will not interfere with future space operations.

Examples of spacecraft removal from orbit (uncontrolled deorbiting category):

- Landsat-4 removal from space. On June 15, 2001, NASA shut down Landsat-4, (launch in 1982) whose instruments were no longer functioning, and initiated an atmosphere reentry maneuver which will result in destruction of the satellite in 5-10 years.

- The SPOT-1 satellite of CNES (1800 kg mass), launched into a sun-synchronous orbit at 830 km altitude in Feb. 1986 for a planned three year imaging mission, was retired in mid-2002 following the launch of SPOT-5. In 2003, CNES decided to de-orbit SPOT-1 to assure a destructive reentry and disintegration in a time period of about 15 years. In Nov. 2003, SPOT-1 was commanded into an elliptical orbit with a perigee of about 550 km (using the remaining fuel in its tanks). 1300) 1301)

- As of April 2004, PanAmSat announced that it has decided to deorbit one of its in-orbit international spares, PAS-6, due to a failure in the satellite’s power system. The GEO spacecraft is located at 43° west longitude; PAS-6 was one of two backup satellites supporting PanAmSat’s international fleet. PAS-6 was launched Aug. 8, 1997, a Loral Space Systems model FS-1300 spacecraft.


1301) “SPOT-1 signs off gracefully,” CNES Magazine, No 21, Jan. 2004, p. 8
Removal of commercial satellites operating in GEO (Geostationary Earth Orbit). In June 2004, the US FCC (Federal Communications Commission) stepped into a years-long debate on orbital debris by ordering tough new measures governing how satellites are to be disposed of by their commercial owners. The FCC ruled that all US-licensed satellites launched after March 18, 2002, will have to be placed into a graveyard orbit at EOL (End of Life), 200 to 300 km above GEO, where most commercial satellites operate. The FCC ruling sets a regulatory standard — that will be difficult for other nations to avoid. 1302)

1.4.13 Some comments on launch deployment capabilities

- Launch vehicles with an upper stage re-ignition capability for payload deployment. This technology represents a cost-efficient solution providing operational/maneuverable freedom in the launch and deployment phase of satellites; a very desirable function is the deployment of multiple satellites into LEO or MEO orbits (release of S/C into various orbits). At the start of the 21st century, solutions with a re-ignition capability are increasingly being offered by the launch service providers. Some examples are:

  - The Soyuz-Fregat launch vehicle of STARSEM and its Russian partners employs the Fregat upper stage with its re-ignition capability. The Cluster-2 missions of ESA [July 16, 2000 (1st launch of 2 S/C), Aug. 9, 2000 (2nd launch of 2 S/C)] were the first flights using the re-ignition capability. Once separated from the Soyuz third stage, Fregat injected the payload into a circular parking orbit with its first burn. This was followed by a cost phase in three-axis stabilized mode. The second burn of Fregat injected the payload into a highly elliptical separation orbit. - The ESA Mars Express mission (launch June 2, 2003) employed also the Soyuz-Fregat launcher configuration.

  - Eurockot Launch Services (a joint venture company between Russia’s Khrunichev Space Center in Moscow and Germany’s EADS Astrium GmbH, Bremen) provides a multiple re-ignition capability of its Breeze-KM upper stage. The first successful multiple orbit mission took place on June 30, 2003 from Plesetsk, Russia. The launch involved a total of eight spacecraft from different agencies and institutions by deploying the various payloads into an elliptical as well as into a sun-synchronous orbit. Additionally a mock-up of the Russian Monitor-E satellite was mounted on Breeze (the Monitor-Experimental bus remained on the upper stage and deorbited with it according to plan). Multiple re-ignitions permitted precise sequential deployment into various orbits. The Czech Mimosa microsatellite was first deployed into an elliptical orbit (323 km x 823 km, inclination of 86.5º), while the other satellites [MOST of CSA and six CubeSats (picosatellites) of various universities] were delivered into sun-synchronous orbits at predetermined intervals. 1303)

  - As of 2002, the Ariane-5V launch program offers multiple re-ignition of the current storable-propellant upper stage.

  - Japan’s H-II launch vehicle features a second stage with a re-ignition capability.

  - The STP--1 mission of DoD (launch March 9, 2007 from Cape Canaveral, FLA) demonstrated for the first time the deployment of multiple spacecraft (6) into two different orbital inclinations and at two different altitudes (both in LEO). This required a total of 3 burns for the upper stage of the Atlas--V launch vehicle. Also first time use of the ESPA (EELV Secondary Payload Adapter) ring, a low--cost concept to launch multiple secondary satellites. The introduction of these new features represents indeed new capabilities for future missions.


1303) Russia (Rosaviakosmos, Khrunichev) is developing the Monitor small-size satellite family (650 - 750 kg) within the project SERSS (Space-based Earth Remote Sensing System) based on the Yakhta standardized space platform. The objective is high-resolution imagery in the optical region and eventually also in the microwave region (SAR). The Monitor-E mission (VNIR coverage) is planned for launch in 2005, followed later by the Monitor-I-1 and I-2 missions (each with VIS and TIR coverage). Monitor-S (Stereo Imaging) is planned thereafter.
1.4.14 ISS (International Space Station) Build-up Phase

The ISS (International Space Station) build-up era in LEO began in 1998. The program of an international space station was first announced/initiated by President Reagan in his ‘State of the Union’ address on Jan. 25, 1984. A total of 45 US/Russian missions are planned up to 2005 to assemble more than 100 elements that will complete the International Space Station (total mass of 460 tons of structures and equipment). Other nations, participating in the ISS project (besides the USA and Russia), include: Brazil, Belgium, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom (all of Europe is represented through ESA). ISS is the largest space structure ever built and represents also largest cooperative space research program in the history of space flight. When assembled ISS will have dimension of: 108 m in length and 74 m in width. The total mass will be more than 460 tons, representing the largest man-made object in Earth orbit. Three of the four operational Shuttles - Discovery, Atlantis and Endeavour - have been modified for increased lift capability (16,000 kg max payload into orbits of 51.6° inclination) to meet the projected needs of ISS. See chapter L.1 for some ISS payload descriptions relating to Earth observation.

- **ISS orbit**: The ISS target orbit altitude is 360 - 460 km, orbit inclination is 51.6°. The increased inclination (from normally 28° for Shuttle flights from KSC) has two advantages: 1) it permits servicing of the ISS from the Russian launch site at Baikonur, and 2) the increased inclination of 51.6° offers a considerably larger observation coverage of the Earth. About 75% of the Earth’s land area and approximately 95% of the Earth’s population is covered with ISS overflights.

The ISS orbit varies in altitude from approximately 460 km to 360 km, based on the paradigm that the Station vehicle is being boosted to it’s maximum altitude every 90 days and allowed to drift down to it’s minimum altitude. This 90-day drift allows for a significant increase in the microgravity period available in comparison to the Space Shuttle. Due to the westward precession of orbit tracks, the ISS overflies the same location every three days, with the identical lighting conditions being repeated every three months.

- The ISS will be a multi-module vehicle when completed, providing research laboratories, stowage for scientific and logistics items, an external truss that accommodates unpresurized payloads, and living quarters for up to seven crew members. Of the four research laboratories, two are supplied by the United States, one by ESA, namely COF (Columbus Orbital Facility), and one by JAXA, the JEM (Japanese Experiment Module). - Each of these laboratories provides for the installation of ISPRs (International Standard Payload Racks), a large commercial structure (size of a refrigerator) that provides a mounting place for a variety of equipment. The United States Laboratory, called Destiny, has 24 locations for ISPRs, of which 13 will be devoted to research capabilities and the remaining 11 to systems functions such as environmental control. In addition, there will be the MLM (Multi-purpose Laboratory Module), the RM (Research Module) of Rosaviakosmos, Russia. MLM is the modified (yet unlaunched) backup FGB-2 (Functional Cargo Block-2); it will eventually be docked to the nadir port of FGB “Zarya”. MLM will provide ISS roll control maintenance; it will also serve as a docking port for “Soyuz” and “Progress” vehicles. 1304)

- The first component of ISS, namely FGB (Functional Cargo Block), also referred to as Zarya (meaning ‘sunrise’), was launched Nov. 20, 1998 on a Proton vehicle from the Baikonur Cosmodrome in Kazakhstan. Zarya serves as the cornerstone of ISS, it is a 20,040 kg pressurized module. Zarya was built for NASA by KhSC (Khrunichev State Research and Production Space Center) of Moscow in cooperation with Russian space industry, under contract with the US Boeing Company.

- The second component of ISS, Unity (11,800 kg, 11 m in total length), referred to as Node 1, with six berthing ports, was launched Dec. 4, 1998 on Shuttle (STS-88, Endeavour) and mated to Zarya three days later.

- The STS-96 Shuttle flight on Discovery (May 27 - June 6, 1999) carried a) internal logistics and resupply cargo for station outfitting, and b) an external Russian cargo crane that was mounted to the exterior of the Russian station segment and used to perform spacewalking maintenance activities.

- The STS-101 flight on Atlantis (May 19 - 29, 2000, assembly mission 2A.2a) services were: a) prepared the station for the arrival of the Zvezda Service Module, b) installed four new batteries, 10 new smoke detectors and four new cooling fans on the Zarya module, c) installed the final parts of the Strela crane on Pressurized Mating Adapter 1, d) removed and replaced the early communications system antenna, and e) installed handrails on the Unity module.

- The Russian-built Zvezda (meaning “star”) Service Module (SM) was launched on July 12, 2000 by a Proton-K vehicle from Baikonur (ISS assembly mission 1R). Zvezda was docked to ISS on July 26, 2000. The Zvezda Service Module provided a) the first primary living quarters for three-person crews, b) primary docking port for Progress-type cargo resupply vehicles, c) power and steering (propulsive attitude control and reboost) capability to keep ISS in a safe orbit.

- Aug. 6, 2000 launch of Russian Soyuz-2 from Baikonur on ISS flight 1P with the Progress M1-3 resupply ship for ISS. Progress docked with ISS on Aug. 9, 2000.

- The STS-106 flight of Atlantis (Sept 8-20, 2000) provided a) internal logistics and resupply cargo for station outfitting, b) a space walk was conducted to perform maintenance on the station.

- STS-92 flight of Discovery (Oct. 11-24, 2000, ISS-05-3A assembly flight) provided: ITS (Integrated Truss Structure) Z1, PMA-3 (Pressurized Mating Adapter-3), a Ku-band communications system, and CMGs (Control Moment Gyroscopes) for non-propulsive attitude control (see also 1.8.2.6). ITS-Z1 is an early exterior framework to allow first U.S. solar arrays on flight 4A to be temporarily installed on Unity for early power. The Z1 truss is the first permanent lattice-work structure for ISS.

- A Russian Soyuz rocket (launch Oct. 31, 2000) lifted the first expedition crew to ISS from Baikonur, referred to as ISS-2R. Objectives: a) to establish the first station manning with a three-person crew (Commander Bill Shepherd; Soyuz Commander Yuri Gidzenko, Flight Engineer Sergei Krikalev), b) provides Russian assured crew return capability without the Shuttle present, c) the “permanent” habitation of ISS has begun. 1305)

- STS-97 flight of Endeavour (Nov. 30 - Dec. 11, 2000). The ISS assembly flight 4A provided the P6 Integrated Truss Segment, a 7700 kg package containing the PV (Photovoltaic) Module, plus S4 and S5 radiators. The US-provided power system increases the available electrical power of ISS by a factor of five. The P6 consists of two identical PVAAs (Photovoltaic Array Assembly), each of which is made up of an SAA (Solar Array Assembly) and a SAW (Solar Array Wing). The two SAWs have a total power generation capability of about 64 kW. Each SAW has a structure size of 35 m x 11.58 m and a mass of 1087 kg. Each SAW contains 33,000 solar arrays, each of size 8 cm x 8 cm with 4,100 diodes. The entire assembly represents the largest structure deployed in space so far (73 m from tip to tip) as well as the largest space-installed power supply.

- STS-98 flight of Atlantis (Feb. 7 - 20, 2001). The ISS assembly flight 5A carried the Destiny Laboratory Module, an aluminum structure of 8.5 m in length and 4.3 m in diameter.

1305) http://spaceflight.nasa.gov/station/assembly/flies/2000/2r.html
The module provides an initial US user capability in the field of near-zero gravity research. The Destiny module features also a nadir-looking window (46 cm in diameter) of the best optical quality ever flown on a crewed spacecraft. Use of the window for Earth science research will begin in earnest sometime after the research infrastructure, called WORF (Window Observational Research Facility), is brought to the space station and installed behind the Laboratory (Destiny) window. WORF will enable researchers to mount cameras, sensors and telescopes behind the window, and to hook up with power, thermal control, and other systems. As of 2006, WORF is scheduled for launch on ULF2 (Utility and Logistics Flight 2) in 2008.

- STS-102 flight of Discovery (March 8-21, 2001). The ISS logistics and resupply flight 5A.1 provided the Leonardo MPLM (Multi-Purpose Logistics Module). The module is about 6.4 m long and 4.6 m in diameter containing equipment racks. Exchange of first crew by a new crew.

- STS-100 flight of Endeavour (April 19 - May 1, 2001). The assembly flight 6A provided the Raffaelo MPLM (lab outfitting) for the US Lab, the UHF antenna (for EVA support), and delivery/installation of the Canadian SSRMS (Space Station Remote Manipulator System), the cornerstone of ISS’s Mobile Servicing System (MMS), also referred to as Canadarm2. SSRMS, has been attached to the Destiny module and used as “construction crane” of ISS, lifting payloads and performing maintenance work. With the installation of Canada’s Mobile Base System (MBS) in June 2002 (STS-111), SSRMS is able to slide along the main truss of the station (lateral mobility), providing an additional functional capability with four Power Data Grapple Fixtures. A further upgrade of Canadarm2 is planned for 2005 with SPDM (Special Purpose Dextrous Manipulator). This smaller two-armed robot has the capability to perform even more delicate tasks at ISS. SSRMS is 17.6 m long when fully extended and has seven motorized joints. This arm is capable of handling large payloads and assisting with docking the Shuttle.

- A Russian Soyuz spacecraft arrived at ISS on April 30, 2001 with the first space tourist ever onboard, namely Dennis Tito, a well-to-do US citizen who paid $20 Million to Rosaviakosmos, the Russian Space Agency (one week stay at ISS). There was considerable criticism and protest from NASA officials prior to the launch, but Rosaviakosmos insisted on Tito’s mission. The agency wanted and needed the cash badly due to the abysmal lack of governmental funding for its space programs. Further space tourists are waiting in the wings for a flight to ISS.

- STS-104 flight of Atlantis (July 12-24, 2001, assembly mission 7A). Installation of an ISS Joint Quest Airlock. The airlock is the primary path for ISS space walk activity (entry and departure of astronauts or cosmonauts) without the presence of a Shuttle or a Soyuz. The airlock is a pressurized flight element consisting of two cylindrical chambers attached end-to-end by a connecting bulkhead and hatch. The airlock structure, built at MSFC, is 6 m in length and 4 m in diameter with a mass of about 6500 kg. There are two main components to the airlock: a crew airlock and an equipment airlock for storing EVA gear and EVA pre-flight preparations. STS-104 also carried a spacelab pallet with four High Pressure Gas Assembly containers that were attached to the exterior of the airlock.


1308) Note: Canadarm1 is the standard payload handling system on Shuttle flights since STS-2 (Nov. 12-14, 1981) with a first deployment of Canadarm1 out of the cargo bay of Space Shuttle Columbia, on November 13, 1981
• A Russian Soyuz/TsSKB-Progress, launched from the Baikonur Cosmodrome in Kazakhstan on Sept. 21, 2001, delivered Docking Compartment-1 (DC-1) and a Strela boom of Rosaviakosmos to ISS. Also delivery of a portion (70 kg) of the CNES Andromède payload. DC-1 provides additional egress and ingress location for Russian-based space walks and a Soyuz docking port.

• A Russian Soyuz/TsSKB-Progress launch vehicle, launched on Oct. 21, 2001 from Baikonur, delivered a three-person crew to ISS for an 8-10 day mission (Oct. 21-31, 2001). The payload is TM-33 of Rosaviakosmos. The Soyuz vehicle was left at the station as a crew return vehicle. CNES of France is using this taxi flight for its Andromède technology mission (85 kg total mass) with investigations covering the fields of Earth observation, life sciences, and material sciences. The Earth observation payload consists of IMEDIAS (film and digital camera), designed to collect images of global change phenomena. In addition, the instrument LSO (Lightning and Sprite Observations) of CEA (Commissariat à l’Energie Atomique - the French Atomic Energy Agency) is used on ISS to measure emissions generated by lightning, sprites and elves. The measured data are needed to define parameters of a future CNES microsatellite mission instrument in France’s Myriade program.

• STS-108 of Endeavour (Dec. 5-16, 2001). The main element of this flight was the payload Raffaello MPLM (Multi-Purpose Logistics Module) with experiment racks for the US module Destiny.

• STS-110 flight 8A of Atlantis (Apr. 8-19, 2002). The primary objective is to deliver and assemble the first segment of the ISS external truss, the S0 (S-Zero) truss of ITS (Integrated Truss Structure). Equipment installed on the truss includes MT (Mobile Transporter) and its associated power and data umbilical reels. MT (built by Boeing) creates a movable base for the station’s Canadian mechanical arm (Canadarm2), allowing it to travel along the station truss after delivery of the MBS (Mobile Base System). ITS has a length of 91 m and is attached to the US Lab.

• STS-111 UF-2 (Utilization Flight-2) of Endeavour (June 5 - 19, 2002). The objectives are: 1) To deliver the Expedition Five crew to the ISS and return the Expedition Four crew to Earth. 2) MPLM (Multi-Purpose Logistics Module) carries experiment racks and three stowage and resupply racks to the station. 3) The US provided MBS (Mobile Base System) is installed on the Mobile Transporter to complete the MSS (Mobile Servicing System) of Canada. The MSS is used to perform ISS assembly operations as well as routine maintenance and video inspection tasks. At this stage, the MSS space segment includes several major elements: 1) Canadarm2 (SSRMS), 2) the MBS (Mobile Remote Servicer Base System) installed on the US-provided Mobile Transporter, 3) SPDM (Special Purpose Dexterous Manipulator), 4) the OCS (Operations Control Software), and 5) the AVU (Artificial Vision Unit). The MSS Operations Complex (MOC), supporting the unique operations of the sophisticated space robotics system, is the MSS ground segment. The mechanical arm of Canadarm2 has now the capability to “inchworm” from the U.S. Lab fixture to the MSS and travel along the truss to work sites.

• STS-112 flight 9A of Atlantis (Oct. 7-18, 2002). The main objective was the delivery and assembly of the right-side ISS truss segment (ITS S1) with a mass of 12,572 kg. The truss contains a new external cooling system for the station, a second S-band communications system to provide enhanced and extended voice and data capability, a cart CETA (Crew and Equipment Translation Aid) which serves as a mobile work platform for future spacewalkers, two new external television cameras and the first Thermal Radiator Rotary Joint (TRRJ).

• STS-113 flight ISS-11A of Endeavour (Nov. 24 to Dec. 7, 2002). Delivery of the Port-side (left-side) ISS truss segment (ITS-P1), assembly to S0. ITS-P1 has a mass of 12,572 kg.

Both P1 and S1 trusses provide structural support for ATCS (Active Thermal Control System), the Mobile Transporter, a CETA (Crew and Equipment Translation Aid) cart, and antennas.

<table>
<thead>
<tr>
<th>ISS Element</th>
<th>Launch Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zarya (Sunrise)</td>
<td>Nov. 20, 1998</td>
<td>Functional Cargo Block (FGB), 20,040 kg pressurized module</td>
</tr>
<tr>
<td>Unity</td>
<td>Dec. 4, 1998</td>
<td>Node 1 (11,800 kg, 11 m in total length)</td>
</tr>
<tr>
<td>Zvezda</td>
<td>July 12, 2000</td>
<td>Service Module</td>
</tr>
<tr>
<td>Z1 truss</td>
<td>Oct. 2000</td>
<td>Zenith truss segment, first permanent lattice-work structure for ISS</td>
</tr>
<tr>
<td>P6 arrays</td>
<td>Nov. 30, 2000</td>
<td>First US arrays, a package of 7,700 kg containing the PV module</td>
</tr>
<tr>
<td>Destiny</td>
<td>Feb. 7, 2001</td>
<td>US laboratory module, structure of 8.5 m in length and 4.3 m diameter</td>
</tr>
<tr>
<td>Canadarm2</td>
<td>April 19, 2001</td>
<td>SSRMS (Space Station Remote Manipulator System)</td>
</tr>
<tr>
<td>Quest</td>
<td>July 12, 2001</td>
<td>Joint airlock, primary path for ISS space walk activity</td>
</tr>
<tr>
<td>Pirs</td>
<td>Sept. 21, 2001</td>
<td>DC-1 (Docking Compartment 1), Russian-based space walks</td>
</tr>
<tr>
<td>S0 truss</td>
<td>April 8, 2002</td>
<td>Center truss segment</td>
</tr>
<tr>
<td>S1 truss</td>
<td>Oct. 7, 2002</td>
<td>First starboard truss segment</td>
</tr>
<tr>
<td>P1 truss</td>
<td>Nov. 24, 2002</td>
<td>First port truss segment</td>
</tr>
</tbody>
</table>

Table 63: Overview of major ISS element buildup phase

- The Shuttle research mission STS-107, Columbia (not a flight to ISS), with a launch Jan. 16 and a scheduled return on Feb. 1, 2003, experienced a reentry catastrophe on Feb. 1, disintegrating over Texas and resulting in the tragic loss of the crew of seven astronauts. Their names are: Rick Husband, William McCool, Kalpana Chawla, David Brown, Mike Anderson, Laurel Clark, and Ilan Ramon. The accident resulted into the largest investigation ever by NASA, with help from many other institutions, finding clues (proof) as to the most possible causes of the accident. The Columbia tragedy has also entailed an examination of the US space program in addition to the accident investigation.

As a consequence of the investigation, the ISS build-up phase came to a complete halt. NASA is planning to resume Shuttle flights to ISS in 2005. The three remaining Shuttles are undergoing extensive tail repairs prior to being cleared for flight again.

During the long vacant period in Space Shuttle flights after the accident, Russia provided significant services to ISS through the provision of crew transportation and with unmanned Progress resupply flight capabilities, to safely maintain a human presence on-orbit. Indeed, a most appreciated and cooperative service by all involved.

- STS-114, ISS-LF1 (Logistics Flight 1) of Discovery (July 26—Aug. 9, 2005). Return to flight test mission (after 2 1/2 years of Shuttle grounding). The payload elements are: a) Raffaello MPLM (Multi-Purpose Logistics Module), b) delivery of the ESP-2 (External Stowage Platform) to ISS, c) removal and replacement of the CMG-1 (Control Moment Gyro-1).

During the mission, the astronauts Soichi Noguchi and Stephen Robinson performed a number of repair and maintenance jobs on the ISS and on shuttle during three spacewalks. The most important tasks to be done were:

1) They inspected the underside of the Shuttle and tested some new techniques for replacing or repairing damaged tiles on the Shuttle.

2) They removed and replaced one of the four CMGs used to orient the ISS (a CMG has a mass of 227 kg). The broken CMG-1 failed on June 8, 2002, leaving ISS with two primary CMGs and one spare for momentum management. That spare shut down in 2004 when a circuit breaker failed. Though subsequently repaired, it failed again in March 2005. The astronauts were also able to fix the faulty circuit breaker of the spare CMG. Hence, the ISS attitude control system is complete again after a successful repair during the EVA on Aug. 1, 2005.
3) During the third spacewalk, Noguchi and Robinson installed and activated an External Stowage Platform on the Station’s Quest Airlock. Noguchi also installed another MISSE (Materials International Space Station Experiment). Finally, Robinson rode the end of the Station’s Canadarm2 to the underside of Shuttle Discovery to remove gap fillers from between the orbiter’s heat shielding tiles. The latter task was critical for a safe return flight of the Discovery and its crew.

- **STS-121**, ULF1.1 (Utility and Logistics Flight 1.1) of Discovery, July 4–17, 2006 (13 day mission). The payload elements are: a) MPLM-7 (Leonardo), b) ICC (Integrated Cargo Carrier), and c) LMC (Lightweight Multi—Purpose Experiment Support Structure Carrier), AstroLab (EC–13). Other payloads are: MEPSI—2A (MEMS-based PicoSat Inspector) and MEPSI—2B of AFRL (DARPA—funded) and the 2nd “ball” of SPHERES. The mission was critical for the US space program’s recovery from the disaster. Like last year’s first post—Columbia flight, the latest shuttle mission was largely aimed at improving safety before NASA resumes regular launches to finish constructing the International Space Station by 2010.

- **STS-115**, flight 12A of Atlantis, Sept. 9—21, 2006 (12 day mission, resumption of ISS construction work, the last assembly flight was in 2002). The primary payload of this assembly flight is the Port 3/4 truss segment (mass of 15,700 kg, each truss has a length of 13.8 m and a width of 4.9 m), the next major addition to the 11—segment integrated truss structure. The P3/P4 integrated truss structure contains several discrete elements: two Solar Array Wings (SAW), Integrated Equipment Assembly (IEA), Solar Alpha Rotary Joint (SARJ), two Beta Gimbal Assemblies (BGA) and the Photovoltaic Thermal Control Subsystem. P3 consists of the SARJ, which continuously rotates to keep the solar array wings on P4 and P6 oriented towards the sun as the station orbits the Earth.  

Following its installation utilizing both the Shuttle and the station robotic arms, a series of three space walks will complete the final connections and prepare for the deployment of the station’s second set of solar arrays. The P3/P4 truss, with its two large solar arrays (73 m in length with a new set of photovoltaic solar arrays), will provide one—fourth of the total power generation capability of the completed station in 2010 (110 kW). The truss also contains a device called SARJ (Solar Alpha Rotary Joint), capable to rotate 360º either clockwise or counterclockwise to position the P4 and P6 solar arrays to track the sun for electrical power generation.  

Other payloads are: MEPSI—3A (MEMS-based PicoSat Inspector) and MEPSI—3B of AFRL (DARPA—funded).

- **STS-116**, flight 12.A.1 of Discovery, Dec. 10—22, 2006 (13 day mission). Delivery of three primary payloads: a) the third port truss segment, b) the Spacehab single logistics module (transfer of supplies, hardware and experiments to and from ISS), and c) the ICC (Integrated Cargo Carrier) with the service module debris panels and the DOD space transportation program deployable experiments.

The P5 Truss connects the power and cooling lines and serves as a spacer between the P4 photovoltaic module (PVM), or solar battery, and P6 PVM, which will be joined during a later assembly mission. The P5 Truss has a mass of 1864 kg and a size of 3.37 m x 4.55 m x 4.24 m. The Truss element is installed robotically with a crew assist. P5 also contains a remote sensor box, two tri—axial accelerometers and two antenna assemblies as part of the EWIS (External Wireless Instrumentation System). ICC contains the following payloads: SMDP (Service Module Debris Panels), STP—H2 (Space Test Program—H2), 15 AMPs (Adjustable Mass Plates), and ISS—PFAR (Passive Flight Releasable Attachment Mechanism).

In addition, the third (and last) “ball”, a nanosatellite of the SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) system of MIT (sponsored by
DoD) was delivered to ISS (Note: the first ball of SPHERES, 20 cm in diameter, was delivered to ISS on April 24, 2006 on a Soyuz – U launch vehicle with the Progress M – 56 payload). SPHERES consists of 3 free-flying satellites inside the ISS. They’re equipped with a cold gas propulsion system for maneuverability; they communicate with each other using radio and ultrasonic frequencies. The satellites will test autonomous formation flying, rendezvous and docking techniques (see description of SPHERES on eoPortal).

The STP – H2 of DoD is a payload which deployed the following satellites after the Shuttle undocked from ISS (Dec. 21, 2006) using the newly developed CAPE (Canister for All Payload Ejections) system: 1313)

- a) Two microsatellites called ANDE (Atmospheric Neutral Density Experiment); the objective is to measure the density and composition of Earth’s thermosphere (see ANDE description on eoPortal).

- b) MEPSI (MEMS-based PicoSat Inspector) of AFRL to demonstrate the use of pico-sats for inspection services;

- c) RAFT (Radar Fence Transponder), student experimental satellites, two CubeSats, of the USNA (US Naval Academy), Annapolis, MD. The objective of RAFT is to calibrate the US Space Surveillance Network’s (SSN) radar fence. As one RAFT picosat flies through the radar fence, it will transmit its location. When the second picosat flies through the radar fence, it exercises the radar fence’s locating capability. This effort will improve the SSN’s ability to track small Resident Space Objects. RAFT also contains an amateur radio onboard to train midshipmen at Annapolis in communications.

• STS-117, flight 13A of Atlantis June 8 – 22, 2007 (14 day mission). Delivery and addition of ITS (Integrated Truss Segment) Starboard – 3/Starboard – 4 (S3/S4), the primary payload for power generation (dimension 13.66 m x 4.6 m and a mass of 16,200 kg). The S3/S4 segments were attached to the S1 segment by the robotic arm.

Figure 28: Post STS-117/13A configuration of the ISS (image credit: NASA)

1.5 Overview of Operational Meteorological Missions

Meteorology is the study of the interplay between atmospheric temperature, pressure, humidity, and winds. Spaceborne operational meteorological services, namely the measurement of short-term weather variations in the lower regions of the atmosphere (in particular the troposphere as well as the Earth’s surface), are provided by two types of satellite constellations: LEO (Low Earth Orbit) and GEO (Geostationary Orbit).

The era of meteorological satellites started with the launch of TIROS-1, a LEO S/C of NASA, on April 1, 1960 (a small spin-stabilized S/C with a mass of 122 kg). The first generation of meteorological spacecraft were de-facto research satellites which played a major role in defining future operational systems. The first operational satellites, ESSA-1 (Environmental Science and Services Administration, launch Feb. 3, 1966 of ESSA-1 ) and ESSA-2 (launch Feb. 28, 1966), were 2nd generation spacecraft, in morning and afternoon orbits, respectively. They provided operational direct readout with ATP (Automatic Picture Transmission) on even-numbered ESSAs, and global imagery with stored Vidicon imagery, odd numbered. It is important to realize that forerunner experimental TIROS-8 (launch Dec. 21, 1963) and Nimbus-1 (1964) satellites provided the first APT broadcast service for worldwide users (see 1.13).

Technologically, spaceborne meteorological instruments and data analysis/interpretation have progressed considerably in quality and quantity over the last 40+ year period, from the era of “pictures” to high-resolution digital renderings from a variety of spectral bands, providing information about the atmosphere, clouds, and land and sea surface properties. Today’s data products are being utilized for a variety of applications that span scales from now-casting to long-term climate studies, and include land, ocean, atmosphere and ecological applications. Indeed it would be difficult to find an area of operational meteorology that had not come under satellite “influence.”

At the start of the 21st century, meteorological information from GEO and LEO satellites is a key factor to the art of local forecasting, across scales from synoptic scale (1000s to 100s km) to mesoscales (100 to 10s km). New observation schemes and sources of meteorological parameter fields are being opened with GPS signal applications: a) in ground-based meteorology (see 1.5.5), b) in radio occultation monitoring (see 1.5.4), and c) in bistatic reflection measurements (see 1.5.6). Note: As of 2002, all of the GPS meteorological signal applications are still in an experimental or demonstration state, but they have the potential to augment considerably the data of the conventional GEO and LEO meteorological satellites - at low cost.

“Today we can make 3-5-day weather forecasts with nearly 80% accuracy. That’s fantastic. In 10 year’s time, with all we can learn from our upcoming missions, we intend to push that out to 7 to 10 days with the same accuracy [Note: The improvement in forecast skill at six days is equivalent to gaining an extension of forecast capability of several hours. This magnitude of improvement is quite significant when compared with the rate of general forecast improvement over the last decade]. With the right investments in observations and computational modeling, we might even push that out to 14 days perhaps 20 years from now.” (Daniel Goldin, NASA Administrator, at JHU/APL address, Oct. 10, 2000, Ref. 18).

Meteorological research has transformed the way society thinks about weather and climate in its relatively short lifetime. 1314) At the beginning of the 20th century, most people assumed that the assimilative capacity of the atmosphere was infinite, climate was relatively constant, and most weather events were unpredictable. In the early 21st century, thanks in large part to meteorological research, most educated people know that the assimilative ca-

pacity of the atmosphere is finite, even on global scales; climate is variable, sometimes abruptly so; and weather is considerably more predictable than previously thought.

The global nature of weather systems and satellite observations places satellite data at the very heart of NWP (Numerical Weather Prediction) needs, especially as forecasts extend out to ranges of several days. Indeed, weather and climate forecasts have been revolutionized during the past 40 years. This is in part due to: a) availability of almost global observations, b) improved computer systems and algorithms, and c) considerable advances in modeling and data assimilation (in particular for tropospheric models).

Surveys from NCEP (National Centers for Environmental Prediction) and ECMWF (European Center for Medium-Range Weather Forecasts) indicate that available meteorological data are under-utilized. The main reasons for this under-utilization include: insufficient communications capability, computer power, and the immaturity of operational models and data assimilation systems that link the S/C data to the numerical model.

- General definition of “hindcast”, “nowcast”, and “forecast” service functions in the context of meteorological weather. 1316)

- A hindcast incorporates past or historical observational data for diagnostic purposes (assessment and/or verification strategy of available data sets of a defined period to evaluate a particular feature or a behavior). Hindcast activities are employed for such functions as: climate research, demonstration of predictive model performance, algorithm verification, improvement tests of forecast products, trend analysis studies of particular phenomena, demonstration of integrated forecast sequence characteristics including control. A hindcast may also be made as an inverse calculation, fitting a forward simulation model to observations.

- A nowcast incorporates recent (and often near real-time) observed meteorological, oceanographic, and/or river flow rate data; covers the period of time from the recent past to the present; and makes predictions for locations where observational data are not available. The present is the time at which the nowcast is made, and at which the most recent observations are from a few minutes to an hour old. A nowcast is used to convey information regarding weather events in the next few (generally 1-6) hours.

- A forecast incorporates meteorological, oceanographic, and/or river flow rate forecasts; makes predictions for locations where observational data will not be available; and is usually initialized by the results of a nowcast. Medium range in forecasting (with periodic update intervals) refers generally to information 3-7 days in advance.

Nowcasting in operational meteorology refers to a chain of processes to be conducted in very short time periods - including spaceborne (airborne and/or ground-based network) event monitoring of mesoscale weather patterns (generally of active convective systems causing local thunderstorms, high winds, flash floods, fog, or outer hazardous events), the quick provision of the data for analysis (short delay times), and the nowcast prediction, reflecting the conditions as they currently exist. The nature of current nowcasting capabilities require a concerted and coordinated (i.e., automated) service approach by all parties involved to be able to broadcast warnings of hazardous events. The technique of nowcasting is increasingly becoming a basic service demand by the various end user communities to be able to react to events causing property damage and in particular to be able to protect life. At the start of the 21st century, most nowcasting definitions/services call for a short-range prediction capability within a timeframe of <3 hours, the conventional approach is to use mostly local detail for initial conditions. More advanced nowcasting methods have expanded to include the blending of extrapolation techniques, statistical techniques, heuristic tech-


niques, and NWP (Numerical Weather Prediction).\textsuperscript{1317} The accuracy of local weather forecasting depends very much on the availability of the nowcasting data, and the quick processing capability of large amounts of complementary data sets for identification of severe weather systems. – Note: For weather forecasting the WMO (World Meteorological Organisation) defines nowcasting as within one hour, with short term forecasting falling between one hour and a day.

While observations from polar orbiting LEO weather satellites often detect mesoscale phenomena at the needed spatial resolutions, they lack the temporal resolution required for many nowcasting applications. GEO satellites are in fact the natural candidates for nowcasting applications - if the spatial and spectral resolution requirements can be met. With regard to repeat observations (i.e. temporal resolution), instrument technology and transmission performance is now available to provide this latter requirement on GEO weather satellites. The spectrum of nowcasting data will also include sensor data from a greater variety of sources such as lightning mappers and SAR instruments next to the conventional radiometric and imaging weather data. Examples of emerging service capabilities for nowcasting are:

- MSG-1 of EUMETSAT (launch Aug. 28, 2002) offers a full disk image every 15 minutes, twice the previous imaging rate (however, the spatial resolution of the IR data is still in the order of 3 km)

- CMC (Canadian Meteorological Center) has developed SCRIBE, an expert system capable of generating automatically or interactively any type of weather products for a region or a specific locality in Canada. As of 2003/4, the system is being upgraded to include the latest local observations and nowcasting data on a continuous basis.\textsuperscript{1319)}

- The era of GOES-R (NOAA 3rd generation geostationary satellite, launch 2014) instrument technology, ABI (Advanced Baseline Imager) and HES (Hyperspectral Environmental Suite) sounder, will be able to provide data at resolutions (spatial, spectral, temporal, even simultaneous multisresolution) fully amenable to nowcasting. The nowcasting function support capability is a prime objective of GOES-R.

Note: As of fall 2006, it looks like the HES instrument has been cancelled due to cost overruns.\textsuperscript{1320)}

Background: Nowcasting methods based on satellite and ground-based Doppler radar data are a topic since the 1980s.\textsuperscript{1321)} However, first nowcasting products from satellite data became available in the 1990s by various weather agencies and institutions. The service hinges very much on the timely availability of sufficient observable data at the needed resolutions (initial state specification is fundamental to nowcasting) to provide quantitative estimates. General warnings of hazardous events have become possible with the availability of mass communications. - Future nowcasting services and products will not only come from weather satellites, but also from other spacecraft observations such as from altimetry and radar missions. For instance, an objective of the Jason-1 (and Jason-2) altimeter missions is to provide a near real-time data and product service for operational activities such as marine nowcasting, and numerical prediction of sea state, ocean circulation, and weather.


1.6.2 The dominant forecasting method in the time frame 2015-2025 is expected to be provided by NWP algorithms and techniques, which by then will be able to resolve the scales of interest in very short-range forecasting.

1.5.1 Contributions of Environmental Satellite Data to Meteorology

Operational meteorology has generally two major sources of satellite data: a) operational meteorological satellites in LEO and GEO, and b) environmental satellites/instruments [availability/integration of R&D (Research & Development) data for operational meteorology (study of complex interactions between the Earth’s atmosphere, oceans and land surfaces, also study of long-term and large-scale effects of the Earth system)]. It should be pointed out that the field of operational spaceborne meteorology has particularly benefited from complementary data of environmental/demonstration instruments flown on several research missions (designed primarily to study specific processes of scientific interest or to test new observing technologies). Of particular importance is wind (tropospheric and ocean surface) data on a global basis in this context (the ocean surface wind vector is a key parameter in understanding the weather due to its dominant role in the energy exchange at the air-sea interface). A few example missions/instruments in this category are [only short recounts are provided, see also chapter 1.2.6 (Sounding of the Atmosphere)]:

- The ERS-1 (launch July 17, 1991) and ERS-2 (launch Apr. 21, 1995) missions of ESA flew the instruments AMI-SCAT and RA-1 (Radar Altimeter-1). The data of both instruments permitted estimation of ocean surface wind speed, AMI-SCAT also of wind direction. In parallel, ATSR provided SST. See D.15.

The ERS program demonstrated among other things that satellite altimetry data is a new and valuable tool to monitor land and ocean surfaces with important applications to such fields as hydrology and regional climate variability (by monitoring slight chances in sea level, ocean currents and polar ice).

- The same findings were provided by the TOPEX/Poseidon mission (launch Aug. 10, 1992) of NASA and CNES. See chapter 1.6.2 (Satellite Altimetry). TOPEX/Poseidon is best known for its ability to monitor the progress of large-scale ocean phenomena like El Niño, La Niña and a long-term ocean feature called the Pacific Decadal Oscillation that waxes and wanes every 20 to 30 years. In 2002, after ten years of operations, TOPEX/Poseidon continues to provide its data for long-term climate forecasting and prediction models. TOPEX/Poseidon produced the first global views of seasonal current changes. It maps year-to-year changes in upper-ocean heat storage. The satellite has improved our understanding of tides, producing the world’s most precise global tidal maps and demystifying deep-ocean tides and their effect on ocean circulation. It monitors global mean sea-level changes, an effective indicator of the consequence of global temperature change. Its data are input into atmospheric models for forecasting hurricane seasons and individual storm severity.


- The TRMM cooperative mission of NASA/NASDA (launch Nov. 27, 1997) is carrying PR (Precipitation Radar) of NASA with the objective to measure 3-D rainfall distribution (from surface to about 20 km). Rain rates down to about 0.7 mm/h can be detected. The normalized radar cross-section of PR offers also the capability to extract ocean surface

winds. In parallel, there is TMI (TRMM Microwave Imager) of NASA to measure SST, wind speed, columnar water vapor, cloud liquid water, and rain rate. The CERES demonstration instrument of NASA measures the radiation from the top of the clouds as well as from the Earth’s surface. TRMM focuses on the intensity of tropical rainfall, which is indicative of whether a cyclone is weakening or strengthening.

- The IRS-P4 (OceanSat-1) mission of ISRO (launch May 26, 1999) carries MSMR (Multifrequency Scanning Microwave Radiometer) to measure sea surface temperature (SST), sea surface wind speed (SSW), atmospheric water vapor (WV), and cloud liquid water content (CLW). See D.22.7.
- The QuikSCAT mission of NASA (launch June 19, 1999) with SeaWinds (wind speed and direction on a swath of 1800 km in width making about 400,000 measurements and covering 90% of the Earth’s surface in one day). See A.25.
- The Terra (launch Dec. 18, 1999) mission of NASA is flying the MODIS instrument providing a number of environmental parameters, in particular SST.
- The Envisat mission of ESA (launch Mar. 1, 2002, see D.11) is with 8,300 kg the largest environmental satellite ever built. It flies a total of 10 instruments, among them RA-2 to estimate the wind speed and significant wave height (besides altimetry). In addition, there are the atmospheric instruments onboard with GOMOS, MIPAS and SCIAMACHY. AATSR (Advanced Along Track Scanning Radiometer) provides SST (with an accuracy of 0.3ºC) and TOA (Top-of-Atmosphere) brightness temperature at 1 km resolution. The MERIS instrument provides operational products relevant for global climate and climate change studies. The most important parameters are the cloud optical thickness, albedo, top pressure, cloud type and reflectance. This set of parameters coupled with the MERIS global and long-term observation strategy should lead to a better understanding of the role of clouds in the global energy budget and their impact on the Earth’s climate.
- The Aqua mission of NASA (launch May 4, 2002) is dedicated to the study of the Earth’s interrelated processes (atmosphere, oceans, and land surface) and their relationship to the Earth system climate changes. The MODIS instrument provides a number of environmental parameters, in particular SST. The AMSR-E provides sea surface wind fields, precipitation rate, water vapor content and surface moisture content. AIRS provides hyperspectral measurements of global temperature/humidity profiles in the atmosphere (among other measurements). AMSU/HSB provides in parallel temperature and humidity soundings of the atmosphere. See D.13.2.
- The ADEOS-II mission of JAXA (launch Dec. 14, 2002) flies SeaWinds (wind speed and direction) a NASA scatterometer. The ADEOS-II instruments provide information in water and energy cycling. AMSR acquires water vapor, precipitation, SST, sea surface wind, sea ice, etc. See D.2.
- The Coriolis mission of NRL (launch Jan. 6, 2003) carries WindSat (Wind Microwave Radiometer) as its prime instrument. The objective of the polarimetric WindSat is to conduct an operational demonstration of the WindSat system (demonstrator to CMIS on NPOESS) and to measure the ocean surface wind vector (speed and direction) for a number of practical applications (secondary measurements are sea surface temperature, rain rate and water vapor). See A.12.
- The CryoSat mission of ESA (launch Oct. 8, 2005 — but launch failure) with SIRAL (SAR Interferometer Radar Altimeter) has the prime objective to observe ice sheet interiors, the ice sheet margins, for sea ice and other topography (variations in the thickness of the Earth’s continental ice sheets and marine ice cover). Sea ice plays a central role in Arctic climate. See E.2.

The EO-3 (Earth Observing-3, GIFT5-IOMI Mission) GEO satellite, a joint NASA, Navy, and NOAA mission (launch 2008), carries the instrument GIFT5 (Geostationary Imaging Fourier Transform Spectrometer) to demonstrate the requirements on NOAA’s future HES (Hyperspectral Environment Suite) capabilities of the GOES-R program. HES is planned to fly on GOES-R (launch in 2014) and beyond. GIFT5 on EO-3, a multi-channel imager and sounding interferometer, is well suited to analyze a variety of atmospheric and surface phenomena (see M.11).

The SMOS (Soil Moisture and Ocean Salinity Mission) of ESA (launch 2007) will demonstrate synthetic aperture radiometry with MIRAS (Microwave Imaging Radiometer using Aperture Synthesis). The objectives are to obtain multi-incidence observations of two crucial variables, namely soil moisture (SM) over land and ocean salinity (OS) over the sea, with sufficient spatial resolution and revisit time for modeling weather and climate. MIRAS also monitors the vegetation water content, snow cover and ice structure. Both variables, SM and OS, are used in predictive atmospheric, oceanographic and hydrologic models and may be important for extreme event forecasting. See D.44.

The NPP (NP0ESS Preparatory Project) of NASA/IPO (launch 2009). The objective is to demonstrate the performance of four advanced instruments: VIIRS (Visible/Infrared Imager and Radiometer Suite), CrIS (Cross-Track Infrared Sounder), OMPS (Ozone Mapping and Profiler Suite), and ATMS (Advanced Technology Microwave Sounder). See G.9.

ADM-Aeolus (Atmospheric Dynamics Mission), the 2nd Earth Explorer core mission of ESA, is planned for launch in 2008. It carries ALADIN (Atmospheric Laser Doppler Instrument), a Doppler wind lidar. The primary objective is to provide highly accurate wind profile measurements over the altitude range 0-20 km, for an improved analysis of the global three-dimensional wind field. Such knowledge is crucial to the understanding of the atmospheric dynamics, including the global transport of energy, water, aerosols, chemicals and other airborne materials - to be able to deal with many aspects of climate research and climate and weather prediction. See A.3.

The GCOM (Global Change Observation Mission) program of JAXA (successor to ADEOS, ADEOS-II) and partners is dedicated to the study of global change phenomena by studying transport processes in the atmosphere of the carbon cycle and the energy cycle. Carbon plays many roles in the Earth system. It forms our food and acts as our primary energy source, but is also a major contributor to the planetary greenhouse effect and the potential for climate change. Carbon GCOM aims at estimating the primary production as well as to monitor the carbon flux; in addition, measurement of greenhouse gases such as CO2, CH4, and O3. The GCOM program consists of three elements:

- **GOSAT (Greenhouse gas Observing Satellite).** The emphasis is on atmospheric monitoring (clarify sources and sinks of CO2 on a continental scale). GOSAT carries TANSO—FTS (Thermal And Near infrared Sensor for carbon Observation — Fourier Transform Spectrometer) and TANSO—CAI (Thermal And Near infrared Sensor for carbon Observation — Cloud and Aerosol Imager). The GOSAT launch is planned for 2008.
- **GCOM-B1.** The focus is on the energy cycle and material cycle. Core instruments planned for GCOM-B1 are: SGLI (Second-generation Global Imager) and AMSR-2.
- **GPM (Global Precipitation Mission) research mission of NASA and JAXA with advanced rain measuring instruments.** The DPR (Dual-frequency Precipitation Radar) is provided by JAXA/ CRL on the core satellite. GPM is a follow-up mission to TRMM encompassing eventually a constellation of a core S/C plus eight microsatellites. The launch of the core satellite is planned for 2009. The EGPM (European Global Precipitation Mission) element of ESA is part of the constellation. The GPM mission aims to measure precipitation on a global basis with sufficient quality, coverage, and sampling to improve prediction of the weather, the Earth’s climate, and specific components of the global water cycle.

1327) Note: The previous name of HES was ABS (Advanced Baseline Sounder) in the NOAA program
• OCO (Orbiting Carbon Observatory) is a NASA/JPL minisatellite science mission within ESSP. The OCO objective is to provide global measurements of atmospheric carbon dioxide (CO₂) needed to describe the geographic distribution and variability of carbon dioxide sources and sinks to address the complex nature of the carbon cycle. A launch of OCO is planned for 2008. OCO will become part of the “A-Train” to correlate the OCO data with data acquired by other instruments (AIRS) on Earth observing spacecraft.

Note: CO₂ is the principal atmospheric component of the global carbon cycle. The overwhelming scientific consensus predicts that human emissions of carbon dioxide will warm the planet over the coming decades and centuries. By how much and how quickly is still up for dispute, but most agree it’s time to take action. Reducing carbon dioxide emissions is the key to counteract global warming.

• SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis) is an Earth Explorer candidate mission in ESA's Living Planet Program. A major objective is to provide detailed and precise measurements of vegetation amounts and conditions with a spatial resolution sufficient to characterize individual vegetation types and to assess the role of the terrestrial component of the global carbon cycle. A launch is expected in 2009.

• The availability of hyperspectral infrared sounding data on AQUA, MetOp, NPP, and NPOESS will improve the temperature and moisture profiling in meteorology.

1.5.2 LEO (Low Earth Orbit) Meteorological Satellite Missions

LEO S/C in polar sun-synchronous orbits provide wide-swath repeat observations (same sun illumination angles) of a given Earth surface region at the same time of the day (due to same latitudinal crossings).

• The first meteorological LEO services started with NASA’s launch of TIROS-1 (Television Infrared Observation Satellite) on April 1, 1960, the first true weather satellite. Since then, five generations of polar-orbiting meteorological S/C were developed by NASA and flown by NOAA as outlined in Table 64. The NOAA 4th-generation polar program (ATN), which started in 1978 with the launch of TIROS-N, is based on the services of two operational satellites flying in complementary sun-synchronous orbits, one in a “morning or AM” orbit, and the second in an “afternoon or PM” orbit.

• The US military services of DoD built their own polar-orbiting meteorological satellite series in parallel to the civil system of NASA/NOAA, referred to as DMSP (Defense Meteorological Satellite Program). The first generation of DMSP S/C started with the launch of a Block 4 series satellite on Jan. 19, 1965 and ended with the launch of a Block 5C S/C on Feb 19, 1976. The various generations of DMSP satellites are listed in Table 468. The OLS (Operational Linescan System) instrument on DMSP provides in addition to its normal daytime (visible) imagery also nighttime imagery with its IR channels.

• The Meteor-1 series of the former USSR started with the launch of Meteor-1-1 on March 23, 1969; the 1st generation series lasted until 1978 with the launch of Meteor-1-28. This was succeeded by the Meteor 2 series from 1975 to 1990 (Meteor-2-1 to 2-21), and further by the Meteor-3 series from 1985 to the present time (see Table 524).

• The Chinese polar-orbiting meteorological program started in 1977 followed by the launch of the FY-1A (Feng-Yun-1) satellite of CMA (China Meteorological Administration) on Sept. 7, 1988 and FY-1B on Sept. 3, 1990, etc.

The 2nd generation polar orbiting program starts with FY-3A (launch 2007) featuring a

1330) http://www.esa.int/esaLP/ASE12YNW9SC_spectra_0.html
global imaging and sounding capability, and a DCS (Data Collection System) capability. The imaging instruments are: VIRIR (Visible and Infrared Radiometer), MERSI (Medium Resolution Spectral Imager), and MWRI (Microwave Radiation Imager). The sounding instruments are: IRAS (Infrared Atmospheric Sounder), ASI (Atmospheric Sounding Interferometer), MWTS (Microwave Temperature Sounder), and MWHS (Microwave Humidity Sounder). \(^{(1331)}\)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Years</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation</td>
<td>1960 - 1965</td>
<td>TIROS series [TIROS-1 (1960) to TIROS-10 (1965)]</td>
</tr>
<tr>
<td>2nd generation</td>
<td>1966 - 1969</td>
<td>TOS (TIROS Operational System) series as pre-launch designation. The in-orbit satellite designation was ESSA [ESSA-1 (1966) to ESSA-9 (1969)], after the S/C operating agency.</td>
</tr>
<tr>
<td>3rd generation</td>
<td>1970 - 1976</td>
<td>ITOS (Improved TIROS Operational System) series as pre-launch designation. The in-orbit satellite designation was NOAA [NOAA-1 (1970) to NOAA-5 (1976)]</td>
</tr>
<tr>
<td>4th generation</td>
<td>1978 - 1994</td>
<td>ATN (Advanced TIROS-N) series. After TIROS-N (1978) the pre-launch designation changed to NOAA-A (the corresponding inflight name was NOAA-6). The pre-launch letter designation was kept throughout. NOAA-8 through NOAA-14 were designated ATN (Advanced TIROS-N) spacecraft, equipped for S&amp;R (Search and Rescue) and growth instruments.</td>
</tr>
</tbody>
</table>

Table 64: Overview of the US civilian polar meteorological programs

- EUMETSAT, the European meteorological service provider, was planning on a polar-orbiting satellite series since the mid 1980s. Since the early 1990s, NOAA and EUMETSAT have been discussing/planning future polar cooperation with increased European responsibility for the “morning orbit” to ensure continuity of the POES (Polar-orbiting Operational Environmental Satellites) services. The basic intent is to join the space segment of the emerging MetOp program of EUMETSAT with the existing POES program of NOAA into a fully coordinated service, thus sharing the costs of a program for synergistic reasons. The plans came to a common baseline and agreement, referred to as IJPS (Initial Joint Polar System), in 1998. IJPS comprises two series of independent, but fully coordinated polar satellite systems, namely POES and MetOp, to provide for the continuous and timely collection and exchange of environmental data from space. EUMETSAT plans to include its satellites MetOp-A, -B, -C and -D for the morning orbit, while NOAA is starting with its NOAA-N and N’ spacecraft for the afternoon orbit of the coordinated system (launch of NOAA-N on May 20, 2005). MetOp-A was launched on Oct. 19, 2006. - In this context, Europe (i.e. ESA, EUMETSAT) refers to its application-oriented missions (this includes operational meteorological and climate monitoring missions) in LEO and GEO as “Earth Watch Missions” (MetOp, MSG). The Earth Watch concept was introduced in 1994/5, dealing in particular with prototype operational missions and serving applications-oriented needs in partnerships of industry and/or public agencies. Long-term operational service provision is the ultimate aim of the ESA Earth Watch program.

- NPP (NPOESS Preparatory Project). NASA and IPO (Integrated Program Office) plan the NPP mission (launch in 2009) with the objective to demonstrate/validate the operation of four advanced instruments (VIIRS, CrIS, ATMS, OMPS) scheduled to fly on NPOESS. ATMS (Advanced Technology Microwave Sounder) is a NASA-provided instrument with the objective to combine the passive-microwave observation capabilities of three heritage instruments, namely AMSU-A1/A2 and MHS, into a single instrument with a correspondingly reduced mass and power consumption and with advanced microwave-receiver electronics technologies. NASA is also providing the NPP spacecraft and the launch.

NPP is considered to bridge the gap between NASA’s EOS spacecraft (Terra, Aqua, and Aura) and the operational NPOESS missions.

<table>
<thead>
<tr>
<th>Satellite Series (Agency)</th>
<th>Launch</th>
<th>Major Instruments</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA-2 to -5 (NOAA)</td>
<td>21.10.1971, 29.7.1976</td>
<td>VHRR</td>
<td>2580 km swath</td>
</tr>
<tr>
<td>TIR-15 (NOAA)</td>
<td>13.10.1978</td>
<td>AVHRR, AVHRR/3</td>
<td>&gt;2600 km swath</td>
</tr>
<tr>
<td>TIR-15 (NOAA)</td>
<td>13.5.1998 - 2007</td>
<td>OLS, SSM/I, OLS, SSM/I,</td>
<td>&gt;2600 km swath</td>
</tr>
<tr>
<td>DMSP Block 5D-1 (DoD)</td>
<td>11.9.1976 - 14.7.1980</td>
<td>AVHRR/3</td>
<td>3000 km swath</td>
</tr>
<tr>
<td>DMSP Block 5D-3 (DoD)</td>
<td>12.12.1999</td>
<td>OLS, SSM/I</td>
<td></td>
</tr>
<tr>
<td>Meteor-3 series of Russia</td>
<td>24.10.1985</td>
<td>MR-2000M, MR-900B</td>
<td>3100 km, 2600 km swath</td>
</tr>
<tr>
<td>Meteor-3M-1 of Russia</td>
<td>10.12.2000</td>
<td>MTVZA</td>
<td>2200 km swath</td>
</tr>
<tr>
<td>Meteor-3M-2 of Russia</td>
<td>2004</td>
<td>SAGE-III</td>
<td></td>
</tr>
<tr>
<td>FY-1A, 1B, 1C</td>
<td>7.9.1988, 3.9.1990, 10.5.2000, 2006, 2009</td>
<td>MVISR, IRAS, etc.</td>
<td>2800 km swath</td>
</tr>
<tr>
<td>FY-3A, FY-3B, FY-3C</td>
<td></td>
<td></td>
<td>1st generation</td>
</tr>
<tr>
<td>MetOp/EPS (EUMETSAT)</td>
<td>19.10.2006 (of MetOp-A)</td>
<td>AVHRR/3, MHS, IASI (8000 channels)</td>
<td>PM complement to NOAA-POES series</td>
</tr>
<tr>
<td>NPOESS (IPO)</td>
<td>2009</td>
<td>VIIRS, CrIS, ATMS OMPS</td>
<td>(NPOESS Preparatory Project)</td>
</tr>
<tr>
<td>NPOESS (IPO)</td>
<td>2012</td>
<td>VIIRS, CMIS, CrIS</td>
<td>Successor of NOAA-POES and DMSP series</td>
</tr>
</tbody>
</table>

| NPOESS (IPO)              | 2012    | VIIRS, CMIS, CrIS | Successor of NOAA-POES and DMSP series |

Table 65: Overview of polar-orbiting meteorological satellite series

- NPOESS (National Polar-orbiting Operational Environmental Satellite System). NPOESS (G.10) represents the future US meteorological polar-orbiting system (merger of NOAA-POES and DMSP programs) with the objective to provide a single national remote-sensing capability for meteorological, oceanographic, climatic and space environmental data. The NPOESS data sets will contain a number of variables that are currently not included in operational measurements (such as: radiation budget, total ozone, wind speed and direction, ocean topography, and ocean color) and will offer improved quality for some variables now being measured (such as: atmospheric moisture and temperature profiles, all-weather SST, and vegetation indices). The IPO plan for NPOESS is to launch its first satellite in the time frame 2009. Initial plans for the merger of the two services started in 1993. The following NPOESS sensor payloads are under development: CMIS (Conical-scanning Microwave Imager/Sounder) of SSM/I (Special Sensor Microwave Imager), SSMIS (Special Sensor Microwave Imager Sounder) and TMI (TRMM Microwave Imager) heritage, CrIS (Cross-Track Infrared Sounder) of HIRS/4, AIRS and IASI heritage, OMPS (Ozone Mapping and Profiler Suite) of SBUV/2, TOMS and GOME heritage, VIIRS (Visible/Infrared Imager and Radiometer Suite) of OLS, AVHRR/3, MODIS, and SeaWiFS heritage, GPSOS (GPS Occultation Sensor) of GRAS (GNSS Receiver for Atmospheric Sounding) and GPS/MET heritage, and SESS (Space Environment Sensor Suite) of SEM-2 heritage. - When operational, the NPOESS system will provide global three-hour repeat coverage.

In the fall of 2002, NGST (Northrop Grumman Space Technology) 1332) [formerly TRW Inc. of Redondo Beach, CA], was awarded a single prime contract, referred to as A&O (Acquisition and Operations), by IPO (for Shared System Performance Responsibility) to build and deploy the NPOESS spacecraft series. NGST, with its teammate Raytheon, is responsible for developing, integrating, deploying, and operating NPOESS satellites to meet the tri-agency requirements for NPOESS over the 10-year operational life of the program.

- The NPOESS system, together with the MetOp/EPS system, will constitute the polar component of the next generation meteorological observing system.

Some LEO meteorological instruments: An overview cannot be complete without giving credit to at least one workhorse instrument, AVHRR (Advanced Very High Resolution Radiometer).

- AVHRR (Advanced Very High Resolution Radiometer) of the NOAA-POES satellite series is the spaceborne instrument with the longest service period, the widest data distribution and data analysis in the history of operational meteorology, oceanography, climatology, vegetation monitoring, and land and sea ice observation. The instrument provides wide-swath (≥2600 km, FOV = ±56°) multispectral imagery of about 1.1 km spatial resolution from LEO polar orbits (nominal altitude of 833 km). The resolution of 1.1 km is still quite high for the wide-swath measurement of large-scale meteorological phenomena. The imagery is used in a great variety of applications, such as: investigation of clouds, land-water boundaries, snow and ice extent, sea surface temperature, day and night cloud distribution, vegetation index, etc.

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>TIROS-N</th>
<th>NOAA-6, -8, -10</th>
<th>NOAA-7, -9, -11, -12, -14</th>
<th>IFOV (mrad)</th>
<th>Principal use of channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.550 - 0.90</td>
<td>0.550 - 0.68</td>
<td>0.550 - 0.68</td>
<td>1.39</td>
<td>Day cloud and surface mapping</td>
</tr>
<tr>
<td>2</td>
<td>0.725 - 1.10</td>
<td>0.725 - 1.10</td>
<td>0.725 - 1.10</td>
<td>1.41</td>
<td>Surface water delineation, vegetation mapping</td>
</tr>
<tr>
<td>4</td>
<td>10.50 - 11.50</td>
<td>10.50 - 11.50</td>
<td>10.30 - 11.30</td>
<td>1.41</td>
<td>SST and night time cloud mapping</td>
</tr>
<tr>
<td>5</td>
<td>repeat of Channel 4</td>
<td>repeat of Channel 4</td>
<td>11.50 - 12.50</td>
<td>1.30</td>
<td>Surface temperature and day/night cloud mapping</td>
</tr>
</tbody>
</table>

Table 66: Spectral channels of AVHRR

The benefit of AVHRR data lies in its high temporal frequency of daily global coverage. The AVHRR instrument was initially designed for meteorological applications. It is of interest to note that initial objectives of AVHRR were to develop a system that would provide a more efficient way to track clouds, estimate snow cover extent, and estimate sea surface temperature. It wasn’t until a few years after the launch of the first AVHRR instrument that its usefulness in monitoring global vegetation became obvious.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Center wavelength (µm)</th>
<th>Spectral Range FWHM (µm)</th>
<th>Channel Noise</th>
<th>Detector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.630</td>
<td>0.58 - 0.68</td>
<td>SNR ≥ 9:1 @ 0.5% albedo</td>
<td>Silicon</td>
</tr>
<tr>
<td>2</td>
<td>0.862</td>
<td>0.725 - 1.00</td>
<td>SNR ≥ 9:1 @ 0.5% albedo</td>
<td>Silicon</td>
</tr>
<tr>
<td>3a</td>
<td>1.61</td>
<td>1.58 - 1.64</td>
<td>SNR ≥ 20:1 @ 0.5% albedo</td>
<td>InGaAs</td>
</tr>
<tr>
<td>3b</td>
<td>3.74</td>
<td>3.55 - 3.93</td>
<td>NEAT ≤ 0.12 K @ 300 K</td>
<td>InSb</td>
</tr>
<tr>
<td>4</td>
<td>10.80</td>
<td>10.30 - 11.30</td>
<td>NEAT ≤ 0.12 K @ 300 K</td>
<td>HgCdTe</td>
</tr>
<tr>
<td>5</td>
<td>12.00</td>
<td>11.50 - 12.50</td>
<td>NEAT ≤ 0.12 K @ 300 K</td>
<td>HgCdTe</td>
</tr>
</tbody>
</table>

Table 67: Spectral parameters of AVHRR/3 (starting with NOAA-15)

Three generations of AVHRR whiskbroom scanning instruments (built by ITT Aerospace of Fort Wayne, IN) provided daily global coverage starting from 1978 (TIROS-N) to the turn of the millennium and beyond. The first 3rd generation instrument (AVHRR/3) with six channels was launched on May 13, 1998 as part of the NOAA-15 sensor complement. Although described in G.14.1, G.14.11, and G.15.1, it is worthwhile to repeat some tables of this remarkable instrument.

AVHRR is of VHRR (Very High Resolution Radiometer) heritage, a two-channel instrument flown on the ITOS (Improved TIROS Operational System) series, starting with NOAA-2 (ITOS-D), launch of ITOS-D on Oct. 15, 1972. The last one of the series flying the VHRR instrument was NOAA-5 (ITOS-H) with a launch July 29, 1976.
1.5.2.1 Sea Surface Temperature (SST) measurements from LEO satellites

- SST is a physical parameter derived from microwave radiometer data as well as from infrared imagery (best retrieval of infrared SST observations in cloudless regions). The analysis of SST observations is an important indicator of the coupling between the ocean surface and the atmosphere - used in climate modeling and in many other fields (meteorology/oceanography). In general, observations at two or three wavelengths (in atmospheric windows) are combined in order to correct for atmospheric attenuation due to water vapor and aerosols.\footnote{E. P. McClain, W. G. Pichel, C. C. Walton, Z. Ahmad, J. Sutton (1983) "Multichannel improvements to satellite derived global sea surface temperatures," Advances in Space Research, Vol. 2, 1983, pp. 43-47.} The ability to monitor global and regional surface temperature has improved considerably; it is now possible to use SST observations as indicators of regional- to basin-scale change, as well as for forecasting stress on the natural flora and faunal assem-

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Spacecraft & Launch Date & Ascending Node & Descending Node & S/C Service Period \\
\hline
NOAA-12 & May 14, 1991 & 19:30 & 07:30 & May 14, 1991 - present \\
NOAA-13 & Aug. 9, 1993 & & & Failure 12 days after launch, NOAA lost contact with the S/C \\
NOAA-16 & Sep. 21, 2000 & 14:00 & 02:00 & Sept. 21, 2000 - present \\
NOAA-17 & June 24, 2002 & & 10:00 & \\
\hline
\end{tabular}
\caption{Temporal AVHRR coverage of NOAA POES series satellites}
\end{table}
blages. SST is also very sensitive to changes in the ocean circulation, as demonstrated time and again by the ENSO cycle. The longest data set of in-situ SST observations is based on observations initially made from ships (capturing buckets of seawater from over the sides of ships and measuring the temperature with a thermometer). From about 1870 onwards the ship observations were sufficiently frequent (very limited spatial coverage) to permit a global SST analysis.

First spaceborne infrared SST data was provided by the VHRR (Very High Resolution Radiometer) instrument flown on NOAA-2 (launch Oct. 15, 1972). Better spaceborne SST retrievals became available from channels 3 and 4 of the AVHRR/1 instrument flown on the TIROS-N S/C (launch Oct. 13, 1978). More accurate SST retrievals became available with the introduction of AVHRR/2, first flown on NOAA-7 (launch June 23, 1981) and subsequent NOAA/POES missions. The AVHRR/3 instrument generation (with 6 bands) was first flown on NOAA-15 (launch May 13, 1998). SST observations are made from AVHRR using statistically derived retrievals schemes, to an accuracy of 0.4 to 0.6 K. The NOAA/NASA Pathfinder AVHRR/SST product is a high quality dataset derived from the NOAA/POES series of satellites that start with the NOAA-9 in 1985. This dataset represents a historical reprocessing of the entire AVHRR time series using consistent SST algorithms, improved satellite and intersatellite calibration, quality control and cloud detection.

The ATSR (Along Track Scanning Radiometer) instrument of ESA is flown on ERS-1/2 missions since July 1991 measuring infrared radiances (3 channels) from the Earth’s surface at spatial resolutions of 1 km. AATSR of ESA (Advanced ATSR), flown on Envisat, provides a radiometric resolution of 0.1 K, an SST accuracy <0.5 K, and a spatial resolution of 1 km. A unique feature of all ATSR/AATSR instruments is their dual-observation geometry (forward and nadir scanning), doubling their retrieval capability. AASTR provides significantly improved calibration and noise parameters as compared to AVHRR/3. However, continuity of AASTR data beyond the Envisat era is not assured unless introduced into an operational system.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteor-2 series starting with Meteor-2-4 (launch Oct. 25, 89)</td>
<td>Klimat</td>
<td>Pre-operational instrument of PLANETA, Russia</td>
</tr>
<tr>
<td>ERS-1 (launch July 17, 1991) ERS-2 (launch Apr. 21, 1995)</td>
<td>ATSR ATSR-2</td>
<td>Pre-operational instrument Pre-operational instrument</td>
</tr>
<tr>
<td>TRMM (launch Nov. 27,1997)</td>
<td>TMI</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>IRS-P4 (launch May 26, 1999)</td>
<td>MSMR of ISRO</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>FY-1B (launch Sept. 3, 1990) FY-1C (launch May 10, 1999)</td>
<td>MVISR (Multichannel Visible and IR Scanning Radiometer)</td>
<td>Pre-operational instrument of CMA, China</td>
</tr>
<tr>
<td>Terra (launch Dec. 18, 1999) Aqua (launch May 4, 2002)</td>
<td>MODIS MODIS, AMSR-E</td>
<td>Pre-operational instrument Pre-operational instrument</td>
</tr>
<tr>
<td>Meteor-3M-1 (launch Dec. 10, 2001), Russia</td>
<td>MTVZA (Microwave Imaging/Sounding Radiometer)</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>Envisat (launch Mar. 1, 2002)</td>
<td>AATSR</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>HY-1A (Haiyang-1, launch May 15, 2002)</td>
<td>COCTS (Chinese Ocean Color and Temperature Scanner)</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>ADEOS-II (launch Dec. 14,2002), JAXA</td>
<td>AMSR (Advanced Microwave Scanning Radiometer), GLI</td>
<td>Pre-operational instrument</td>
</tr>
</tbody>
</table>

1336) http://www.met-office.gov.uk/research/nwp/satellite/infrared/sst/sst_climate.html
<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coriolis (launch Jan. 6, 2003)</td>
<td>WindSat</td>
<td>Demonstration for CMIS</td>
</tr>
<tr>
<td>Sich-1M (launch Dec.24,2004) Russia, Ukraine</td>
<td>MTVZA-OK (Combined Microwave-Optical Imaging/Sounding Radiometer)</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>NPP (NPOESS Preparatory Project), launch in 2009</td>
<td>VIIRS (Visible/Infrared Imager and Radiometer Suite)</td>
<td>Pre-operational instrument</td>
</tr>
<tr>
<td>SMOS of ESA (launch 2007)</td>
<td>MIRAS (for SSS and SST retrieval)</td>
<td>Demonstration instrument</td>
</tr>
<tr>
<td>GCOM-B1, JAXA (2008)</td>
<td>SGLI (Second-generation Global Imager) and AMSR-2</td>
<td>Pre-operational instruments</td>
</tr>
<tr>
<td>NPOESS (launch in 2012)</td>
<td>VIIRS, CMIS (Conical-scanning Microwave Imager/Sounder)</td>
<td>Operational series</td>
</tr>
</tbody>
</table>

Table 69: Overview of spaceborne LEO instruments suitable for SST retrieval

The accuracy of SST data is of great importance for climate modeling and climate change detection/prediction [numerical climate modeling with GCMs (Global Climate Models)]. The energy (gas) transfer between the ocean surface and the atmosphere is highly dependent on the “skin temperature” of the surface waters (surface winds are another important factor). For illustration: An error of 0.1 K in SST knowledge corresponds to an error in the global flux of CO₂ of 15%, while an error of 0.5 K leads to an error of 75% in CO₂ flux. The algorithms for SST retrieval include the MCSST (Multichannel SST) and NLST (Non-Linear SST) algorithms, and the newly implemented experimental ACSST (Aerosol-Corrected SST) scheme.

Passive microwave radiometers offer an all-weather observation capability for measuring SST (some atmospheric attenuation is experienced). The challenge with microwave instruments is to increase the spatial resolution of the data (which are in the ranges of 20-100 km depending on channel frequency). The first such instruments are: TMI (TRMM Microwave Imager) on TRMM, MSMR (Multifrequency Scanning Microwave Radiometer) on IRS-P4 (ISRO), MODIS and AMSR-E on Aqua (NASA) and AMSR on ADEOS-II (JAXA). MODIS is also flown on the Terra spacecraft of NASA. The CMIS (Conical-scanning Microwave Imager/Sounder) of the planned NPOESS series, an advanced instrument of SSM/I and SSMIS heritage of the DMSP (US/DoD) satellite series, is a dual- and single look passive polarimetric microwave radiometer. SST is going to be one of the CMIS data products with a medium-scale spatial resolution of about 25 km. Note: Microwave SSTs cannot be obtained within about 100 km of the coast with current sensors because of contamination in the 5% sidelobes, and can be biased by islands of scale 1 km within the main field of view. But nonetheless, for non-coastal, lower resolution applications, MW SSTs are an excellent addition to the infrared SST observing system.

1.5.3 GEO (Geostationary Orbit) Weather Satellites

The geostationary orbit provides new observation concepts, a synoptic view of Earth’s disk. Satellites in geostationary orbits exhibit a fixed-position, constant-signal and a continuous-

1342) Note: Earlier microwave radiometers like SMMR on SEASAT and Nimbus-7 (both launches in 1978) were poorly calibrated for SST retrieval. The SSM/I instrument, flown on the DMSP series, did not have the low frequency channels needed for accurate SST retrieval algorithms.
coverage relationship with large area coverage between the satellite and its ground segment. Conventional observation data, provided by the S/C instruments from GEO locations (about 45 times further away than LEO systems at altitude of 800 km), are generally of coarse resolution (in the order of kilometers). However, the data are ideal to monitor large-scale weather phenomena. Since the mid 1960s a global network of geostationary meteorological satellites has been built up continuously around the equator orbital plane by the various national agencies of the world to provide an ever-increasing service to its user community. The data of the various satellite series also contribute to GARP (Global Atmospheric Research Program) of WMO.

- The NASA ATS (Application Technology Satellite) series set the stage for demonstrations (in particular communication experiments, first meteorological observations, etc.) in geostationary orbits. ATS-1 (launch Dec. 6, 1966, with a mass of 414 kg) flew SSCC (Spin-Scan Cloudcover Camera) to provide continuous cloudcover patterns of the full-disk Earth view. The telescope photomultiplier assembly could be tilted in discrete steps to ±7.5º to a north-south scan (equivalent to ±52º latitude). The east-west scan was provided by the S/C spin of 100 rpm. A ground resolution of about 4 km was obtained. SSCC operated on ATS-1 until Oct. 16, 1972.

ATS-1 (Applications Technology Satellite), a spin-stabilized S/C (mass of 352 kg), built by Hughes Aircraft Company, was the first experimental near-geostationary weather satellite (position at 150º W longitude) with the ability to “see weather systems” with SSCC, an instrument built by Hughes SBRC. The optical system consisted of a two-element Cassegrain-type telescopes. SSCC provided imagery of the Earth in the visible spectrum. Within the first month of the availability of ATS-1 imagery, a time-sequence movie of mesoscale cloud patterns in motion was shown on TV (the animated imagery revealed atmospheric motion and their potential use for research and operations). By the early 1970s ATS imagery was being used in US operational forecast centers. ATS-1 also served as a platform for several communication experiments:

- C-band communications experiment (also used for international TV broadcasts)
- VHF communications package. The VHF experiment tested the ability to act as a link between ground stations and aircraft, demonstrated collection of meteorological data from remote terminals, and evaluated the feasibility of using VHF signals for navigation.
- A WEFAX (Weather Facsimile) system experiment was flown for the first time with the intention to test satellite retransmissions of meteorological data products to participating ground stations.

The ATS-3 S/C (launched Nov. 5, 1967, positioned at 70º W, spin stabilized, mass = 365 kg, equipped with a mechanically despun antenna) flew for the first time the MSSCC (Multicolor Spin-Scan Cloud Camera) instrument (built by SBRC) providing full-disk Earth-cloud images in color. A cartwheel mounting configuration was realized with MSSCC (the concept was first introduced on TIROS-9), i.e., the instrument was mounted with its optical axis perpendicular to the S/C spin axis, permitting to view the Earth through a special aperture in the S/C cylindrical wall.

- NASA's demonstration of two Synchronous Meteorological Satellites (SMS) began with the launch of SMS-1 on May 17, 1974. NOAA's operation of the GOES series followed with the launch of GOES-1 in October 1975. The SMS satellites carried VISSR (Visible Infrared Spin-Scan Radiometer) as prime instruments. VISSR provided high-quality day/night images of the Earth's surface.
night cloudcover data and made radiance temperature measurements of the Earth-atmosphere system. - The evolution of ATS into SMS and eventually into the GOES series permitted new services like the routine tracking of clouds with infrared imagery available for cloud height determination and nighttime tracking capabilities.

<table>
<thead>
<tr>
<th>S/C Series (Agency)</th>
<th>Launch</th>
<th>Major Instruments</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES-1 to -7 (NOAA)</td>
<td>16.10.1975, 26.2.1987</td>
<td>VISSR</td>
<td>1st generation</td>
</tr>
<tr>
<td>GOES-8 to -12 (NOAA)</td>
<td>13.4.1994, 23.7.2001</td>
<td>GOES-Imager, Sounder</td>
<td>2nd generation</td>
</tr>
<tr>
<td>GOES-R series (in planning)</td>
<td>for 2014-2029 period</td>
<td>ABL, HES</td>
<td>(GOES-P) 3rd Generation</td>
</tr>
<tr>
<td>GMS-1 to -5 (JMA)</td>
<td>14.7.1977, 18.3.1995</td>
<td>VISSR</td>
<td>1st generation</td>
</tr>
<tr>
<td>MTSAT-1 (JMA, et al.)</td>
<td>Nov. 15, 1999 (launch failure of H-2 vehicle)</td>
<td>Imager (GOES heritage)</td>
<td>2nd generation</td>
</tr>
<tr>
<td>MTSAT-1R (JMA)</td>
<td>Launch Feb. 26, 2005</td>
<td>JAMI</td>
<td></td>
</tr>
<tr>
<td>MTSAT-2 (JMA)</td>
<td>Launch Feb. 18, 2006</td>
<td>JAMI</td>
<td></td>
</tr>
<tr>
<td>Meteosat-1 to -7 (Eumetsat)</td>
<td>23.11.1977, 3.9.1997</td>
<td>MVIRI</td>
<td>1st generation</td>
</tr>
<tr>
<td>Meteosat-8 [(MSG-1) to -4]</td>
<td>28.8.2002 for period after 2015</td>
<td>SEVIRI, GERB</td>
<td>2nd generation</td>
</tr>
<tr>
<td>MTG series (in planning)</td>
<td></td>
<td></td>
<td>3rd generation</td>
</tr>
<tr>
<td>INSAT-1B to -1D (ISRO)</td>
<td>30.8.1983 - 12.6.1990</td>
<td>VHRR</td>
<td>Starting with -2E</td>
</tr>
<tr>
<td>INSAT-2A to -2E (ISRO)</td>
<td>9.7.1992 - 2.4.1999</td>
<td>VHRR/2</td>
<td>Communications only</td>
</tr>
<tr>
<td>INSAT-3B (ISRO)</td>
<td>21.3.2000</td>
<td>VHRR/2</td>
<td></td>
</tr>
<tr>
<td>INSAT-3A (ISRO)</td>
<td>9.4.2003</td>
<td>VHRR/2</td>
<td></td>
</tr>
<tr>
<td>MetSat-1/Kalpana-1 (ISRO)</td>
<td>12.9.2002</td>
<td>Imager+sounder</td>
<td></td>
</tr>
<tr>
<td>INSAT-3D (in development)</td>
<td>2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GOMS-1 (Russia/Planeta)</td>
<td>31.10.1994</td>
<td>STR</td>
<td>1st generation</td>
</tr>
<tr>
<td>GOMS-2 (Electro-L, Russia)</td>
<td>2006</td>
<td></td>
<td>2nd generation</td>
</tr>
<tr>
<td>FY-4 series (in planning)</td>
<td>2009 for period after 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMS-1 (KARI) Korea</td>
<td>2008</td>
<td>MI (Meteorological Imager), GOCI (Geostationary Ocean Color Imager)</td>
<td>1st generation</td>
</tr>
</tbody>
</table>

Table 70: Overview of geostationary meteorological satellites

- The current 2nd generation GOES system of NOAA (GOES-8 to -12 and -N to -P series) consists of two operational satellites covering the East and West portions of the Americas. The constellation consists of environmental sensors, auxiliary payload services and rebroadcast capabilities. GOES auxiliary payload services consist of DCS (Direct Communication Services), EMWIN (EMergency Weather Information Network), LRIT (Low Rate Information Transfer), and S&R Sat (Search And Rescue Satellite Aided Tracking). Initial LRIT operations were started in Aug. 2003, the transition will be complete in 2005. LRIT is a digital communications transmission system, a broadcast service with increased capabilities (data compression, larger volumes, etc.), provided by the GOES satellites, replacing the current analog WEFAX (Weather Facsimile) transmission system.

- Japan started its geostationary meteorological program with the launch of GMS-1 (Geostationary Meteorological Satellite-1, referred to as Himawari-1 in Japan) of JMA (Japan Meteorological Agency) and JAXA (formerly NASA) on July 7, 1977 (see F.3). The newest entry into the ring, MTSAT-1 (Multifunctional Transport Satellite-1) with a launch Nov. 15, 1999 (however, a launch failure of the H-2 vehicle occurred), provides the double service of an “aeronautical mission” (providing navigation data to air-traffic control services in the Asia-Pacific region) and a “meteorological mission.” In the latter function, MTSAT is a successor program to the GMS series. A replacement satellite, MTSAT-1R, was launched Feb. 26, 2005. The prime instrument of the meteorology mission on MTSAT-1R is JAMI (Japanese Advanced Meteorological Imager), see F.10.1.2. MTSAT-2 was launched on Feb. 18, 2006.
The METEOSAT program of Europe was initiated by ESA in 1972 followed by a launch of METEOSAT-1 (a demonstration satellite) on Nov. 23, 1977. The EUMETSAT convention was signed on May 24, 1983 by 16 countries. On January 1, 1987, responsibility for the operation of the METEOSAT spacecraft was transferred from ESA to EUMETSAT (F.8). The MSG (METEOSAT Second Generation) series with a launch of MSG-1 on Aug. 28, 2002 provides considerable improvements (location at 100° W).

India started planning of the INSAT series in the 1970s with a launch of INSAT-1B on April 30, 1983 (see F.6). INSAT is a multipurpose operational satellite system series (geostationary) employed for meteorological observation over India and the Indian Ocean, as well as for domestic telecommunications (nationwide direct TV broadcasting, TV program distribution, meteorological data distribution, etc.). The ISRO-developed prime instrument VHRR (Very High-Resolution Radiometer) was enhanced several times providing high-quality data of 2 km spatial resolution in the visible and SWIR bands, and 8 km resolution in the IR and TIR bands. VHRR/2 was introduced with INSAT-2E (including a water vapor band at 5.7-7.1 μm). The last satellite of INSAT-1 series, namely INSAT-1D, was deactivated on May 14, 2002 after providing useful services for about 12 years.

In 2000, the Government of India approved a dedicated GEO weather satellite program named MetSat (Meteorological Satellite). The launch of MetSat-1 into GTO took place on Sept. 12, 2002 with ISRO’s PSLV (Polar Satellite Launch Vehicle) from SHAR (Sriharikota High Altitude Range), India (launch mass of 1055 kg including 560 kg of propellant; S/C position at 74° E). MetSat-1, equipped with VHRR, is expected to fill the void caused by two important meteorological payloads, namely VHRR/2 on INSAT-2E which failed already in 1999. On Nov. 4, 2000, ISRO was forced to retire INSAT-2B, after it ran out of station-keeping fuel (in July 2000, INSAT-2B completed its design life of seven years of operation). This action stopped of course also the VHRR instrument on INSAT-2B, used for operational meteorology. Note: In a commemorative ceremony on Feb. 6, 2003, the MetSat-1 satellite of ISRO was renamed to Kalpana-1 by Indian Prime Minister Atal Bihari Vajpayee. This is to honor Kalpana Chawla, born in Karnal (1961), India, who died as a NASA astronaut on Feb. 1, 2003 over the southern USA when Space Shuttle Columbia (flight STS-107, Jan. 16 - Feb. 1, 2003) and her crew perished during reentry.

Russia launched GOMS-1 (Geostationary Operational Meteorological Satellite-1) on October 31, 1994. STR (Scanning TV Radiometer) is the prime instrument to observe
Clouds and underlying surface in VIS and IR bands. GOMS-1, also referred to as Electro-1, ended operations in Nov. 2000. Russia plans to launch Electro-L in the time frame 2006. Until that time, the Russian weather service is dependent on the services provided by Meteosat of EUMETSAT with regard to GEO data.

- China joined the geostationary meteorological club in 1997 with the launch of FY-2A (Feng-Yun-2A) on June 10, 1997. The prime sensor, S-VISSR (Stretched - Visible and Infrared Spin-Scan Radiometer) is an optomechanical system, providing observations in three bands (at resolutions of: 1.25 km in VIS, 5 km in IR and water vapor). Upgrade of VISSR on FY-2C, -2D, -2E (5 channels). - The 2nd generation satellites in GEO, FY-4 series, is expected to be launched beyond the time frame of 2010.

- Definition of GOES-R (start in 2000). The next-generation (3rd) geostationary weather satellite family of NOAA, under definition/development at NOAA, NASA as well as at other institutions, begins with the GOES-R spacecraft and its newly defined sensor complement (launch of GOES-R is planned for 2014). The GOES-R objectives are to overcome some of the shortcomings of the current system by providing: mission continuity [with the current system data losses occur for several hours each day during the weeks around the spring and fall equinoxes (eclipse)], simultaneous hemispheric, synoptic, and mesoscale imaging, and data timeliness (considerable improvements in data latency). The new series will provide greatly enhanced observation capabilities with two prime instruments: ABI (Advanced Baseline Imager), and HES (Hyperspectral Environmental Suite), an infrared sounder. The key enabling technology introduced by both instruments is the provision of multiple simultaneous observation scenes (multiresolution data of three pointable target regions of different size and resolution - spatial and temporal), permitting new and better data interpretation capabilities. ABI offers imaging of three area sectors, referred to as: FD (Full Disk), CONUS (Contiguous USA), and Mesoscale, each with a different coverage size. Temporal coverage of: 1 FD, 3 CONUS and 30 Mesoscale images, every 15 minutes; the spatial coverage is 0.5 km for VIS and 2 km for IR. The HES operational concept consists also of three regional observation functions on different scales (can be performed simultaneously): high-resolution hemispheric DS (Disk Sounding), SW/M (Severe Weather/Mesoscale) soundings, and CW (Coastal Water) imaging. HES will feature about 1500 narrow spectral bands in IR for much improved vertical sounding, and a 4 km ground spatial resolution on the sounder. Considering both spatial and spectral performance, the HES specifications require about a two order of magnitude performance increase over the currently used GOES-I-P atmospheric sounder. Synergistic use of ABI and HES data provide products with better accuracy than that from either system alone. GOES-R will provide partial global repeat coverage every 15 minutes or less -- representing a contributing element in the USA to an IEOS (Integrated Earth Observation System), together with NPOESS. A GMS (Geostationary Microwave Sounder) is also considered to be part of the payload on the GOES-R (-S, -T, -U) series to demonstrate observations in the microwave region. Considering both spatial and spectral performance, the HES specifications require about a two order of magnitude performance increase over the currently used GOES-I-P atmospheric sounder. Synergistic use of ABI and HES data provide products with better accuracy than that from either system alone. GOES-R will provide partial global repeat coverage every 15 minutes or less -- representing a contributing element in the USA to an IEOS (Integrated Earth Observation System), together with NPOESS. A GMS (Geostationary Microwave Sounder) is also considered to be part of the payload on the GOES-R (-S, -T, -U) series to demonstrate observations in the microwave region.

- Preparatory activities for the MTG (Meteosat Third Generation) series planning (user mission consultation process and requirements, and pre-phase A concept studies) were initiated by EUMETSAT and ESA at the end of 2000. The development and test phase of the MTG system is planned for the time frame 2009-2014.

1347) E. Miller, M. Madden, B. Nelson, “National Oceanic And Atmospheric Administration’s (NOAA) - Next Generation Geostationary Satellite (GOES-R),” ISRSE, Honolulu, HI, Nov. 10-14, 2003
1.5.3.1  Sea Surface Temperature (SST) from GEO satellites

SST products are also being generated from multi-channel infrared brightness temperatures, referred to as MCSST (Multi-Channel SST) of instruments on weather satellites in GEO - complementing the SST products from LEO. A newer SST retrieval scheme is based on RTM (Radiative Transfer Modeling) algorithms. SST observations from GEO permit high temporal resolutions in particular of the oceans up to moderate latitudes. There is now the capability to determine the diurnal cycle of SST throughout most of the world’s oceans [in regions of persistent cloud cover, observations from GEO increase the likelihood of obtaining a clear-sky observation and thus allow the possibility of resolving the diurnal cycle of SST]. This represents also an important step in the production of a global high-resolution SST analysis that combines polar and geostationary observations. SST data products from GEO represent a more recent development. Some examples of missions are:

- NOAA/NESDIS is providing SST products from the GOES Imager of its GOES-9 (on an experimental basis), -10, and -12 satellites, located at longitudes 154.5° E, 135° W and 75° W, respectively. This service began in 2000 by offering the first operational products.

- SEVIRI (Spinning Enhanced Visible and Infrared Imager) of EUMETSAT is flown on MSG-1 (launch Aug. 28, 2002). The MSG-1 processing chains of SST products (SEVIRI brightness temperatures at 3.9, 11 and 12 µm) started in mid-2003.

- CMA of China is also readying its algorithms for SST product generation from its FY-2 (launch June 10, 1997) spacecraft in GEO.

- The MTSAT-1R (Multifunction Transport Satellite) of JMA (launch Feb. 26, 2005) is equipped with JAMI (Japanese Advanced Meteorological Imager) on its meteorological mission. JAMI features four infrared bands, two of them (TIR1 and TIR2) are providing SST and water vapor retrievals.

- GIFTS (Geostationary Imaging Fourier Transform Spectrometer), a technology demonstrating sounder on the EO-3/IOMI mission of NOAA, NASA, DoD (launch 2008 ????), will provide SST and emissivity as well as LST (Land Surface Temperature) and emissivity observations at resolutions of 4 km from GEO.

1.5.4  GPS/GNSS meteorology - RF (Radio Frequency) occultation monitoring

Refractive occultation monitoring, also referred to as RF occultation monitoring (Earth-observation applications of navigation systems and use of GPS receivers as science instruments in meteorology applications). In 1995, retrievals of Earth’s atmospheric limb soundings (moisture and temperature distributions) were first demonstrated by GPS receiver sounding techniques referred to as “refractive occultation monitoring.” The measurement

technique makes use of occulting navigation signals of the GPS constellation satellites (rising or setting behind the Earth’s limb) as they pass through the atmosphere and are intercepted by a GPS receiver located either on a LEO S/C, or anywhere on the surface of Earth (the signal refraction angle and/or retardation is measured with the GPS receivers). The highly accurate measurements, obtained with these special-function GPS receivers, permit the derivation of vertical profiles of the temperature $[\text{temperature profiles with an high vertical resolution (\leq 1 \text{ km}) and accuracy (\leq 1 \text{ K})]}$, pressure and humidity in the atmosphere, as well as profiles of electron content in the ionosphere. 1357) 1358) 1359)

GPS occultation measurements from LEO S/C represent a valuable and economic data source in addition to the traditional meteorological measurements (e.g., radiosonde, nadir-viewing satellite based radiometers) and ground-based GPS networks (antenna zenith delays).

Background: The radio occultation technique was proposed/invented in the early 1960s by a team of NASA/JPL and Stanford University (the first relevant proposal came from Stanford University Center for Radar Astronomy in 1962). It was first successfully demonstrated in NASA’s planetary exploration program to Mars (Mariner-IV flyby in 1964). Since then nearly every US planetary mission has included a radio occultation instrument. 1360)

The occultation technique was applied to Earth’s ionosphere in 1974-1975 using the radio link between the GEOS-3 and ATS-6 satellites. Applying this technique to the Earth’s atmosphere and using the GPS constellation as a source and a GPS receiver in LEO was first suggested in the late 1980s in two papers: a) A. S. Gurvich, T. G. Krasilnikova, “Navigation Satellites for Radio Sounding of the Earth’s Atmosphere,” Issled. Zemli Kosmosa, Vol. 6, 1986 (in English: Soviet Journal of Remote Sensing, 6, 1990), and b) T. P. Yunck et al. “The role of GPS in precise Earth observation, Proceedings of the IEEE Position, Location, and Navigation Symposium, Orlando, FLA, 1988. Also in 1988, JPL submitted a proposal for the development of GGI (GPS Geosciences Instrument) to be flown on NASA’s EOS (Earth Observing System) spacecraft. Unfortunately, GGI was never flown, but the development effort enabled eventually the development of GPS/MET. - The deployment of GNSS (Global Navigation Satellite Systems) constellations such as GPS and GLONASS with their network of navigation signals made radio occultation techniques possible in the Earth’s atmosphere for applications of weather and climate studies. Prior to GPS, there was a general lack of radio sources suited to meet the performance requirements of refractive radio occultation.

• The GPS/MET instrument of UCAR/JPL on OrbView-1/Microlab-1 (launch April 3, 1995, B.11) introduced this alternate sounding technique to Earth observation, starting a new era of atmospheric profiling technology. 1361) 1362) 1363) 1364) GPS/MET temperature retrieval accuracies of better than 1K have been demonstrated in the altitude range of 10-30 km during the proof-of-concept phase of the mission with vertical resolutions of better than...
1 km. This all-weather sounding technique promises to greatly contribute to global atmospheric monitoring, offering an abundance of data for operational meteorology and climatology. TEC (Total Electron Content) profiles of the ionosphere may be obtained by means of the Abel inversion technique which assumes spherical symmetry. The TRSR (TurboRogue Space Receiver) instruments of GFO (GEOSAT Follow-On, launch Feb. 10, 1998), SUNSAT and Ørsted (both were launched Feb. 23, 1999) missions are a further development of the GPS/MET instrument on OrbView-1/Microlab-1. The TRSR instruments of NASA/JPL were manufactured by Allen Osborne Associates Inc. of Westlake Village, CA.

- The following missions use the BlackJack configuration (built by SpectrumAstro of Gilbert, AZ, for JPL - AstroNav is the SpectrumAstro product name for BlackJack) a new generation of GPS flight receiver and a TRSR successor: SRTM (Feb. 11-22, 2000), CHAMP (launch July 15, 2000), SAC-C (launch Nov. 21, 2000), Jason-1 (launch Dec. 7, 2001), GRACE (launch March 17, 2002), ICESat (use of two BlackJack units, launch Jan. 13, 2003). \(^{1365}\)\(^{1366}\)\(^{1367}\) As an integrated service system (offering the functions of tracking mode, occultation mode, and altimetry mode support), the full BlackJack configuration is using a multiple antenna design. Other missions using refractive radio occultation techniques are: a) MetOp-A (launch Oct. 19, 2006) with GRAS (GNSS Receiver for Atmospheric Sounding), and b) ROC-Sat-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate), a collaborative US/Taiwanese six-microsatellite constellation, a launch took place on April 14, 2006. ROCSat-3/COSMIC (A.27) with its IGOR GPS receiver (of BlackJack heritage) will demonstrate - for the first time - the usefulness of microsatellite constellations in obtaining global atmospheric “snapshots” in near-real-time. The system has the potential to furnish valuable data for weather prediction, global climate-change analysis and research, and ionospheric research and prediction.

The basic functions of the radio occultation technique include: a) reception of signals that have crossed the atmosphere at varying altitudes by means of two antenna arrays; b) acquisition of such signals, also during the rise (ascending) of occultation events, when a signal first appears after crossing dense tropospheric layers causing large dynamics in amplitude and phase; c) signal tracking to provide precise amplitude and phase measurements; d) on-board processing to support occultation-event predictions, also to aid the tracking.

- As of 2002, preliminary evaluations of BlackJack data from CHAMP and SAC-C indicate this technology will be applicable to fields as diverse as weather prediction and climate research, Sun-Earth interaction research, solid Earth dynamics and oceanography. It may also be used to create the first 3-D images of Earth’s ionosphere, a turbulent and mysterious shroud of charged particles that, when stimulated by solar flares, can disrupt communications around the world.

- The ACE+ (Atmospheric Climate Experiment Plus) Earth Explorer constellation of ESA features a GRAS-2 receiver for GNSS-LEO occultation measurements. In addition, ACE+ features a LEO-LEO crosslink X/Ka-band transmitter/receiver payload for the collection of additional occultation observables. \(^{1368}\) The requirements call for global accurate profiles of atmospheric parameters (temperature up to 50 km and water vapor up to 15 km) with radio occultation measurements (GPS+Galileo occultation receivers + LEO- ...

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LEO crosslink X/Ka-band transmitter/receiver). A cluster of four LEO minisatellites in two orbital planes and at two different LEO altitudes is used. The LEO-LEO crosslink occultation measurements represent an alternate source and extension of the conventional GPS-LEO occultation technique. An ACE+ launch is planned for 2008 (see A.1).

![Figure 31: Schematic occultation monitoring configuration for a S/C in LEO](image)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>OrbView-1/Microlab (launch Apr. 3, 1995)</td>
<td>GPS/MET</td>
<td>NASA/UCAR</td>
</tr>
<tr>
<td>GFO (launch Feb. 10, 1998)</td>
<td>TRSR (JPL)</td>
<td>US Navy</td>
</tr>
<tr>
<td>SUNSAT (launch Feb. 23, 1999)</td>
<td>TRSR</td>
<td>University of Stellenbosch, South Africa</td>
</tr>
<tr>
<td>Ørsted (launch Feb. 23, 1999)</td>
<td>TRSR</td>
<td>Danish geomagnetic mission</td>
</tr>
<tr>
<td>SRTM (Feb. 11-22, 2000) Shuttle mission</td>
<td>BlackJack (JPL)</td>
<td>NASA, DLR, ASI</td>
</tr>
<tr>
<td>CHAMP (launch Jul. 15, 2000)</td>
<td>BlackJack</td>
<td>GFZ, DLR</td>
</tr>
<tr>
<td>TiungSat (launch Sept. 26, 2000), D52.19</td>
<td>Experimental GPS</td>
<td>ATSB (Malaysia) S/C built by SSTL. Refractive sounding of the ionosphere</td>
</tr>
<tr>
<td>SAC-C (launch Nov. 21, 2000)</td>
<td>BlackJack/GOLPE; INES</td>
<td>CONAE, NASA/JPL Laben/ASI (INES prototype instrument)</td>
</tr>
<tr>
<td>PICOSat (launch Sept. 30, 2001) of USAF/SSP</td>
<td>IOX (SMC)</td>
<td>Ionospheric Sounding Experiment measures electron profiles (TEC) with GPS, IOX is of TRSR heritage</td>
</tr>
<tr>
<td>FedSat (launch Dec. 14, 2002), TEC (Total Electron Content)</td>
<td>BlackJack (AstroNav)</td>
<td>Australian mission (CRCSS), single antenna configuration, TEC monitoring</td>
</tr>
<tr>
<td>GRACE (launch March 17, 2002)</td>
<td>BlackJack</td>
<td>US-German mission</td>
</tr>
<tr>
<td>ROCSat-3/COSMIC (launch Apr. 14, 2006)</td>
<td>IGOR</td>
<td>Taiwanese-US mission. Note: The mission is also referred to as FormoSat-3</td>
</tr>
<tr>
<td>TerraSAR-X (launch June 15, 2007)</td>
<td>TOR</td>
<td>DLR/EADS Astrium mission, TOR provided by GFZ and UTA/CSR</td>
</tr>
<tr>
<td>ACE+ (Atmosphere Climate Experiment) cluster of 4 microsatellites, (launch 2008)</td>
<td>GRAS-2 CALL</td>
<td>ESA (proposed) mission using GPS+ crosslink occultation measurements</td>
</tr>
</tbody>
</table>
1.5.5 GPS/GNSS meteorology - ground-based networks

Atmospheric GPS-signal monitoring can be done by ground-based as well as space-based distributed network receivers from LEO spacecraft. Ground-based GPS meteorology refers simply to permanently installed GPS receiver networks, whose data is used for estimates of atmospheric conditions, in particular of the total column IWV (Integrated Water Vapor) content of the atmosphere. [Note: In some publications reference is made to IPW (Integrated Precipitable Water-Vapor) which is of course the same as total column IWV]. Water vapor, not evenly distributed in the Earth’s atmosphere, is a significant component of the dynamics of the atmosphere, its interaction with other atmospheric constituents correlates strongly with daily weather patterns. IWV refers to the amount of water (in mm of height) that would result from condensing all of the water vapor in a column of air, extending from the Earth’s surface to the top of the atmosphere. Generally, the ground-based measurements include barometric pressure, temperature, and humidity necessary to determine the precipitable water vapor, or IWV.

The technique is based on the estimation of the tropospheric delay time of GPS signals. The delay, regarded as a nuisance parameter by some signal users (like geodesists), can be directly related to the amount of water vapor in the atmospheric column; hence, it is a product of considerable value for meteorologists in NWP (Numerical Weather Prediction) and climate models. The new GPS application of IWV measurement has been developed starting in the mid-1990s. Such GPS signal measurements can be obtained under all weather conditions; they have an accuracy comparable to IWV data derived from radiosonde and water vapor radiometers measurements.

Accurate, frequent, and dense sampling of IWV is needed for operational weather forecasting as well as for weather and climate research. Given the present operational weather data systems, inadequate resolution of the temporal and spatial variability of water vapor has been cited as the single greatest obstacle to improved short-range precipitation forecasts. The field of GPS meteorology has made great strides over the past few years. Numerous groups have demonstrated the ability to use GPS receiver networks to estimate IWV over a regional area. Some examples of early ground-based refractive occultation monitoring networks are:

- A demonstration network of ground-based GPS receivers has been established by NOAA/FSL (Forecast Systems Laboratory) in Boulder, Colorado to test the new weather

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1372) http://gpsmet.fsl.noaa.gov/jsp/background/background.jsp
1373) http://www.paroscientific.com/gpsmet.htm
observing and climate monitoring system for NOAA (in Feb. 1999 the demonstration network contained 40 active sites; it contained 200 sites by 2002). 1376)

- Other demonstration networks are reported by AGRS.NL (Active GPS Reference System Netherlands). Three Dutch institutes executed a two-year project (September 1996-October 1998) on GPS Water Vapor Meteorology. 1377)

- AGNES (Automated GPS Network for Switzerland). The network was started in 1998; at the end of 2001 it consisted of 29 permanently operating GPS tracking stations. AGNES is a multipurpose network which serves as reference for surveying, real-time positioning services and for scientific applications. Since Dec. 2001, the GPS data are additionally processed on an hourly basis. So-called ZTD (Zenith Total Delay) estimates are derived every hour. With known surface pressure and temperature these values are converted to integrated water vapor (IWV).

- EUREF (European Reference Frame) started out in the 1990s for geodetic applications (Earth reference frame). Over 100 GPS stations were part of the EUREF network in 2000. Interdisciplinary monitoring/investigations including geodynamics, sea level monitoring and GPS meteorology were started in the late 1990s. Within the EU COST (Cooperation in the Field of Scientific and Technical Research) program, a number of processing centers were set up (COST Action 716, starting in early 2001) for the “Exploitation of Ground Based GPS for Climate and NWP” in near-real time (NRT). As of mid-2003, there are seven analysis centers in Europe each serving a number of GPS stations: ASI (Agenzia Spaziale Italiana), Matera, Italy, 38 stations; GOP (Geodetic Observatory Pecný), Czech Republic, 45 stations; GFZ (GeoForschungsZentrum) Potsdam, Germany, 71 stations; IEEC (Institut d’Estudis Espacials de Catalunya), Barcelona, Spain, 13 stations; LPT (Federal Office of Topography), Wabern, Switzerland, 62 stations; NKGN (Nordic Geodetic Commission, Statens Kartverk, Norway), Onsala, Sweden, 25 stations; NKGS (Nordic Geodetic Commission, Onsala Space Observatory), Sweden, 44 stations. 1378)

- In 2000, the Institute of Engineering Surveying and Space Geodesy of the University of Nottingham, UK, received a three year contract from the EC (European Commission) to assess the feasibility and accuracy of producing GPS IPW estimates for both meteorological and climatological applications.

- A GASP (GPS Atmosphere Sounding Project) initiative was started in 2000 at GFZ (Potsdam, Germany) with the establishment of a NRT (Near-Real-Time) GPS network service. GASP consists of two parts: a) ground-based monitoring of IWV, using mostly SAPOS (Satellite Positioning Service), a ground-based DGPS network of over 200 sites of DGPS reference stations in Germany, and b) GPS radio occultation measurements of the CHAMP satellite mission. 1379) 1380) GASP assimilates the inputs from both information sources into atmospheric and ionospheric modeling and analysis, exploring the impact of these new products for such applications as numerical weather prediction (NWP), climate variability studies, and space weather monitoring. The GASP NRT service provides its IWV data within 40 minutes of reception.

Obviously, the GPS-IWV measurement technique is more advantageous than conventional water vapor observing systems because of its relatively low-cost, high-measurement accuracy, all-weather operability, and long-term measurement stability. Furthermore a ground-
based GPS receiver network can operate autonomously providing nearly real-time data to the meteorologists. Since ground-based GPS-IWV data are compatible with spaceborne IWV data retrievals, they provide an independent method for calibrating and validating global satellite observations. A disadvantage of the GPS-IWV data retrieval method is that so far no direct information is provided as to the actual vertical distribution of water vapor in the atmosphere (what is known is the total column content of water vapor).

1.5.6 GPS/GNSS bistatic ocean reflection measurements

Ocean surface reflection measurements of GNSS signals (GNSS-R) are being used in a bistatic radar configuration as sources of opportunity (a passive bistatic/multistatic remote sensing technique to obtain altimetric as well as other information, surface wind parameters). The underlying principle in GNSS-R is the use of reflected signals to infer properties of the reflecting surfaces. The sea surface provides the ocean-atmosphere link, regulating momentum, energy and gas exchange, and several fundamental ocean circulation features are directly related to wind-wave induced turbulent transports in the oceanic mixed layer. In particular, eddies and gyres are fundamental agents for mixing, heat transport and feedback to general circulation, as well as transport of nutrients, chemicals and biota for biochemical processes.

Note: A multistatic altimeter can be regarded as a multistatic radar for which the transmitters and the receivers belong to different systems.

The idea to use satellite radionavigation system satellites as signal sources of opportunity is of great interest to the Earth observation community. Satellite radionavigation systems are closely related to radar systems in that they are also based on the spread-spectrum principle. They operate in L-band, which is almost free of rain attenuation. With current GNSS signal bandwidths in the range of 2-20 MHz, they rank at the lower end of state-of-the-art spaceborne radar instruments; however, the GNSS signals are emitted with exclusive timing accuracy and the position of the transmitting satellites is precisely known. The current existence of two GNSS constellations, GPS/NAVSTAR and GLONASS, and one in development, GALILEO, are providing a continuous pool of signals of opportunity which may be used for wide-area spaceborne reflectometry measurements (GNSS-R).

Background: The detection of bistatic GPS signals scattered and reflected off the ocean surface were obtained experimentally on an aircraft platform in 1991 and reported by a French team (Dassault Electronique) in 1994. Earlier work by Boeing had revealed the exis-

1381) http://www.fsl.noaa.gov/~vondaust/f200/f300b.html
1382) E. Fragnier, R. Weber, “The impact of precise orbit information on ZTD and IWV estimates using ground based GNSS data,” GNSS 2003, Graz, Austria, April 22-25, 2003
1390) Information provided by T. P. Yunck of NASA/JPL
1391) J. S. LaBrecque, L. Loewe, L. Young, E. Caro, S. Wu, L. Romans, “Recent Advances in the study of GPS Earth surface reflections from orbiting receivers,” UNAVACO Community Meeting, 1998
tence of such signals in connection with multipath effects (Boeing Co. report FAA-RD-73-57-V of 1973). In 1993, Manuel Martin-Neira of ESA/ESTEC proposed and presented a multistatic sea surface altimeter concept, referred to as PARIS (Passive Reflectometry and Interferometry System), based on an interferometric approach which combines the direct and ocean-reflected GNSS signals. \(^{1393}\) That work included accuracy analysis and discussions of alternative altimetry constellations. With 24 satellites (transmitters) in the GPS constellation, a single GPS receiver on a spacecraft represents a multistatic system (in combination with the GPS constellation), capable of intercepting reflections from several ocean regions simultaneously. Then, in 1994, French engineers reported the accidental acquisition of ocean reflected GPS signals by an aircraft-mounted GPS receiver. \(^{1394}\) Stephen J. Katzberg and James L. Garrison of NASA/LaRC first analytically predicted the change in GPS signal structure following an ocean reflection. \(^{1395}\) They then demonstrated the tracking of reflected GPS signals with airborne off-the-shelf GPS receivers [three aircraft fights over the Chesapeake Bay and the Eastern Shore of Virginia were conducted in Aug. 1996 using a DDMR (Delay Doppler Mapping Receiver)]. \(^{1396}\) \(^{1397}\)

On the spaceborne side, GNSS signal reflections (referred to as GNSS-R or as GPS-R) were first observed by a JPL team after the SRL-02 (Shuttle Radar Laboratory-02) mission (STS-68, Sept 30 - Oct. 11, 1994). \(^{1398}\) On hindsight, GNSS-R signals were also discovered for the SRL-01 mission (SIR-C/X-SAR on flight STS-59, Apr. 9-20, 1994). In 1998, Stephen T. Lowe et al., conducted a search of possible GPS-R data in the SRL-01 mission data and discovered 4 seconds worth of GPS-R signals (with the expected temporal shape and coherence properties), reflected of the ocean and embedded in recordings of calibration data.

The concept of GPS (or better: GNSS) signal reflection measurements (as a source for bistatic surface scattering) is based on ocean surface roughness which results in multipath signal reflections emanating from the GPS and GLONASS satellite constellations. \(^{1399}\) \(^{1400}\) \(^{1401}\) \(^{1402}\) In this measurement configuration, each point of the reflected surface introduces various kinds of modulation to the signal, concerning amplitude, delay, phase and its derivatives. This modulation is partially due to the measurement geometry, i.e. the geometry between transmitter, reflecting surface and receiver, and partially due to the surface and its variability in time, in particular the sea-surface motion, but also due to atmospheric effects.

If the geometry is well known, the geometric modulation of delay and phase cannot only be removed but it can be used to separate the signals reflected from different areas of the surface by combined frequency-domain filtering and time-domain gating, which is referred to as DDMR (Delay Doppler Mapping Receiver) system. The signals filtered in this way contain only the modulation due to the surface and the atmosphere. Essentially, this is a multipath channel characterization setup. In contrast to nadir-looking instruments the bistatic

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The concept allows for measurements under grazing angles. On the one hand this allows to achieve better spatial resolution for a given number of orbiting instruments and on the other hand, certain surface features, invisible to nadir-looking instruments, can be observed.

The measurements picked up by a DDM receiver system may be used to determine such parameters as wave height, wind speed, and wind direction. The strength of the reflected signals (normally regarded as surface clutter or simply as noise) is also a discriminator between wet and dry surface areas and, therefore, can be applied to coastal and wetland mapping. In this concept, high spatial resolutions are obtained with wide-beam and low-gain receiving antennas by using the GPS carrier-phase and its PRN code modulation. This is similar to the SAR (Synthetic Aperture Radar) technique in which the Doppler frequency shifts and pulsed-signal time delays are used to create a small footprint on the mapped surface. By combining code-range and Doppler measurements, a receiver can distinguish particular patches of the ocean surface illuminated by GPS signals. In some ways, the above GPS ocean surface reflection discovery is similar to that of using GPS to map the ionosphere’s TEC (Total Electron Content) by measuring propagation delay differences between the L1/L2 frequencies.

The GNSS-based concept of altimetry with reflective pseudorange noise (PRN) operates in a bistatic/multistatic geometry (i.e., the transmitted and received signals travel two different paths) with the following features:

- Up to 20 ocean height measurements are possible simultaneously with a single LEO receiver for the measurement of reflected GNSS signals. In comparison, traditional altimetry is limited to looking in the nadir direction and obtaining one height observation at a time below the altimeter.

- GNSS reflection coverage is very dense but random, while in traditional altimetry, the coverage is regular according to a certain repeat pattern. However, the reflected signal retrieval produces only modest SNRs with low-gain antennas. Hence, exploitation of GNSS reflections observed from space is still rather speculative at the start of the 21st century. It will require high gain antennas (preferably >26 dB gain) with multiple independently steerable beams. A single platform might typically see 10-12 reflections at once over the oceans. Measurement precision will be modest; hence, massive averaging is required to get to the 5-cm level that will be needed for mesoscale ocean circulation. Recent ESA studies show that a GNSS-R mission should allow mapping of the mesoscale variability in high eddy variability regions better than Jason-1+Envisat together.

- When the GNSS signal impinges on the ocean surface, it is scattered randomly with maximum power in the direction of the specular reflection. Since the ocean reflectance depends on the surface temperature and salinity, in principle, measuring the return power with sufficient accuracy could eventually by used to infer these parameters.

- The GNSS reflection relies on detecting the amount of energy return of the GNSS signal by correlating the pseudo-random code of the reflected signal and a delayed model of the same code generated in the receiver. By examining the power return at different delays and Doppler shifts, different parts of the ocean are sensed. The footprint of GNSS reflection is determined by the intersection of iso-Doppler and iso-range contours.

- The BlackJack GPS receiver configurations/implantations of the missions CHAMP (launch July 15, 2000; see BlackJack description under E.1) and SAC-C (launch Nov. 21,

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2000) have the added capability of bistatic ocean reflection measurements, originating from the GPS and GLONASS constellations (besides refractive atmospheric occultation monitoring). This relatively new technique of “GNSS reflected pseudorange altimetry” recovery with onboard GPS (or GNSS) receivers will eventually permit applications such as oceanic circulation sensing (particularly eddy-scale currents that are missed by today’s altimetry missions), and scatterometry (measuring the shape of the reflected pulse) for determining wind speeds. The CHAMP and SAC-C GNSS reflection experiments are considered simple engineering tests of opportunity with antenna gains of only 6-9 dB. Thus, long averaging times are needed just to detect the signals. Essential to the success of GNSS-recovered altimetry and scatterometry is the ability to see multiple reflected signals simultaneously.

Note: The Blackjack instrument on SAC-C is also referred to as GOLPE (GPS Occultation and Passive reflection Experiment) provided by JPL.

The UK—DMC microsatellite (launch Sept. 27, 2003) is carrying a GPS Reflection Experiment by using the SGR-10 (Space GPS Receiver-10) along with 3 antennas. As of 2005, the instrumentation collected over 30 data sets, mostly from the ocean but also from land and ice surfaces.

A general limitation of the current GNSS signals for ocean altimetry is their relatively narrow bandwidth, about 20 MHz, which limits the achievable ranging precision to 1 m, using the civil C/A code pseudorange. The modernized GPS signal, however, and the future Galileo system will provide more satellites (thus more observations) and more frequencies for civilian use (each system up to three), featuring also more power and more bandwidth. These GNSS enhancements will contribute decisively to the improvement of the return when used as a remote sensing tool. One particular characteristic, offered by future GNSS signals, is the possibility of performing combined carrier-phase measurements from different carrier frequencies. The reflected signals have a Doppler spread inherent to the geometry of the measurement system, such as a LEO spacecraft flying over the rough ocean surface illuminated by the constellation of GNSS transmitters.

The proposed concept by ESA/ESTEC (Martin-Neira, et al.) employs the PIP (PARIS Interferometric Processing) technique, using several carrier frequencies as transmitted by the GPS and the future Galileo GNSS systems, to obtain a phase observable out of the complex cross-correlation between the fields. In this concept, the PIP technique handles the reflected signals from the ocean surface as a “typical radar return produced by a distributed target” - the signals remain coherent over a short time and have large amplitude variations. Several PIP validation experiments/campaigns have been done or are in progress. All indications are that using the technique of “wide-lane processing,” that is, the combination of the phases from the different carriers, a more coherent observable is obtained which is quite powerful for ocean remote sensing. In addition to altimetry, the measurement of the GNSS multi-carrier reflected signals can potentially provide accurate surface wind speed estimations based on the analysis of statistical fluctuations over the carrier phases.


An inspection of Figure 32 leads to the conclusion\textsuperscript{1411} that a spaceborne scatterometer for reflected GNSS signals could be designed, a passive or “parasitic” scatterometer configuration so to speak, monitoring all signals of opportunity. Obviously, further research and demonstrations are needed to develop this technique.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure32.png}
\caption{Schematic illustration of GPS multistatic ocean reflection}
\end{figure}

As of 2003, a first spaceborne PARIS demonstration is being planned/designed for the L-SAR instrument of the TerraSAR-L mission of ESA (launch 2008). In this setup, the L-SAR instrument antenna is passively listening for the GNNS-R (Reflected GNSS signal) observables from the ocean surface.

Today’s GNSS constellations represent a continuous pool of RF signal sources that are transmitted toward Earth (through the atmosphere), thus providing numerous signals of opportunity that are reflected by the Earth’s surface (ocean or land) and may be acquired by an airborne or spaceborne antenna and receiver (bistatic altimetry application, etc.). Unlike monostatic radar altimetry with rather narrow sub-trajectory coverage capability (a line of discrete small-area measurement points is provided), the method of ocean-reflected GNSS signal monitoring promises to offer eventually much wider coverage swaths, which will to a better extent enable the study of large-area phenomena such as ocean eddies and in particular ocean currents.

A further use of GNSS-R\textsuperscript{1412,1413} data is anticipated in ionospheric tomography monitoring applications by extracting information about the ionospheric electron density distribution. The GNSS-R approach offers the means to provide a high number of bistatic TEC (Total Electron Content) measurements over the oceans.

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1.6 Oceanography — A growing demand in Earth Observation

Oceanography is the study of Earth’s oceans comprising three major interdisciplinary fields of investigation:

1) Physical oceanography: the study of all the physical properties of the ocean — e.g. currents and waves, marine geodesy, etc.

2) Chemical oceanography: the study of its chemistry


The scope of this chapter is mostly limited to the various topics of physical oceanography which is by itself a very large interdisciplinary field of study, requiring effective international cooperation in many programs.

Oceans cover 71% of the Earth’s surface. The total ocean volume (salt water) is estimated to be $1.35 \times 10^9$ km$^3$, representing a gigantic reservoir of energy and resources. The mass of the oceans is about 300 times larger than the mass of the atmosphere; the heat storage capacity of the oceans is 1200 times the heat capacity of the atmosphere; the oceans provide 70 times the carbon storage capacity of the atmosphere. The oceans play indeed a decisive role in the evolution of the world’s climate. Through irradiation of the sun and exchanges with the atmosphere, they receive considerable quantities of heat, in particular at the intertropical latitudes, which they store due to their high thermal capacity, and which the ocean currents redistribute from the equatorial regions to the polar regions. Thus, the world’s oceans represent a major regulating factor in our climatic system. Their circulation and evolution must be understood (via satellite observations and other means of observation) to account for the climate variability.

Status quo in 2006: The age of global satellite observations, in particular the introduction of continuous spaceborne altimetry missions since the early 1990s, have revolutionized the concepts of conventional oceanography. The availability of precise altimetric data required great initial efforts in modeling techniques for numerical data analysis, which in turn resulted in greatly improved GMCs (General Circulation Models) on various scales (regional or mesoscale, global scale). The ocean is seen to be time varying on all space and time scales — something we must live with. The designers of the altimetric missions anticipated many of the major results, including the very strong El Nino signals, the ability to determine the mesoscale variability everywhere, the estimation of frequency—wavenumber spectra and the considerable, if still limited, capability of determining the absolute circulation.

The very high accuracies and precisions of the altimetry missions produced some results which were not anticipated. These include, especially, the very strong high latitude barotropic fluctuations, and the internal tide results.\(^{1414}\) The latter in particular triggered a huge new interest in the role of tides in controlling the ocean circulation and more generally in the question of the energetics of the circulation. Another major surprise, of widespread interest, was that the measurements proved accurate enough to detect global sea-level rise at an accuracy of about 1 mm/year. For the first time, the spatial complexity of the sea level rise patterns could be seen. The observations have stimulated a major, and continuing, effort to partition the rise between heating, cooling and net evaporation and precipitation.\(^{1415}\)

The key observables from space today are the measurement of: a) altimetric height (sea level) to infer sea surface topography, wave heights and wind patterns, and ocean currents, b) SST (Sea Surface Temperature), and c) ocean color. These variables are the backbone prog-

\(^{1414}\) Note: The term “barotropic” refers to a state in a water mass in which the surfaces of constant pressure are parallel to the surfaces of constant density.

nostic indicators in operational oceanography. The near future will add a further key observable, namely SSS (Sea Surface Salinity), to study the links between ocean circulation and global water cycles — to be demonstrated in the SMOS mission of ESA and the SAC-D/Aquarius mission of NASA/CONAE.

The Jason-2/OSTM mission of CNES/NASA (launch 2008) is considered to be the first “operational altimetry mission” representing a switch of service support from ‘research institutions’ to ‘operational institutions’ (NOAA and EUMETSAT). The objective is to foster near real—time operational applications in the fields of oceanography, marine meteorology, seasonal prediction and climate monitoring.

The long-term goals of oceanography are to understand the processes and their interactions at the various time and space scales, to simulate these processes (modeling), and to make predictions, if possible. In particular, this requires sustainability of service provision on a long—term basis in the future. 1416)

Some historical background: Man’s earliest attempts to master the ‘great waters’ (oceanography) required him to know something more than just the performance of his ship. History has shown repeatedly that some understanding of the sea and atmospheric conditions was helpful, if not vital. Knowledge, for example, of prevailing winds aided the success of the seafarers from early times on. The primary concern of any seafarer was — and is — navigation and safe passage in foreign, as well as domestic, waters. 1417)

The formal gathering of ocean knowledge as a science discipline (oceanography) started in the early to mid 19th century. It provided new insights and understanding of the phenomena and turned up a number of innovations to aid navigation. Some examples are:

- Development of the mechanical gyroscope in the early 1800s
- Development of more accurate chronometers
- Charts of wind and current patterns were developed (including first charts of the Gulf Stream)
- The British “Challenger Expedition” (1872—1876, on the corvette H.M.S. Challenger II), sponsored by the Royal Society and Royal Navy, was the first modern, deep—ocean, global sampling expedition and was one of the most important voyages of the 19th century. Challenger visited all of the world oceans covering a total distance of 127,000 km. Scientists on board studied the physical conditions of the deep ocean, the chemical composition of seawater, physical and chemical characteristics of seafloor deposits, and the distribution of organic life at all water depths. The depth of the Mariana Trench (about 11ºN, 142ºE) just east of the Mariana Islands in the Pacific was measured at 8185 m. The “Report of the Scientific Results of the Exploring Voyage of H.M.S. Challenger” covered 50 volumes (practically the foundation of oceanography, published between 1885 and 1895), analyzed by over 100 scientists.
- In 1893, the Norwegian Explorer Fridtjof Nansen (1861—1930) lead a voyage to the Arctic to test his theories about surface circulation in Arctic waters. This was the beginning of the exploration of Polar Seas that continued into the early 20th century.
- At the strat of the 20th century, lead line soundings still remained the best method for plumbing the depth of the ocean bottom.

As technological advances of the 20th century were made in engineering and later also in electronics, the ability to explore the ocean in greater detail became increasingly sophisticated. Advances during the two world wars were also important as the sea became an important ”battle field”. Use of sonar (echo location), developed during WW-I and WW-II, has proved crucial to our increased understanding of the morphology of the ocean basins.

- Study of underwater acoustics

1417) http://inventors.about.com/library/inventors/bloceanography.htm
- The sonar technique was developed during WW-I (based on reflected sound waves) to detect submerged targets.
- Measurement of water body depths in ocean basins, referred to as bathymetry (sonic depth finder — which determines depth by measuring the elapsed time of an echo). The ocean floor had distinctive features (ridges, mountains, etc.).
- etc.

### 1.6.1 Physical oceanography

Physical oceanography is the study of the fluid motions of the ocean environment, e.g. surface and internal waves, air-sea exchanges, turbulence and mixing, acoustics, heating and cooling, wave and wind-induced currents, tides, tsunamis, storm surges, large-scale waves affected by Earth’s rotation, large-scale eddies, general circulation and its changes, coupled ocean-atmosphere dynamics for weather and climate.

![Temporal and spatial scales of key physical and biological processes in the ocean](image)

As illustrated in Figure 33, the timescales of ocean physical processes extend from seconds to years, and the spatial scales range from mm to 1000 km to cover the various phenomena. Imagery from SAR (Synthetic Aperture Radar) missions provides key data on ocean swell, internal waves, mesoscale circulation including fronts and eddies, and a wide range of atmospheric processes. Data on atmospheric processes include measurements of wind speed and direction, detection of atmospheric roll vortices and turbulence, and identification of the extent and structure of storms and rain cells. Even the processes with relatively longer time-

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1418) Note: The illustration was originally presented in Ref. NO TAG and in Ref. 6534) and kindly provided by Benjamin Holt of NASA/JPL.
scales, such as fronts, eddies, and gyre circulations, may fluctuate over a period of a few days or even less. In terms of operational interests, service monitoring of ship traffic, detection of natural and anthropogenic slicks, identification of icebergs, and sea ice navigation are perhaps best done with SAR imagery. 1419) 1420) 1421)

**How is the ocean sampled from satellites?** In general terms (and not including altimetry, which is dedicated to gyre circulation), the primary satellite ocean sensors enable routine monitoring of nearly the entire global ocean every 12 h to 2 days. These include sensors (radiometers) for SST (Sea Surface Temperature) and ocean color, some instruments have about 3000 km swath widths with 1 km resolution and provide twice-daily global coverage. **Scatterometers** for measuring ocean surface winds (see 1.2.3.5) have swath widths varying between 500 and 1800 km with resolutions from 25 to 50 km.

The SAR and altimeter instruments are capable of making wave measurements. The altimeter provides estimates of sea surface height, wind speed, significant wave height and wave period, but only in a very narrow swath of spot measurements directly beneath the track of the satellite). The SAR data with sufficient resolution provides good detail of the ocean’s short wave field as it responds to interactions with the atmosphere, longer waves, and currents. Passive microwave imagers have viewing parameters similar to those of scatterometers.

In addition, DCS (Data Collection Systems), such as the **Argos** system on a number of spaceborne meteorological platforms, and the **Argo network** (or Argo array) of freely-drifting ocean profiling floats at various ocean depths, gather environmental in situ data from autonomous platforms in the ground segment (on and in the ocean) and deliver their data via satellite to a worldwide user community. Argo is an international effort of collecting high-quality temperature and salinity profiles from the upper 2000 m of the ice-free global ocean and currents intermediate depths. The Argo data come from battery-powered autonomous floats that drift mostly at depth, where they are stabilized at a constant pressure level by being less compressible than sea water. The Argo network is capable of monitoring effectively the pulse of the global heat balance, because over 90% of the observed increase in heat content of the air/land/sea climate system over the past 50 years occurred in the ocean. Initial deployment of Argo floats began in 1999/2000 (see Part C). 1422) 1423) 1424)

In Dec. 2003, the Argo network consisted of 1000 deployed profiling floats. When fully deployed (global array of 3000 floats), Argo will provide a quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport. Given the national commitments of Argo-floating provision, the full Argo array should be reached by 2006. The target array represents one float at every 3° latitude and longitude.

The Argo data are of vital importance for two global projects that were Argo’s originators/sponsors, **GODAE** (Global Ocean Data Assimilation Experiment) and CLIVAR (Climate Variability and Predictability) in which the ocean’s role is crucial. Argo is also a pilot project of **GOOS** (Global Ocean Observing System).

Since early 2005, the ocean observing system has included global elements of subsurface and satellite data. Hence, there have been a number of applications that combine the Argo

1424) http://www.argo.ucsd.edu/
array, altimetry, as well as other datasets in the “integrated approach.” The global sea level makes a good example of this type of application. Changes in global average sea level are due to both— to volume expansion by warming (thermosteric sea level), and to changes in the oceans’ mass (eustatic sea level) through exchange with continental sources from ice and stored water. Each of these is observed individually: total sea level by satellite altimetry, thermosteric sea level by Argo, and the eustatic sea level by the satellite gravity mission (GRACE). 1425)

The major external forces acting on the ocean are those of wind (generating waves, turbulence, large scale waves, circulation), heating due to the sun and geothermal energy, cooling, evaporation due to sun and wind, precipitation, tidal potential of the moon and the sun, earthquakes, gravity, friction. Internal forces acting on the ocean are those of pressure gradients, viscosity and/or friction, etc. 1426)

The available capabilities for climate change predictions are still decades away at the start of the 21st century due to insufficient knowledge of the processes involved and the interactions between the different components of the climate system. There are also difficulties in understanding and representing some of the processes in numerical models. Further long-term ocean observations (spaceborne, in-situ, etc.) are needed to cover the various time- and space scales and to improve the fidelity of GCMs (Global Climate Models). 1427)

1.6.2 Satellite Altimetry

Surface topography (sea level) measurements are the most essential observable required for global operational oceanography as it is a strong constraint to infer the 4D ocean circulation. This observable is obtained thanks to altimeter systems allowing global, real—time and all—weather measurements with high space/time resolution. Altimeters also measure significant wave height and winds, which are essential for operational wave forecasting.

Satellite altimetry offers the capability to observe Earth (the sea surface) in a time frame of several days, providing data products on a grid-scale (the small footprint of the measurement itself and the sampling frequency along the orbital path offer only a limited coverage). Due to the favorable reflective properties of water, the method of altimetry is especially suitable for measurements over the ocean. The spaceborne height measurement technique of the sea surface provides in effect not only the height measurement, but an integrated information set along the measurement path, from the sea surface to the spacecraft. The analysis of this altimetry data is being used in a great variety of applications involving such fields as meteorology (sea surface winds), climate, ocean topography, ocean currents, oceanography, geoid modeling, plate tectonics, etc. Altimetry itself needs in turn good reference frames - to be able to relate its monitoring data reliably to all these services and functions.

• Altimeters are active microwave instruments for the accurate measurement of vertical distances (between the spacecraft and the altimeter footprint on the ocean surface). It is important to note that all altimeters are profiling instruments and do not yield an image. Thus, they essentially provide only spot measurements of water surface elevations. 1428)

The technology determines the two-way delay of the radar pulse echo from the Earth’s surface to a very high precision (in the 1990s to less than a nanosecond). The concept has also

1426) http://gyre.ucsd.edu/sio210/sep26/index.html
1428) Note: Due to this feature of ocean-floor mimicry, first attempts have been made to use sea surface topography measurements to derive data for mapping structure, geology and topography of the sea floor. This is done through conversion of sea surface topography to gravity and then to sea floor topography through a series of mathematical calculations and modeling. Features greater than approximately 15 km wide can be identified and structures beneath sediment cover are “exposed” on gravity maps. http://www.globalserve.net/~wallace1/tectonics/webpres/
the capability to measure the power and the shape of the reflected radar pulses. The data provide in particular information on ocean topography [the gravity grids reveal also all of the major structures of the ocean floor. The “equipotential surface” of the ocean bulges outward and inward mimicking closely the topography of the ocean floor. - The actual ocean surface deviates by up to 100 m from the ideal ellipsoid. The bumps and dips (troughs) in geoid height are caused by minute variations in the Earth’s gravitational field].

Background: Spaceage altimetry got really start in August 1969 with the NASA—sponsored Williamstown Conference (Williamstown, MA) — where it was decided to use space systems to learn more about the Earth and the oceans. Specifically, the conference recommended that:

- Satellite geodesy to measure the Earth’s gravity field
- Ocean altimetry for physical oceanography and studies of the rheology of the oceanic lithosphere
- Space techniques such as Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Lunar Laser Ranging (LLR) to measure plate motion and deformation, and Earth orientation.

These recommendations were incorporated into a NASA plan which led to the establishment in 1972 of the Earth and Ocean Dynamics Applications Program. First among the recommendations was the development of satellites with “10 cm accuracy altimeters...to measure the geopotential and mean sea level accurately enough to...determine the general circulation of the oceans (and) to resolve the spatial variations in the gravity field to 100 km half wavelength.”

First spaceborne monostatic altimetry measurements (demonstrations) of ocean surface heights started in 1973 with S-193 (Passive Microwave Radiometer/Active Scatterometer and Radar Altimeter) instrument on NASA’s Skylab missions SL-2, SL-3 and SL-4 (1973-1974) at an altitude of 435 km (see L5). Using a pulse width of 0.1 microsecond this system was able to get a resolution of 15 m. The availability of the S-193 altimeter data opened the way to a direct comparison of the altimeter heights with a computed gravimetric geoid.

In altimetry the variation of the return signal strength (as the cube power of height) and the footprint area with the altitude requires the use of the pulse compression for higher altitudes. Since GEOS-3 (launch Apr. 9, 1975), flying at an average altitude of 840 km, all altimeters have used pulse compression - the resolution due to this compression has been improved. GEOS-3 offered significant improvements over the Skylab altimeter (S-193), including improved performance as well as greater global coverage.

The SeaSat (launch June 26, 1978) ALT instrument, designed and built by JHU/APL, is regarded the first high performance altimeter (first use of the full-deramp technique; introduction of the capability of waveform sampling). In contrast with previous designs, the samples are now an integral part of the altitude tracking process and are used in such a way that the system adapts as a function of wave height to tracker performances. Despite the premature demise of the SeaSat S/C after only 100 days in orbit, the altimeter performance clearly demonstrated the significance of the signal processing innovation, it was adopted as

the standard approach for new radar altimeters. GEOSAT (1985 - 1990) altimetry introduced also measurements of sea-state and ocean surface winds. GEOSAT performed two separate missions: a) the primary geodetic mission, and b) the ERM (Exact Repeat Mission, Nov. 8, 1986 to Jan. 5, 1990), in which it retraced the SEASAT ground tracks, provided the first long-term high-quality altimeter measurements to the scientific community.

The modern age of satellite altimetric studies of ocean surface topography began in the early 1990s: The RA-1 altimeter on ERS-1 (launch 1991) and on ERS-2 of ESA (since 1995) was designed to optimize its performance over all types of surfaces. RA-1 provided high-accuracy (3 cm precision) elevation measurements of the ocean surface topography, wave height and wind speed from a sun-synchronous orbit (the first polar-orbiting satellite with an altimeter on-board). ERS-1 was in ERM (Exact Repeat Mission), a 35-day repeat orbit from April 1992 to December 1994 and from mid-1995 to 1999 (mission end). The geodetic mission (GM) of ERS-1 started in April 1994 and included two, successive 168-day repeat periods whose tracks were offset by 8 km producing a 366-day super-cycle. The ERS/GM observations are considered the “most important marine geological and geophysical data set collected in the past (15 years)” and enabled mapping of virtually the entire global marine gravity field to a two-dimensional, full-wavelength spatial resolution of 20 km or better. 1434) 1435)

The ALT instrument on TOPEX/Poseidon (launch Aug. 10, 1992), designed to optimize performances over ocean surfaces, is regarded the first dual-frequency altimeter, permitting the estimation of ionospheric range delay. The TOPEX/Poseidon mission has demonstrated the time variation of ocean topography (dynamic and thermodynamic) can be determined with an accuracy and precision of a few centimeters. For the first time, the seasonal cycle and other temporal variabilities of the ocean have been determined globally with high accuracy, yielding fundamentally important information for testing ocean circulation models. TOPEX/Poseidon was the first mission specifically designed to measure sea-surface topography for the determination of ocean circulation. The missions ERS-1/2 and TOPEX/Poseidon are part of international oceanographic and meteorological programs, such as WOCE (World Ocean Circulation Experiment) and TOGA (Tropical Ocean and Global Atmosphere), both linked to WCRP (World Climate Research Programme). Major observations/phenomena of the TOPEX/Poseidon mission data analysis are: (see Ref. 1323)
- Oceanic circulation, including the movement of Rossby and Kelvin waves 1436) 1437)
- Oceanic and coastal tides
- El Nino, La Nina, and the Pacific Decadal Oscillation
- El Nino-like circulation in the Atlantic Ocean
- Oceanic seasons in the Mediterranean
- Ocean floor topography from surface data used to refine the geoid model

Historical background: The Rossby waves are named after Carl-Gustav Rossby (1898 – 1957) of Stockholm, Sweden (Swedish-US meteorologist). In 1928, he organized the first university level meteorological program in the United States at the Massachusetts Institute of Technology (MIT). In 1939, he became the assistant chief of research at the US Weather Bureau, and in 1940 the chairman of the Department of Meteorology at the University of Chicago.

Rossby waves owe their existence to the rotation of the Earth. They are easily observed in the atmosphere (i.e. as large-scale meanders of the mid-latitude jet stream). Their exis-

1437) Carl Gustav Rossby (1898–1957) was born in Stockholm, Sweden. In the 1930s he became a US citizen and worked for the US Weather Bureau. He became a pioneer in the field of large-scale circulations.
tence in the oceans was first theorized by Rossby in the 1930s. Rossby waves couldn’t be detected until the advent of radar altimetry because they occur internally and are very small on the ocean surface, about 10 cm high, making them impossible to detect from onboard an oceanographic research vessel.

Rossby waves are also known as planetary waves, they are solutions of simplified forms of the equations governing the dynamics of the atmosphere and oceans (large-scale ocean dynamics phenomena). They serve as archetypes for the sinuous large-scale motions of the mid-latitude troposphere. They are horizontal transverse waves with large values of vorticity and with divergence which is negligible by comparison. Their most characteristic feature is that they move westward relative to the zonal atmospheric flow. This strange lopsidedness is a result of the Earth’s rotation, which breaks the symmetry of east-west reflection. Rossby waves of very long wavelength are important in communicating changes in the large-scale circulation to the gyre interior. Kelvin waves can run around the boundaries of an ocean and transmit information about changes in large-scale forcing or boundary conditions eastward along the equator. 1438) 1439)

- Ocean-surface topography measurements beyond the TOPEX/Poseidon era. The successor altimetry missions (Jason-1, Envisat, Jason-2, etc.) have broadened the list of science objectives. Data analysis of these missions is expected to:
  - Measure global sea-height change and provide a continuous view of changing global ocean surface topography
  - Calculate the transport of heat, water mass, nutrients, and salt by the oceans
  - Increase understanding of ocean circulation and seasonal changes and how the general ocean circulation changes through time
  - Provide estimates of significant wave height and wind speeds over the ocean.

**Ocean reflection measurements of GNSS signals as sources of opportunity** (a passive altimetry technique). See chapter 1.5.6.

- Starting in the 1990s, altimetry missions were more and more integrated into international oceanographic and meteorological programs such as WOCE (World Ocean Circulation Experiment) and TOGA (Tropical Ocean and Global Atmosphere), both are linked to the WCRP (World Climate Research Program).

Systematic monitoring of the sea level (as well as of large lakes and rivers) is the prime objective of spaceborne altimetry applications. Covering about 70% of the Earth’s surface, the oceans are the best guardians of the delicate balances controlling our planet. There are three main reasons for the rise and fall in sea level throughout the Earth’s geological history: 1440)

1) Changes in the shape and volume of ocean basins due to plate motions

2) Movements of water masses between the polar ice caps and the oceans through ice formation and melting

3) Variations in water density with changes in temperature and salinity.

The first of these phenomena is rather slow, while the other two may be quick, they are closely tied to climate change. However, while a rise in sea level due to an inflow of water masses is rapid and uniform, it takes in the order of 1000 years for a rise in temperature to spread throughout the oceans. This is why sea level changes due to warming are spatially very unequal.

1439) http://www.soc.soton.ac.uk/JRD/SAT/Rossby/Rossbyintro.html
Aside from sea level monitoring, altimeter data has also proved invaluable for a suite of practical applications including:

- Ocean forecasting systems
- Ship routing
- Precision marine operations such as cable-laying and oil production
- Ocean acoustics for Navy operations
- Fisheries management
- Marine mammal habitat monitoring
- Hurricane forecasting and tracking
- Debris tracking

- Spaceborne radar altimeters have been profiling the ocean surface continuously since 1991, through the ERS-1, TOPEX/Poseidon, ERS-2, GFO (GEOSAT Follow-On), Jason-1, and Envisat missions. Their observations have afforded the geoscience community a revolutionary and dramatically—improving view of the global marine gravity field — and geoid. These altimetric marine gravity fields have led directly to a greatly improved understanding of global bathymetry, marine tectonics, ocean circulation and climate variability. Planetary waves can certainly be considered a success story for altimetry, given the quantum leap in the quality of the observational evidence made possible by the availability of high—quality SSH (Sea Surface Height) fields, and the substantial revision of our theoretical understanding of planetary waves sparked by those observations. The global altimetry observations highlighted significantly faster waves with respect to the classical theory of planetary wave propagation, calling for a revision of the theory. 1442) 1443)

- The altimeters of ICESat and CryoSat, GLAS (Geoscience Laser Altimeter System) and SIRAL (SAR Interferometer Radar Altimeter), respectively, are considered primarily as research instruments to measure such parameters as: ice sheet topography, cloud heights, planetary boundary layer heights, and aerosol vertical structure. Sea ice plays a central role in arctic climate.

<table>
<thead>
<tr>
<th>Mission/ Sensor</th>
<th>Launch Date</th>
<th>Range Precision (cm)</th>
<th>Frequency (GHz)</th>
<th>Uncompressed Pulse Width (μs)</th>
<th>Compressed Pulse Width (μs)</th>
<th>Peak Power (W)</th>
<th>Beam Limited Footprint (km)</th>
<th>Pulse Limited Footprint (km)</th>
<th>Orbit altitude, inclination (km/º)</th>
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<td>GEOS-3, ALT</td>
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Operational altimetry is becoming more and more a reality at the start of the 21st century—because it has demonstrated interdisciplinary applications across many fields such as: oceanography, geodesy, hydrology, glaciology, and geophysics. It qualifies itself as an essential component of global Earth observing systems. There is a generally accepted need for long, accurate time series of multi-mission altimeter data, which requires standards on formats, geophysical corrections and reference frames, as well as the knowledge of the long-term stability of altimeter and its ancillary sensors. The latter implies cross-calibration between past, present, and future altimeter missions as well as between different altimeter technologies (pulse limited, laser, lidar, wide swath, Delay Doppler, etc).  

Operational altimetry refers to a sufficient infrastructure to make data products available in a timely and continuous manner to the needs of a larger operational oceanography community. In particular, this is a main objective of GODAE (Global Ocean Data Assimilation Experiment), an international framework to eventually obtain an integrated and comprehensive ocean observing system. Several pioneering research programs (international multi-year campaigns) have already contributed or are contributing to the GODAE goal.  

- WOCE (World Ocean Circulation Experiment). The WOCE program is a cooperative international effort (WCRP initiative of 1983) involving scientists from 40 nations.  
- TOGA/COARE (Tropical Oceans and Global Atmosphere Experiment / Coupled Ocean Atmosphere Response Experiment). TOGA was initiated in 1985 by WMO.  
- CLIVAR (Climate Variability and Predictability). A major WCRP (World Climate Research Program) initiative since 1993.  
- Argo (Array for Geostrophic Oceanography). Argo represents a global network of sea-going floats for a better understanding of the world’s oceans. Argo is an international ocean program, part of GCOS/GOOS and CLIVAR - eventually it will consist of an array of 3000 free-drifting (Lagrangian) profiling floats, at various depths, that measure the temperature and salinity of the upper 2000 m of the ocean; start of deployment in 2000, more than  

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1446) http://www.gos.udel.edu/goos/Argo_program_overview.htm
3000 floats are expected by 2006. Argo provides data complementary to remote sensing data to initialize and constrain ocean models.

To perform operational oceanography, spaceborne and in-situ measurements of the ocean state (of as many missions as possible and of many buoys in the ocean) must be merged with physical models of the oceans (assimilation process) to deliver regional and global analysis of the ocean state, to be able to make forecasts of its future state. Oceanic variability especially affects major oceanic currents, has a significant effect on climatic changes. Obviously, operational oceanography data products are an important ingredient in this operational oceanography effort.

With regard to spacecraft operations of future altimetry missions, the following changes are being implemented. While mission operations of Jason-1 are still being conducted by NASA and CNES, the operational function of Jason-2 (launch 2008) will be carried out by NOAA and EUMETSAT, respectively (the operators of US and European weather satellites). This switch of service support from research institutions to operational institutions is a definite sign of a service mature enough to become operational.

- Plans for the Jason-2 mission (NASA, CNES, launch 2008) called for a conventional core mission, based on the Jason-1 follow-on instrumentation, and in parallel a demonstration mission of NASA/JPL involving the new concept of an interferometric radar configuration, referred to as WSOA (Wide Swath Ocean Altimeter). The objective of the experimental WSOA was to demonstrate for the first time ocean topography observations (using cross-track interferometry) from a single platform over swaths of 200 km. The design of the WSOA configuration uses two antennas separated by a 7 m mast and the interferometric technique to map directly under the satellite and over a 200 km swath the dynamic sea surface topography.

Note: As of March 2005, NASA has decided to cease further development of the Ocean Surface Topography Mission (OSTM) WSOA instrument (Wide—Swath Ocean Altimeter).

1.6.2.1 Altimetry principles

Conventional altimetry can be described as run-of-time distance measurements taken from a vertically tracking satellite to the geoid. A spaceborne radar altimeter maps the sea surface, which is complex, but which largely conforms to the equipotential surface known as the geoid. The ocean surface departs significantly (at the meter level) from the geoid - this departure is of great interest to the science community (oceanographers, meteorologists, geophysicists, etc.) for it reflects the global circulation patterns and also, in the form of tides and changes in sea level, fundamental climatic and solid Earth phenomena. Furthermore, altimetry provides approximate estimates of the geoid itself, in the form of a mean surface obtained by averaging measurements taken over many satellite passes over the same locations. More detailed explanations on altimetry are given below.

- A radar altimeter onboard a satellite permanently transmits signals at high frequency to the Earth’s surface, and receives the echo from the sea surface. This is analyzed to derive a precise measurement of the round-trip time between the satellite and the sea surface. By averaging the estimates, say, over a second, this produces a very accurate measurement of the satellite-to-ocean range. However, as electromagnetic waves travel through the atmosphere, they can be decelerated by water vapor or by free electron ionization effects in the ionosphere. Once these phenomena are corrected for, the final range R is estimated within 2 cm.

- Satellite orbit: The ultimate aim is to measure sea level relative to a terrestrial reference frame. This requires independent measurements (accurate tracking) of the satellite...
orbital trajectory, i.e. exact latitude, longitude and altitude coordinates. The critical orbital parameters for satellite altimetry are altitude, inclination and period.

- **Sea surface height (SSH):** SSH is the range at a given instant from the sea surface to a reference ellipsoid. SSH is simply the difference between the satellite height (S) and the altimetric range (R): $SSH = S - R$. The SSH value takes account of such effects as:

  - The sea surface height which would exist without any disturbances (wind, currents, tides, etc.). This surface, called the **geoid**, is due to gravity variations around the world, which are in turn due to major mass and density differences on the sea-floor. For example, a denser rock zone on the sea-floor may deform the sea level in the order of tens of meters; this is visible as a hill on the geoid.

  - The ocean circulation, or dynamic topography. The ocean circulation, which comprises a permanent stationary component (permanent circulation linked to Earth’s rotation, permanent winds, etc.) and a highly variable component (due to wind, tides, seasonal variations, etc.). The mean effect is on the order of one meter.

Conventional altimeter payloads on such missions as TOPEX/Poseidon, ERS-1/2, Envisat, and Jason-1 are looking for dynamic topographic signals. These may be only a few cm in height, against a background of height variations of the geoid that run as large as ±150 m the globally-averaged geoid. Further, the topographic signals may have large-scale resolutions of 1000 km and more. The consequence of these requirements is that the altimeter should follow a repeating track (to an accuracy of ±1 km or better) so that after many cycles, the geoid can be determined. Once that is in hand, then the cm-level signals can be extracted. Dynamic topographic objectives carry other implications as well. The sea surface height must be measured absolutely. It should be recalled that a radar (altimeter) does not measure distance, it measures time delay, which if the speed of propagation is known, can be converted to distance. When accuracies of ~1 cm over a range of ~1000 km are required, even very small variations in the speed of light can generate unacceptable errors. Hence, all sources of path delay, etc., have to be estimated and compensated. Thus, a state-of-the-art ocean topographic altimeter uses two frequencies (to measure and remove delays from free electrons in the ionosphere), and requires a bore-sighted two- or three-frequency radiometer (to estimate and remove delays from atmospheric moisture).

- **Altimetry over inland water heights.** 1448) The most well-established use of altimetry over land is the measurement of inland water heights. This field has evolved rapidly over the past two decades (since the mid 1980s). Initial work over a handful of large targets has expanded to the current capability to monitor thousands of river and lake heights worldwide. Two factors have been critical to the advances made in inland water monitoring. The first is the inclusion of a designed capability to track rapidly varying land surfaces, deployed on the ERS RA–1 and RA–2 on Envisat. The second is in the analysis of inland water echoes, with the ability to identify and re-track to that part of a complex return corresponding to the underlying water surface. In particular, TOPEX/Poseidon and ERS–2 have obtained long-time series of data, now being continued by Envisat and Jason–1. The unique multi-mission dataset already gathered, with its varied temporal sampling, frequencies of operation, and differing instrument characteristics has provided a vast database of echoes over more than a decade and sampling many thousands of rivers and lakes worldwide. This decadal global dataset holds a vast amount of climate related information; one conclusion from all researchers in this field is that this valuable monitoring capability must be continued by future altimeter missions. The comparatively recent area of research in inland water height applications is evolving rapidly, and the potential of this technique is only now being realized.

1.6.2.2 Geodetic altimetry

Geodetic altimetry is fundamentally different from “conventional” oceanographic altimetry. In contrast, geodesy (according to the Sandwell and Smith algorithm) requires only that mean sea surface slopes be measured, over scales of < 200 km. Absolute sea surface height is not needed. Hence, a “simple” single-frequency altimeter is sufficient. Sea surface slope estimation down to scales as small as 6 km (half wavelength), however, can only be obtained if:

1) The instrument precision (height variance) is very small, and
2) The average spacing between neighboring tracks is 6 km or less.

These two requirements dictate: 1) a delay-Doppler instrument, and 2) a non-repeating orbit, respectively. The delay-Doppler approach increases the degrees-of-freedom in the height waveform; hence, its inherent precision is better (by nearly a factor of two) than that of a conventional altimeter. In spaceborne altimetry all measurements are made at nadir. A cross-track resolution is the result of a non-repeating orbit, so that, after a year or so, the density of surface tracks accumulates; hence, their average proximity decreases with time. An example of a non-repeating orbit altimetry mission is the so-called geodetic mission of GEOSAT (March 1985 to Sept. 1986), the phase during the first 18 months of the mission.

1.6.2.3 Delay-Doppler altimeter concept

The delay-Doppler altimeter differs from a conventional radar altimeter concept in that it exploits coherent processing of groups of transmitted pulses and the full Doppler bandwidth is exploited to make the most efficient use of the power reflected from the surface. While the conventional altimeter technique is to measure the distance between the satellite and the mean ocean surface, the delay/Doppler method differs from those instruments in two ways:
- Pulse-to-pulse coherence and full Doppler processing to allow for measurement of the along-track position of the range measurement
- Use of two antennas and two receiver channels that allow for measurement of the across-track angle of the range measurement.

This is a significant improvement over conventional Doppler beam sharpening.\(^{1452}\)\(^{1453}\) In order to exploit this full bandwidth, the range variation that exists across the Doppler bins is removed as part of the data processing. The reflected pulses from a given area of the observed surface are integrated over the entire time that the target area is within the radar beamwidth. As a result, much more of the reflected energy is captured and a smaller transmitted power is required to obtain a given level of performance.

The central innovation of the delay/Doppler technology is that the returns from a group of transmissions along-track are coherently processed together, rather than incoherently as is customary. The coherent along-track processing allows much more of the instrument’s radiated power to be converted into height measurement data.\(^{1454}\) The phase between two otherwise identical coherent signals is a direct measure of the time shift between them (referred to as phase-monopulse technique). If the geometry of the observation space is

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\(^{1449}\) Courtesy of R. Keith Raney of JHU/APL, Laurel, MD
\(^{1454}\) http://sd---www.jhuapl.edu/Intro/2.6ocean.html#3
known, then the observed phase shift can be inverted to an angular offset. The phase-monopulse technique uses this principle to estimate the angle of arrival between two signals collected through separated antennas.

- An airborne instrument named **D2P** (Delay-Doppler Phase-monopulse Radar) was developed and built by JHU/APL which demonstrated the technology in various test flights in the spring and summer of 2000 (P62). In addition, S/C missions (WITTEX, ABYSS) with the objective of altimetric bathymetry recovery from sea surface slopes have been proposed based on delay-Doppler technology.

- **SIRAL** (SAR Interferometer Radar Altimeter), the CryoSat mission altimeter of ESA (launch on Oct. 8, 2005 — but launch failure), employs the concepts that have been demonstrated with the D2P radar. The SIRAL dual-beam concept (C+Ku-band) offers for the first time some swath information, a significant advance over conventional pencil-beam altimeters (thus, offering a better capability of ocean current pattern recognition). 1455) 1456) 1457) 1458)

- **SRAL** (SAR Radar Altimeter), a dual-band (C+Ku-band) altimeter operating in conventional radar—altimeter mode as on Poseidon-3 (Jason-2), and in advanced SAR mode (burst mode) over sea ice and coastal regions. The instrument is being developed for the Sentinel-3 mission of the European GMES program. The SRAL concept is of Poseidon-3 and SIRAL instrument heritage.

### 1.6.3 SST (Sea Surface Temperature)

The topics of spaceborne SST measurements from LEO and from GEO are covered in chapters 1.5.2.1 and 1.5.3.1, respectively. The SST variable has a strong influence on the exchange of heat, momentum, water and gases between the ocean surface and the atmosphere. Its knowledge is essential for predicting the dynamic behavior of the atmosphere and the ocean. SST is also an important indicator of climate and climate change, so to speak a finger on the pulse of the planet itself.

### 1.6.4 Ocean color observations

The spectra retrieved with an imaging spectrometer show absorption features that are matter specific and depend on quantum mechanical interactions as well as molecular structure and scattering properties of the observed material. Observing reflected solar illumination (thermal emissions) with such detailed spectral resolution enables direct identification of virtually all diagnostic absorption features in minerals and soils, the examination of physical and biological components in marine and inland waters, and the study of biochemical processes in vegetation.

“Ocean color” is a shorthand term for a specific set of optical measurements from airborne or spaceborne instruments used to determine the radiance backscattered from water and across the air-sea interface at some or many spectral bands. Ocean color is determined by the interactions of incident light (reflected sunlight) with substances or particles present in the water. The most significant constituents are free-floating photosynthetic organisms (phytoplankton) and inorganic particulates.

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1456) http://www.estec.esa.nl/explorer/cryosat/index.html
The value of ocean-color data lies in the long-term monitoring of the marine environment, thereby providing a better understanding of the role of oceans in the global carbon cycle [the carbon cycle \(^{1459}\) feedback has a very important influence on climate research; the ocean has a significant role in the carbon cycle due to the dissolution of CO\(_2\) in water and the release of dimethyl sulfide (DMS) gas by phytoplankton (ocean algae)]. The prime observables of ocean-color instruments are basically the chlorophyll and gelbstoff concentrations in the surface layer of the ocean. The concentration of chlorophyll is used to estimate the abundance of phytoplankton in ocean waters, and hence the abundance of ocean biota. The observations permit also concentration estimations of algae over large ocean regions and the study of near-surface phytoplankton “blooms” and ocean pollution.

- A spaceborne spectroradiometer (multi-channel scanning radiometer) by the name of CZCS (Coastal Zone Color Scanner), launched on Nimbus-7 (Oct. 24, 1978) provided first images of ocean color (chlorophyll and gelbstoff concentration) distribution. CZCS measured in five optical and one TIR band at a spatial resolution of 825 m on a swath of 1600 km. The measurements were optimized for use over water. The CZCS instrument operated for seven years. The data of this first-generation ocean color instrument contributed greatly to our understanding of the marine environment and its biological, biochemical, and physical processes. Monitoring of marine phytoplankton is of great importance because it accounts for nearly half of the world's total primary productivity. Biomass turnover rates for plankton ecosystems are 100 times faster than those for terrestrial systems, leading to a close relationship between upper-ocean ecology and physical forcing.

<table>
<thead>
<tr>
<th>Sensor, Sensor Provider</th>
<th>Platform</th>
<th>Launch/Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCE, NASA/GSFC, USA</td>
<td>Shuttle (SIR-A mission), STS-2</td>
<td>Nov. 12-14, 1981</td>
</tr>
<tr>
<td>MOS, DLR, Germany</td>
<td>IRS-P3 (ISRO, India) Priroda (MIR module, Russia)</td>
<td>March 21, 1996 April 26, 1996</td>
</tr>
<tr>
<td>OCTS, NASA, Japan</td>
<td>ADEOS</td>
<td>Aug. 17, 1996 - June 30, 1997 (some ocean color products)</td>
</tr>
<tr>
<td>POLDER, CNES, France</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SeaWiFS, OSC/Orbimage, USA</td>
<td>OrbView-2/SeaStar (previous name)</td>
<td>Aug. 1, 1997</td>
</tr>
<tr>
<td>OCI, NSPO, Taiwan</td>
<td>ROCSAT-1 (Formosat-1)</td>
<td>Jan. 26, 1999</td>
</tr>
<tr>
<td>OCM, ISRO, India</td>
<td>IRS-P4 (OceanSat-1)</td>
<td>May 26, 1999</td>
</tr>
<tr>
<td>MODIS, NASA/GSFC, USA</td>
<td>Terra (previous name: EOS/AM-1)</td>
<td>Dec. 18, 1999</td>
</tr>
<tr>
<td>EOSMI, KARI, Korea</td>
<td>KOMPSAT-1</td>
<td>Dec. 20, 1999</td>
</tr>
<tr>
<td>MERIS, ESA, Europe</td>
<td>Envisat</td>
<td>Mar. 1, 2002</td>
</tr>
<tr>
<td>MODIS, NASA/GSFC, USA</td>
<td>Aqua (formerly EOS/PM-1)</td>
<td>May 4, 2002</td>
</tr>
<tr>
<td>COCTS, SITP, China</td>
<td>HY-1A (Haiyang-1)</td>
<td>May 15, 2002</td>
</tr>
<tr>
<td>Polder-2, CNES, France</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCM, ISRO, India</td>
<td>OceanSat-2</td>
<td>planned for 2007</td>
</tr>
<tr>
<td>VIIRS, IPO, USA</td>
<td>NPP</td>
<td>planned for 2009</td>
</tr>
<tr>
<td>VIIRS, IPO, USA</td>
<td>NPOESS</td>
<td>planned for 2012</td>
</tr>
</tbody>
</table>

Table 73: Overview of spaceborne sensors for ocean color detection

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Ground Resolution (km)</th>
<th>Swath Width (km)</th>
<th>Spectral Bands (range nm)</th>
<th>Data Repetivity (days)</th>
<th>Sensor Tilt Capability</th>
<th>Absolute Radiomet. Accuracy</th>
<th>Polarization Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZCS</td>
<td>0.825</td>
<td>1600</td>
<td>5 bands 443-800 + TIR</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCE</td>
<td>0.90</td>
<td>180</td>
<td>8 bands 464 - 773</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOS-A</td>
<td>1.57 x 1.40</td>
<td>195</td>
<td>4 bands 475-768</td>
<td>13 (408-1011)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOS-B</td>
<td>0.52 x 0.52</td>
<td>200</td>
<td>13 (408-1011)</td>
<td>1 (1600)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOS-C</td>
<td>0.52 x 0.64</td>
<td>192</td>
<td>4 (755-768)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensor | Ground Resolution (km) | Swath Width (km) | Spectral Bands (range nm) | Data Repetivity (days) | Sensor Tilt Capability | Absolute Radiomet. Accuracy | Polarization Sensitivity
--- | --- | --- | --- | --- | --- | --- | ---
OCTS | 0.70 | 1400 | 8 bands 402 - 885 + 4 IR | 2 | ±20º | <10% | <2-5%
SeaWiFS | 1.1 LAC 4.5 GAC | 2800 LAC 1500 GAC | 8 bands 402 - 885 | 2 | ±20º | <5% | <2%
MODIS | 1 | 2330 | 9 bands 402 - 877 | 2 | none | <3% | <2% (<5% at 412 nm)
OCM | 0.36 | 1420 | 8 bands 402 - 885 | 2 | ±20º | <10% | <2%
OCI | 0.80 | 691 | 6 bands 433 - 885 | | | | |
COCTS | 1.1 | 1400 | 8 bands 402-885 + 2 TIR | 2 | | 10-40% |
OSMI | 1 0.85 nadir | 800 | 8 bands 400 - 885 | | ±45º | |
MERIS | 0.3 and 1.2 | 1150 | 15 bands 390 - 1040 | 3 | <2% | <0.5% |
GLI | 1/0.25 | 1600 | 36 bands 375 - 2250 | 2 | | <2% |

Table 74: Some performance parameters of ocean color sensors (multispectral radiometers)

1.6.5 SSS (Sea Surface Salinity)

SSS (Sea Surface Salinity) and its variation across the oceans is an important parameter in physical oceanography. Even small variations in SSS can have dramatic effects on the water cycle and ocean circulation. SSS is a measure of concentration, in particular the concentration of dissolved salts in the upper layer (a few cm) of the ocean surface. Throughout Earth’s history, certain processes have served to make the ocean salty. The weathering of rocks delivers minerals, including salt, into the ocean. Evaporation of ocean water and formation of sea ice both increase the salinity of the ocean. However these “salinity raising” factors are continually counterbalanced by processes that decrease salinity such as the continuous input of fresh water from rivers, precipitation of rain and snow, and melting of ice.

Seawater, on the average, contains 35 g of salt per 1 kg of seawater. The salts in seawater affect the structure and properties of the water in seawater. The salts in seawater are really ions. Ions, in turn, affect the physical properties of water. The density of seawater is greater than the density of pure water. Hence, changes in salt concentration at the ocean surface affect the weight of surface waters. Fresh water is light (lower density) and floats on the surface, while salty water is more dense and sinks.

Together, salinity and temperature determine seawater density and buoyancy, driving the extent of ocean stratification, mixing, and water mass formation. Greater salinity, like colder temperatures, results in an increase in ocean density with a corresponding depression of the sea surface height. In warmer, fresher waters, the density is lower resulting in an elevation of the sea surface. These height differences are related to the circulation of the ocean. The changes in density bring warm water poleward on the surface to replace the sinking water driving the global thermohaline (heat & salt) circulation within the ocean called the Global Conveyor Belt. 1460)

As of 2006, two radiometric missions are under development with the objective to demonstrate the measure the SSS distributions over the oceans. Both missions are using L-band radiometry to observe ocean surface brightness temperature.

1460) http://science.hq.nasa.gov/oceans/physical/SSS.html
1) The **SMOS** (Soil Moisture and Ocean Salinity) mission in LEO (Low Earth Orbit) of ESA (launch scheduled in late 2007) employs the synthetic aperture radiometer concept with **MIRAS** (Microwave Imaging Radiometer using Aperture Synthesis).

2) The **SAC-D/Aquarius** mission, a cooperative project of NASA and CONAE under development (launch scheduled for 2008), employs the pushbroom radiometer concept with a large antenna.

**SSS** is one of the fundamentals variables for which global sustained observations are needed in **CLIVAR**, the international program on **CLImate VARiability and predictability**, and **GOOS**, the Global Ocean Observing System.

### 1.6.6 Oversight of ocean programs by global organizations

The global effects of the oceans on climate and the environment is of concern to all of civilization. The fostering and coordination of ocean programs is provided by **GOOS** (Global Ocean Observing System), a joint program of **IOC** (Intergovernmental Oceanographic Commission), *WMO* (World Meteorological Organization), **UNEP** (United Nations Environmental Program), and **ICSU** (International Council of Scientific Unions). The GOOS structure integrates real-time in-situ and satellite observations with numerical models to form model-based information products for a variety of applications. The initial GOOS was formed in 1991. European GOOS (EuroGOOS) was formed in 1994 as one of several regional GOOS activities. Operational programs such as **GODAE** (Global Ocean Date Assimilation Experiment), **MERCATOR** (a program of French institutions for GODAE, since 1996) and **Argo** (Array for Geostrophic Oceanography) are GOOS pilot projects.

**WOCE** (World Ocean Circulation Experiment) is an unprecedented effort during the period 1990-1997 by scientists from more than 30 nations to study the large-scale circulation of the ocean (use of data from satellites, many ships, in-situ data from thousands of instruments, and campaigns (like TOGA/WOCE) - to obtain a basic description of the physical properties and circulation of the global ocean). **JGOFS** (Joint Global Ocean Flux Study) is an international and multi-disciplinary program with participants from more than 20 nations that was initiated in 1987 by **ICSU**. The objectives of JGOFS are to assess more accurately, and to understand better the processes controlling, regional to global and seasonal to interannual fluxes of carbon between the atmosphere, ocean surface and ocean interior, and their sensitivity to climate changes.

**IGOS** (Integrated Global Observation Strategy) was initiated in 1998, an international effort aimed to globally monitor quantitative information on carbon sources. Long-term observations are required to improve the understanding of the present state and future behavior of the global carbon cycle, particularly the factors that control the global atmospheric **CO₂** (carbon dioxide) level. The buildup of atmospheric **CO₂**, driven by the combustion of fossil fuels along with deforestation and other changes in land use, is the largest contributor to the global increase in the greenhouse effect. The concentrations of **CO₂** and **CH₄** in the atmosphere are the highest they have been in the past 25 million years. In fact, the **CO₂** level has increased by over 30% since the start of the industrial age. The recent climate history indicates that there has been a global warming of about 0.5 °C over the past 100 years which is generally attributed to increasing concentrations of the greenhouse gas **CO₂**. **1461** **1462**

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**1461** The development and implementation of the IGOS is through a partnership, IGOS-P, among space agencies, as represented by **CEOS** (Committee on Earth Observation Satellites); **GOOS** (Global Ocean Observing System), **GTOS** (Global Terrestrial Observing System), and **GCOS** (Global Climate Observing System), and the research community, as represented by two major international research programs, **IGBP** (International Geosphere-Biosphere Program) and **WCRP** (World Climate Research Program).

1.7 Solar-Terrestrial Connection

The sun as the central star in the solar system plays a fundamental role to all planets in our constellation, in particular to all life on Earth. Hence, the interactions of all kinds (magnetic fields, radiative energy, solar wind, energetic particles, etc.) between the sun and the Earth are of vital interest to humankind. The scope of documentation includes also missions with direct observations of the sun itself and its variability over time (see Part K). In the context of solar-terrestrial connection, the following topics are of particular interest: a) interaction of solar radiation with Earth’s atmosphere, b) Earth’s radiation budget, c) the solar wind, d) space weather, and e) X-ray imaging. The mixed payload complement of a number of missions is the reason why the topic of X-ray imaging is part of this document. 1463)

The sun is the source for almost all radiation (i.e. energy) that Earth is intercepting from the universe, consisting of a large portion of the EMS (Electromagnetic Spectrum). For most solar observations, the relevant physical phenomena of interest require an observation coverage over extremely broad temporal, spatial, and spectral ranges, generally covering a span of 8-10 orders of magnitude for each range. As it turns out, the entire breadth of EMS radiation is only available and observable from an orbital vantage point (i.e., a spaceborne instrument in Earth orbit or further out). In particular, accurate measurements of solar radiation can only be made from space, due to the variable (and incompletely known) transmission of the Earth’s atmosphere. The possibility that these changes can induce sufficiently large changes in the troposphere to affect Earth’s climate is a subject of active research. Hence, by placing observing instruments into orbit (instead of on the ground) provides the following advantages: 1464)

- Extended wavelength coverage. The terrestrial atmosphere is effectively opaque to UV, EUV, and soft X-ray radiation; in the IR spectrum, only a few narrow transmission windows are available. Hence, most of the EMS does not reach the ground.

- Extended or continuous temporal coverage. Studies of solar phenomena often require many hours, days or weeks of continuous coverage. For some studies a network of ground-based observations around the world can provide the continuity, but this is not possible at wavelengths that do not reach the ground.

In addition to solar radiation variability, celestial mechanics impose quasi-cyclical variations in the parameters of the Earth orbit and rotation, thereby inducing major changes in the distribution of solar radiation incident upon the Earth surface and the timing of seasons, with still poorly understood consequences for the succession of glacial and interglacial climates. 1465)

1.7.1 Solar radiation and Earth’s atmosphere

- Atmospheric effects: Not all of the solar radiation received at the periphery of the atmosphere reaches the surfaces of the Earth. This is because the Earth’s atmosphere plays an important role in selectively controlling the passage towards the Earth’s surface of the various components of solar radiation. 1466)

A considerable portion of solar radiation is reflected back into outer space upon striking the uppermost layers of the atmosphere, and also from the tops of clouds. The fraction of solar

irradiation reflected back into space is termed the "albedo" and is highly variable depending on the surface type and intervening atmosphere (e.g. clouds). In the course of penetration through the atmosphere, some of the incoming radiation is either absorbed or scattered in all directions by atmospheric gases, vapors, and dust particles (aerosols). In fact, there are two processes known to be involved in atmospheric scattering of solar radiation. These are termed selective scattering and non-selective scattering. These two processes are determined by the different sizes of particles in the atmosphere.

- Selective scattering is so named because radiations with shorter wavelengths are selectively scattered much more extensively than those with longer wavelengths. It is caused by atmospheric gases or particles that are smaller in dimension than the wavelength of a particular radiation. Such scattering is caused by gas molecules, smoke, fumes, and haze. Under clear atmospheric conditions, therefore, selective scattering turns out to be much less severe than when the atmosphere is extensively polluted from anthropogenic sources.

Selective atmospheric scattering is, broadly speaking, inversely proportional to the wavelength of radiation and, therefore, decreases in the following order of magnitude: gamma-ray, X-ray, far UV > near UV > violet > blue > green > yellow > orange > red > infrared. Accordingly, the most severely scattered radiation is that which falls in the ultraviolet, violet, and blue bands of the spectrum. The scattering effect on radiation in these three bands is roughly ten times as great as on the red rays of sunlight. — It is interesting to note that the selective scattering of violet and blue light by the atmosphere causes the blue colour of the sky.

- Non-selective scattering occurring in the lower atmosphere is caused by dust, fog, and clouds with particle sizes more than ten times the wavelength of the components of solar radiation. Since the amount of scattering is equal for all wavelengths, clouds and fog appear white although their water particles are colourless. Atmospheric gases also absorb solar energy at certain wavelength intervals called absorption bands, in contrast to the wavelength regions characterized by high transmittance of solar radiation called atmospheric transmission bands, or atmospheric windows.

The Earth’s atmosphere and oceans are components of a vast heat engine which governs our weather and climate. The heat source for this engine is the solar radiation which is absorbed by the Earth atmosphere/ocean/land/cryosphere system and the heat sink is the radiation emitted by this system.\textsuperscript{1467} This system is extremely complex and has a number of modes of response ranging from microscale in time and space to planetary scale interdecadal variations. - The components of the Earth’s radiation field, i.e. the absorbed solar radiation and the emitted radiation are dynamic quantities which vary in space and time. The radiation components are both, cause and effect, due to their interactions with the other parts of the weather/climate system. The radiation energy from the sun drives many biological, geophysical and biogeochemical processes that may ultimately influence climate itself.

- Clouds play a major role in Earth’s radiation budget. They are extremely variable in space and time and can either heat or cool the Earth, depending on their height. With their high albedo, clouds reflect sunlight, tending to cool the Earth. Low clouds also serve to reflect radiation from the surface, thereby retaining heat within the system. Absorption of sunlight causes clouds to dissipate. Radiation from cloud tops increases the turbulence and mixing near the cloud top, and absorption of radiation from the lower ground increases turbulence near the bottom of the cloud, except in inversion situations, such as the polar winters, where radiation from the cloud bottom tends to suppress turbulence and mixing. The interaction of clouds with the surface can be important to the cloud’s lifetime. A cold ocean for example can maintain a cloud cover over it as a feedback system.

- Most solar radiation which is absorbed by the Earth system is absorbed at the surface. Radiation absorbed at the surface provides sensible and latent heat, which evaporates sur-

face water and melts snow and ice. Because of the small heat capacity of land, most of this sensible heat is transferred to the air. For the ocean, the sensible heat raises the sea surface temperature (SST). It has been shown that the surface radiation of a region is so intimately related to the various processes that its climate classification can be determined from the annual mean and ranges of the net shortwave and longwave fluxes at the surface. Snow cover is important in interseasonal variations because the high albedo of snow causes a positive feedback so that the presence/absence of snow tends to extend itself. This change of energy balance at the surface will affect the flow of air, possibly creating effects at a distance.

- The oceans are driven by friction of wind, by temperature gradients and by salinity gradients, which are created by rain and melting of ice. The SST is a major factor in climate variability, as its large thermal inertia causes it to have response times of months and greater. The sea surface temperature SST is driven largely by radiation and air/sea interactions. The radiation is in turn modulated by cloud cover, which is highly variable. The coupling of cloud cover to the ocean is an area of active research, as this interaction affects both the ocean temperatures and the clouds, leading to climate variations which are not yet understood.

![Solar Irradiance Curves](image)

**Figure 34:** Solar irradiance curves at top of the atmosphere and at ground level

- Estimation of the Earth’s radiation energy distribution at the Earth’s surface - also referred to as SSI (Surface Solar Irradiance). All of the energy available at the Earth’s surface for heating and cooling of the air (sensible heat), evaporating water from the soil and vegetation (latent heat), and heating or cooling of the soil (soil conduction) is a response to the fluxes of solar and thermal radiation within the Earth-atmosphere system. Solar radiation causes a response in TIR (Thermal Infrared) reradiation at the Earth’s surface with important consequences for local and global energy balances. The monitoring and modeling of the solar energy balance at the Earth’s surface has applications in many disciplines (e.g.
agriculture, water resources, climate change research).\(^{1468}\) While land surface fluxes can be measured with in-situ techniques, there has been a steady progress in estimating the components of the land (as well as the ocean) surface energy balance from orbit since the first meteorological satellites were launched in the 1960s. Researches on the estimation of SSI were made using the data in particular from geostationary meteorological satellites, since GEO satellites have an advantage to observe solar radiation that is reflected by the Earth’s surface and clouds (reradiation), or diffused by the atmosphere in the visible channel of the satellite instruments.\(^{1469}\)

Albedo is defined as the fraction of incident radiation that is reflected by a surface. While reflectance is defined as this same fraction for a single incidence angle, albedo is the directional integration of reflectance over all sun-view geometries. Albedo is therefore dependent on the bidirectional reflectance distribution function (BRDF). It turns out that small increases or decreases in surface albedo can significantly impact regional and global climate. Remote sensing instruments do not directly measure surface albedo. As a result, albedo must be inferred through analysis, i.e. a series of manipulations to the measured data.

At the start of the 21st century, satellite data can already provide a data quality similar to ground-based measurements and at very high spatial resolution, taking into account the physical and optical properties of clouds (clouds have a high albedo, causing much of the solar irradiation to be reflected back to space before it can ever reach the Earth’s surface). For the oceans, the amount and intensity of light reaching the ocean surface is a crucial variable affecting the production of carbon by phytoplankton (primary production).

### 1.7.2 Earth’s Radiation Budget and Solar Constant

Historically mankind has long recognized the importance of understanding the sun as the Earth’s energy source. The development of the telescope in the early seventeenth century brought the sun under close scrutiny and discoveries rapidly followed — sunspots, filaments, prominences, faculae, etc. Developments and improvements in spectroscopy were applied to the sun, and likewise led to discoveries of new atomic species and unexpected high states of ionization. Coronagraphs and other specialized instruments also have had great success in unraveling the mysteries of the sun. Naturally as the science of radiometry progressed, attempts were made to record the radiative output from the sun and to determine the amount of solar variability.\(^{1470}\)\(^{1471}\)\(^{1472}\)\(^{1473}\)

Since the 1880s, routine solar irradiance measurements were made from the ground to detect an eventual variability. The irradiance was referred to as the “solar constant” because atmospheric transmittance variability, of the order of several percent, prevented the detection of any systematic irradiance changes from the Earth’s surface in those early measurements.

[The observation of the sun’s radiation budget from a ground-based reference is difficult at best, because this measurement must be corrected for atmospheric absorption and scattering. Rayleigh scattering, aerosol scattering, and molecular and atomic absorption all attenuate the solar radiation. In order to recover the TOA (Top of Atmosphere) irradiance, the ground-based observations had to be extrapolated, but the necessary adjustments were large. In the final analysis the estimated TSI values were deemed valid to only]


\(^{1469}\) J. D. Tarpley, 1979: Estimating incident solar radiation at the earth’s surface from geostationary satellite data,” Journal of Applied Meteorology, Vol 18, 1979, pp. 1172-1181


the order of a couple of percent. In the final analysis, there was general consensus that long-term variations of the sun were probably less than the measurement error of a couple percent, and at this level the solar irradiance could be considered “constant” — and this was referred to as the “solar constant” up for the most part of the 20th century — a persistent misnomer as we know today.]

The space age permitted for the first time a more accurate measurement and assessment of the Earth’s radiation energy budget from orbit (i.e. the incoming solar radiation measured from outside the atmosphere). The “solar constant,” nowadays more accurately referred to as TSI (Total Solar Irradiance), is the radiative power received normally onto a unit area at the mean Earth/Sun distance. Along with Earth’s global average albedo and the emitted longwave radiation, it determines Earth’s global average equilibrium temperature. Solar radiation is the primary power source driving our climate system. Hence, knowledge of the long-term TSI variability is essential in understanding the past and future climate changes.

The solar irradiance varies slightly over an 11-year cycle (about 0.1%). The larger portion of variability in solar radiation at short wavelengths (UV and below) is known to affect the chemistry and composition of the stratosphere, with the magnitude of the effect increasing with altitude through the mesosphere and thermosphere. The variations occur over time scales from a day up to and exceeding the 11-year solar cycle. This cycle of the sun’s magnetic activity alters its energy output, as well as the occurrence of sunspots, solar flares, and CMEs (Coronal Mass Ejections), the latter represents a huge eruption of material from the solar atmosphere into interplanetary space. While solar flares affect the ionosphere, CMEs occur when the magnetosphere is disturbed by plasma that propagates through interplanetary space to the Earth after sudden disruptions in the solar magnetic field.

The solar constant, as defined for planet Earth, is the amount of radiative energy per unit time per unit area (i.e., energy flux or radiative power at normal incidence) intercepted by Earth at the average distance from the sun (1 AU) — on top of Earth’s atmosphere. The most accepted value of the “average solar constant” is 1366 W m⁻² as projected on Earth’s disk; it is now referred to as the total solar irradiance (TSI), i.e. the integrated solar spectral irradiance over all wavelengths.

The continuous observation of the solar irradiance at the highest possible precision and accuracy is an important objective of the Earth climate change program. It requires high quality metrology in the space environment linked to ground solar radiometric comparisons supported by laboratory characterization activities.

The Earth radiation budget (ERB) is the difference between the Earth’s absorbed solar radiation and the longwave radiation emitted by the Earth and its atmosphere. The concept applies globally to the whole Earth and locally to any place, with important consequences due to its gradients. Similarly, the net radiation at TOA (Top of the Atmosphere) is derived as a function of the planetary albedo and the longwave radiation emitted by Earth into space. ERB measurements seek to contribute to two key scientific goals: 1) the determination of how long- and shortwave fluxes are distributed in the atmosphere and how they vary in time, and 2) the development of a quantitative understanding of the links between the radiation budget and the properties of the atmosphere and the surface related to the energy budget and its processes. Accurate solar irradiance data are not only of particular importance for the assessment of the radiative forcing of the climate system, but also necessary for an efficient planning and operation of solar energy systems.

First Earth radiation budget measurements of the space age go back to the late 1950s, with instruments flown on Soviet and US satellites. — NASA launched Explorer-7 on Oct. 13, 1959. The “Thermal Radiation Experiment” of Explorer-7 was designed to measure incident and reflected solar UV radiation and terrestrial IR radiation in order to obtain a better
understanding of the driving forces of the Earth-atmosphere system. The primary instrumentation consisted of five bolometers (detectors) in the form of hollow silver hemispheres that were thermally insulated from, but in close proximity to specially aluminized mirrors. The hemispheres thereby behaved very much like isolated spheres in space. Two of the hemispheres had black coatings and responded about equally to solar and terrestrial radiation. A third hemisphere, coated white, was more sensitive to terrestrial radiation than to solar radiation. A complete set of four temperature observations and one reference sample required 30 s. Thus, in each orbit, about 180 temperature measurements could be obtained. The experiment was a success, and usable data were obtained from launch until February 28, 1961. Although the measurement method was rather crude by today’s standards, it provided the first valuable data on the basic radiation energy balance of the planet. Maps of radiation (reflected and emitted) were mapped for the first time from LEO.

In the early 1970s, the importance of improving knowledge on the Earth’s radiation budget was recognized [i.e., the balance between incoming energy from the sun and the outgoing thermal (longwave) and reflected (shortwave) energy from the Earth] and its relationship with the Earth’s climate. NASA built a multichannel absolute radiometer instrument (blackbody calibrated) by the name of ERB (Earth Radiation Budget) which was flown for the first time on Nimbus-6 (launch June 12, 1975, M.26.6). However, the analysis of the ERB data failed to detect any irradiance variability due to degraded responses of the ERB radiometer.

An improved version of ERB was subsequently flown on Nimbus-7 (launch Oct. 24, 1978, M.26.7; TSI broadband data from ERB on Nimbus-7 were available until the end of 1993). This radiometer was stable enough to detect short-term and long-term solar irradiance variability. ERB was the first long term solar monitor utilizing the ESCC (Electrically Self Calibrating Cavity) technique.

The modern ESCC radiometer technique introduced two operational features: the so-called ‘active cavity’ operational mode and the differential measurement approach. The active cavity operational mode is one in which the same thermodynamic state is maintained for the cavity sensor in both the solar observation (shutter open) and reference (shutter closed) phases of a measurement. The differential measurement approach utilizes only the differences between solar observation and reference values, eliminating measurement dependence on the International Practical Temperature Scale. The active cavity operation is achieved by using an electronic servosystem to provide electrical heating power for the cavity detector during both shutter open and closed phases of measurement. The power is controlled at the amount required to sustain constant relative, internal instrument temperatures in the two measurement phases. The measurement then reduces to relating the cavity heating power in the shutter open and closed phases and several other key sensor parameters to the International System of units (SI). Operation does not depend on the International Practical Temperature Scale and the observational uncertainties are reduced to differences between small terms in the two measurement phases. The combination of these techniques greatly decreases the overall measurement uncertainty.

The design of the absolute cavity radiometer technique is based on the principle of substitution of electrical power for radiative power (the idea of the cavity design is to come as close as possible)

1474) http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1959--009A&ex=1
1475) Note: The Thermal Radiation Experiment was developed by V. E. Suomi (1915-1995) and his colleagues at the University of Wisconsin, Madison, WI
1478) Note: The prototype ESCC pyrheliometer with many of the essential features in use today was developed by Charles Abbot of the Smithsonian Astrophysical Observatory (SAO, Cambridge, MA, USA) in the first decade of the 20th century.
as possible to a “perfect absorber” of solar radiation). The function of the cavity is to provide a physical enclosure for the trapping (absorption) of all incoming (broadband) solar radiation. All of these substitution radiometers are of the type “broadband”, i.e. they are using all or a major portion of the spectrum (in two steps or so) for a hemispherical flux measurement, as opposed to “spectrally resolved” instruments.

The success of ERB on Nimbus-7 resulted in the development of a number of TSI instruments for various missions. Since the solar constant is one of the prime determining factors of the Earth’s climate (together with the cloud cover and the Earth’s thermal emission), the data obtained is used in such applications as climate change, solar physics studies, and Earth radiation budget estimates. Solar-constant instruments are generally very sensitive and accurate radiometers for the measurement of solar radiation. Most sensor designs employ the method of “active cavity detector geometry” pyrheliometers (detector in equilibrium with incident solar radiation) and variations thereof. Following is a survey of “Earth radiation budget missions,” most of them with absolute or active cavity radiometers for the measurement of TSI; there are also instruments (such as HCMM, SeaRaB and GERB) that are not of the absolute radiometer type.

- A first comprehensive thermal survey of the Earth’s surface was provided by HCMM (Heat Capacity Mapping Mission, launch April 26, 1978, end of mission Sept. 30, 1980) of NASA. The satellite featured a Heat Capacity Mapping Radiometer (HCMR) for the measurement of the heat budget, in particular the thermal inertia of the land surface for geological studies.

- SMM (Solar Maximum Mission, launch Feb. 14, 1980, ACRIM data until 1989) flew ACRIM-I (Active Cavity Radiometer Irradiance Monitor) of NASA/JPL and provided data until 1989. The ACRIM-I and ERB/Nimbus-7 instruments detected a short-term (less than 27-day solar rotational period) irradiance variability of as much as 0.2% and a long-term variability of about 0.1%.1481)

- A new generation instrument was realized with ERBE (Earth Radiation Budget Experiment) of NASA/LaRC, first flown on ERBS (Earth Radiation Budget Satellite, launch Oct. 5, 1984), then on NOAA-9 (launch Dec. 12, 1984), and NOAA-10 (launch Sept. 17, 1986). ERBE was able to provide more accurate and systematic parameters for estimating the Earth’s radiation budget. ERBE flew both wide-field-of-view, flat-plate radiometers and the narrow-field-of-view scanning radiometric telescopes measuring with three channels the “short wave”, the “long wave” and the “total” radiances. The improved spatial resolution of flux data achieved with this scanner, by taking into account the bidirectional reflection functions at the TOA, is perhaps the most important advance offered by ERBE, because it led to better estimates of the difference between cloudy and clear-sky fluxes and thus a better estimate of the effect of clouds on Earth’s radiation budget.1482) 1483) 1484) 1485)

- The instruments ACRIM-II, SOLSTICE (Solar/Stellar Irradiance Comparison Experiment) and SUSIM (Solar Ultraviolet Spectral Irradiance Monitor), all with the objec-

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tive to measure solar radiation, are flown on NASA's UARS (Upper Atmosphere Research Satellite) mission. Launch Sept. 12, 1991, the S/C is operational as of 2001 (UARS standby mode as of Sept. 30, 2001 - seven of the ten instruments are still functional).

- EURECA-1 (European Retrievable Carrier). An ESA long-term free-flyer platform (J.5.1) launched on Shuttle flight STS-46 on July 31, 1992 and retrieved with STS-57 on July 1, 1993. Two instruments aboard EURECA were dedicated to solar observations, namely SOVA (Solar Constant and Variability Instrument) with D. Crommelynck as PI, and SOSP (Solar Spectrum Instrument) with G. Thuillier as PI.

- The ScaRaB (Scanner for Radiation Budget) program of CNES (France, Russia and Germany are program partners), started in 1987 with the objective to measure the terms of the Earth's radiation budget. Two of three instruments, built by CNRS/LMD and operated by CNES, were flown already on Meteor-3-7 (launch Jan. 25, 1994, ScaRaB stopped operating March 5, 1995) and Resurs-O1-4 (launch July 10, 1998 - failure of the backup downlink on Apr. 8, 1999 causing a termination of ScaRaB operations), respectively. The third instrument is planned to be flown on a future mission (currently a CNES/ISRO climate mission in the tropics is considered the most likely candidate, namely Megha-Tropiques). (1486) Note: ScaRaB performs no measurements of TSI. However, the overall radiation budget analysis of ScaRaB uses solar constant values from other sources (such as ISP-2).

- VIRGO (Variability of Solar Irradiance and Gravity Oscillations), an ESA AO instrument package flown on SOHO (launch Dec. 2, 1995, operational as of 2004). The subunits DIARAD (Differential Absolute Radiometer) and PMO6-V are the absolute radiometers in this assembly. Regularly updated observations of the solar constant can be found at the following reference: (1487)


- CERES (Clouds and the Earth's Radiant Energy System), a scanning thermistor-bolometer instrument of ERBE heritage of NASA/LaRC, is flown on TRMM (Tropical Rainfall Measuring Mission), launch Nov. 27, 1997, as a single cross-track radiance sensor of short (0.3-5 μm), long- (8-12 μm) and total wave (0.3-100 μm; prototype flight model flown on TRMM) TRMM CERES data was provided from Dec. 1997 to Sept. 1998. Two further advanced CERES instruments are also being flown on NASA's Terra mission (launch Dec. 18, 1999) as a dual-track scanner (two radiometers) in XT (Cross-Track) support or in a RAPS (Rotational Azimuth Plane Scan) support mode. Another CERES instrument system (two radiometers) are being flown on Aqua (formerly EOS/PM1) of NASA (launch May 4, 2002).

- ACRIM-III on ACRIMSAT (NASA), launch Dec. 20, 1999 (see A.2)

- First Earth radiation budget measurements from GEO. GERB (Geostationary Earth Radiation Budget) is an ESA-developed instrument of the EUMETSAT MSG-1 (Meteosat Second Generation) mission, a two-channel broadband radiometer, provided by a consortium led by the UK (NERC), Belgium (SSTC) and Italy (ASI). The launch of MSG-1 (Meteosat-8) took place on Aug. 28, 2002. (1488) The instrument measures the radiances leaving the Earth at TOA (Top of the Atmosphere); it provides an image of the reflected sunlight and infrared radiation at a five-minute sampling rate, covering the shortwave (0.32 - 4.0 μm) and longwave (4.0 > 100 μm) regions of the spectrum. A full Earth view period of GERB detec-

1486) Information provided by M. Rouzé of CNES
1489) http://gerb.oma.be/
tors require 250 revolutions of the spin-stabilized S/C (150 s). Hence, a full disk measurement plus calibration of one channel is obtained in 2.5 minutes. - The overall radiation budget analysis of GERB uses solar-constant values from other sources. GERB data analysis is a joint effort between RAL (UK) and RMIB (Royal Meteorological Institute of Belgium), Belgium. Since the evaluation of the TOA Earth radiation balance terms (conversion of radiance to TOA fluxes) are being made available to within three hours after observation, the GERB observations can make a unique contribution to the understanding of the Earth’s climate balance (diurnal sampling), since such measurements have never been carried out before from geostationary orbit (see F.9). GERB instruments are also planned to be flown on the follow-up MSG missions. Note: The imaging data of GERB are acquired by EUMETSAT, sent to RAL for pre-processing and then forwarded to RMIB for further processing and distributing to the community. GERB data are also being compared with CERES data in LEO on the Terra S/C of NASA. The GERB FOV (Field of View) from GEO is a particularly good test bed for studying the interaction between aerosols and the climate system.

- NASA funded TIM (Total Irradiance Monitor), developed at LASP (Laboratory for Atmospheric and Space Physics) of the University of Colorado, flown on SORCE (Solar Radiation and Climate Experiment). SORCE is part of NASA’s ESE (Earth Science Enterprise) program with a launch Jan. 25, 2003. Besides very precise and accurate solar irradiance measurements with TIM, the other instruments of SORCE, namely SOLSTICE (Solar/Stellar Irradiance Comparison Experiment), SIM (Spectral Irradiance Monitor), and XPS (XUV Photometer System), complement the solar spectral irradiance measurements at wavelengths extending from the far ultraviolet to the near infrared. - A TIM instrument, referred to by the name of TSIS (Total Solar Irradiance Sensor), is also planned to fly on NASA’s NPP (NPOESS Preparatory Project) with a launch in 2009 and on NPOESS (National Polar-orbiting Operational Environmental Satellite System) of IPO (Integrated Program Office) with a first launch projected for 2012.

- NISTAR (National Institute of Standards and Technology Advanced Radiometer) is a three-channel cavity radiometer of the NASA mission Triana (currently no planned launch, the entire payload is in mothball) which measures the Earth’s “irradiance” in the small angle as seen from a halo orbit at L1 (Lagrangian point 1), about 1.5 million km from Earth in the direction of the sun. The NISTAR TSI measurements offer a great opportunity to compare its radiances with instruments in LEO (Low Earth Orbit) and in GEO (GERB). Note: NASA has terminated the Triana mission as of Jan. 2006. 1490)

- Solar-A (Solar Monitoring Observatory) is an ESA experiment package on ISS consisting of three instruments, namely SOVIM (Solar Variability and Irradiance Monitor) covers the near-UV, VIS and TIR, developed by the Observatory of Davos, Switzerland; SOLSPEC (Solar Spectral Irradiance Measurements) covers the range 180-3000 nm, developed by CNRS of France; and SOL-ACES (Solar Auto-Calibrating EUV/UV Spectrophotometers) with a coverage of 17-220 nm, developed by the Fraunhofer Institute, Germany. SOVIM and SOLSPEC are the upgraded versions of instruments that have already accomplished several orbital flights without failure. The overall objective is to measure the solar spectral irradiance with unprecedented accuracy (L.2.16). The three instruments cover the combined wavelength range from 17-3000 nm. The Solar-A package will be located on CEPF (Columbus External Payload Facility), part of COF (Columbus Orbital Facility), the ESA module of ISS. A launch of Columbus is planned for the timeframe of 2007. 1491)

- Picard is a CNES solar-terrestrial microsatellite mission (launch in 2009), named after Jean Picard (1620-1682), a French astronomer. Two instruments measure the solar constant: SOVAP (Solar Constant Variability, Picard) of RMIB (Royal Meteorological Institute of Belgium) in Brussels, and PREMOS (Precision Monitoring of Solar variability)

1491) http://esapub.esrin.esa.it/sp/sp1270/chapter3_sp1270.pdf
photometric spectral band measurements of WRC (World Radiation Center) of Davos, Switzerland. The measurement of the solar diameter is done by SODISM (Solar Diameter Imager and Surface Mapper), a CNRS/SA (Verrières-le-Buisson, France) instrument in collaboration with ESA/ESTEC.

- The US NPOESS satellite series (with a first launch in 2012) will be flying two radiation budget instruments:
  
  - ERBS (Earth Radiation Budget Sensor). The objective is to measure Earth radiation budget parameters and atmospheric radiation from the top of the atmosphere to the surface. ERBS is allocated to fly on the LTAN 13:30 S/C series.
  
  - TSIS (Total Solar Irradiance Sensor) instrument of TIM (Total Irradiance Monitor) heritage, flown on SORCE (Solar Radiation and Climate Experiment). TSIS is a total solar irradiance monitor plus a 0.2-2 µm solar spectral irradiance monitor. The objective is to measure the variability in the sun's radiative output. TSIS is allocated to fly on the LTAN 17:30 NPOESS S/C series.

- Periodic (short-term) measurements were conducted in particular with SOLCON (Solar Constant Sensor) on a number of Shuttle flights. The SOLCON-1 instrument is a cooperative effort of RMIB (Belgium), Space Science Dept. of ESA, and NASA/LaRC. The SOLCON radiometer is the first differential absolute solar radiometer in space based on a full symmetrical metrological design (two side by side cavities) and operation (successive opened and closed state of the measurement cavity). During Shuttle flights, SOLCON is used to determine the SARR (Space Absolute Radiometric Reference) adjustment coefficients of other satellite solar constant instruments that are active at the same time (the objective of SARR is to relate all existing total solar irradiance measurements with each other). 1492) 1493) 1494) 1495)

The first such SARR measurements were conducted on the STS-56 mission of ATLAS-2 in 1993, determining the adjustment coefficients of ACRIM-II flown on UARS and on ERBS (Earth Radiation Budget Satellite), and those of SOVA (Solar Constant and Variability Instrument) on EURECA-1 [SOLCON-2 was of the same design as SOVA with the SOVA1 Dual Differential Absolute Radiometer (DIARAD) composed of two independently characterized channels and the SOVA 2 set of two mono-channel active and backup radiometers]. Further SARR measurements of SOLCON were conducted with the following radiometers: 1496)

- STS-95 (1998) flight. VIRGO (Variability of Solar Irradiance and Gravity Oscillations) radiometers flown on SOHO, and ACRIM-II flown on UARS and on ERBS.
- On flight STS-107 SOLCON-3 has been used to determine the SARR coefficients of ACRIM-III on ACRIMSAT and to verify the VIRGO coefficients on SOHO.

<table>
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<tr>
<th>Launch Vehicle</th>
<th>Date</th>
<th>Mission</th>
<th>Instrument</th>
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<tbody>
<tr>
<td>STS-9 (Shuttle)</td>
<td>Nov. 28 - Dec. 8, 1983</td>
<td>Spacelab-1 (ESA)</td>
<td>SOLCON-1</td>
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<td>STS-45</td>
<td>March 24 - April 2, 1992</td>
<td>ATLAS-1 (NASA)</td>
<td>SOLCON-2, ACRIM-II</td>
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<td>STS-56</td>
<td>April 8-17, 1993</td>
<td>ATLAS-2 (NASA)</td>
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<td>STS-66</td>
<td>Nov. 3-14, 1994</td>
<td>ATLAS-3 (NASA)</td>
<td>SOLCON-2, ACRIM-II</td>
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<td>Aug. 7-19, 1997</td>
<td>Hitchhiker (NASA)</td>
<td>SOVA-1</td>
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</table>

1492) http://sspp.gsfc.nasa.gov/
1493) http://estirm2.oma.be/solarconstant/articles/article1.html#references
1494) http://estirm2.oma.be/solarconstant/articles/article3.html
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<td>STS-107</td>
<td>Jan. 16-Feb. 1, 2003</td>
<td>FREESTAR (NASA)</td>
<td>SOLCON-3</td>
</tr>
</tbody>
</table>

Table 75: Chronology of Shuttle-based solar-constant measurements with absolute radiometers

### 1.7.3 Solar Wind Observation

The solar wind is a thin blast of electrified gas—a plasma or “particle radiation” consisting of protons, alpha particles (two—fold ionized helium), heavy ions and electrons—emitted by the surface of the sun, which blows radially from the sun in all directions, naturally also toward and past the Earth at speeds ranging from 300 - 1000 km/s (or about 1—3.3 million km/h). The solar wind provides the medium through which the sun interacts directly with the Earth; it shapes the Earth’s magnetosphere and supplies energy to its many processes. Earth itself possesses a strong internal magnetic field that prevents the solar wind from hitting the upper atmosphere. Instead, the solar wind becomes diverted around the Earth’s magnetic obstacle, called the magnetosphere. 1497) 1498)

The presence of the solar wind is directly indicated by the continuing fluctuations of the geomagnetic field at the surface of Earth, particularly at high latitudes, the continuing aurora at high latitudes, the varying intensity of the galactic cosmic ray radiation, and the antipodal orientation of the gaseous tails of comets. However, these effects, known individually for decades and centuries, are evidence only of some form of external disturbance, and the scientific challenge over the last century has been to work out precisely what that disturbance really is.

The existence proof of the solar wind is a discovery of the space age by data analysis first conducted from the Soviet Luna spacecraft series [Luna-1 (launch Jan. 2, 1959), Luna-2 (launch Sept. 12, 1959), and Luna-3 (Oct. 14, 1959)] on their flight to the moon. 1499) 1500) The first tentative evidence of the solar wind was observed with an experiment of Konstantin I. Gringauz (1918-1993, USSR) and his team onboard the Luna-2 and Luna-3 spacecraft. The total electric charge of arriving ions was measured in the “ion trap experiment” (4 ion traps in the voltage range of -10 V to +15 V on Luna-2) Gringauz noted that the signal fluctuated as the spacecraft spun around its axis, suggesting an ion flow was entering the instrument whenever it faced the sun.

In 1961, James Dungey (UK) proposed a mechanism for transmitting solar wind energy to the magnetosphere by direct magnetic linkage between the two. The magnetopause, the boundary between magnetosphere and the solar wind, was observed for the first time by NASA's Explorer-10 in 1961 (launch March 25, 1961). The S/C featured an elaborate ion trap, called Modulated Faraday Cup, built by a team of MIT (Herbert Bridge, Bruno Rossi). The first variations in the speed of the solar wind (27 days intervals) were observed in 1962 from the Mariner-II spacecraft of NASA/JPL (launch Aug. 27, 1962) on its way to Venus with an instrument called CPA (Curved Plate Analyzer). CPA measured 113 days of data (continuous radial flow of high and low solar wind streams), the general properties of the solar wind (speed, temperature, and helium content) were surveyed. The data analysis of the IMP-1 (Interplanetary Monitoring Platform 1, launch Nov. 27, 1963, the mission is also known as Explorer-18) revealed a large bow shock formed in the solar wind ahead of the magnetosphere, and a long magnetic tail on the night side of the Earth. In 1983, the ISEE-3 (International Sun-Earth Explorer 3) mission explored the distant magnetotail, before

1498) http://www.noaanews.noaa.gov/magazine/stories/mag93.htm
1499) T.I. Gombosi, “Modeling Gringauz's legacy from the solar wind to weakly magnetized solar system bodies,” International Symposium on Space Plasma Studies by In-Situ and Remote Measurements (Gringauz Symposium), Moscow, Russia, June 1-5, 1998.
1500) http://www---spof.gsfc.nasa.gov/Education/whsolwi.html
heading for comet Giacobini-Zinner. The Ulysses S/C (launch Oct. 6, 1990), a joint ESA/ NASA solar mission (365 kg of launch mass, the total instruments mass is 55 kg), passed above the sun’s south pole in Sept. 1994, and above the north pole in 1995 (the second set of polar passes took place from Sept. 2000 to Jan. 2001 (south) and Sept. to Dec. 2001 (north). This first mission with an out-of-ecliptic orbit confirmed that the polar regions of the sun also have such outwards-directed field lines, as evidenced by the “polar plumes” seen in the corona during a total eclipse of the sun. The existence of a steady fast-flowing solar wind above the solar poles was observed along with many associated phenomena. 1501) 1502)

Characteristics: The solar wind plasma consists of primarily of hot electrons and protons with a minor fraction of He\(^{2+}\) ions and some other heavier ions (typically at high charge states). The solar wind originating from the streamers (closed field lines of the sun) is slow, while that originating from the coronal holes is fast. This creates the so-called ”corotating interaction regions” (CIR) in the interplanetary space. As the solar wind moves away from the sun, tangential discontinuities and interplanetary (fast) shocks are formed, creating pressure variations. Typical periodicities in the solar wind can be divided into those that reflect the time scales of the solar processes themselves, those that reflect the rotation of the Sun, and those that reflect the orientation of Earth (the most typical observation point) with respect to the Sun. The first include the 11- and 22-year solar cycles and the 1.3 year and 154 day cycles. The scale sizes of solar wind/IMF structures are typically smaller than the extent of the Earth’s magnetosphere (about 40 \(R_E\)). 1503)

<table>
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<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
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<td>Flux (cm(^{-2}) s(^{-1}))</td>
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<td>3</td>
<td>100</td>
</tr>
<tr>
<td>Velocity (km s(^{-1}))</td>
<td>200</td>
<td>400</td>
<td>900</td>
</tr>
<tr>
<td>Density (particles/cm(^3))</td>
<td>0.4</td>
<td>6.5</td>
<td>100</td>
</tr>
<tr>
<td>Helium (%)</td>
<td>0</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>B (nT)</td>
<td>0.2</td>
<td>6</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 76: Some characteristics of the solar wind

Effect on Earth and planets: All planets of the solar system are surrounded by the hot, magnetized, supersonic collisionless solar wind plasma capable of conducting electrical current and carrying a large amount of kinetic and electrical energy. Due to the supersonic nature of the solar wind, shock waves are formed in front of the planets (see bow shock). Some of the solar wind energy finds its way into the Earth’s magnetosphere, ionosphere and atmosphere, and

- Drives the magnetospheric convection system and energizes much of the plasma on the Earth’s magnetic field lines
- Drives field line resonances and other geomagnetic pulsations
- Creates geomagnetic activity
- Heats the polar upper atmosphere
- Drives large neutral atmospheric winds.

Because of these effects, the changes in the solar wind plasma parameters (density, velocity, etc.) and IMF (especially direction in relation to Earth’s own field) are very important for magnetospheric and ionospheric physics, and the scientific community tries to have continuous monitoring of these parameters via satellites. Also, interactions between the solar wind and the Earth’s magnetic field lead to creation of the auroral oval - a high latitude region of the Earth’s ionosphere. In the auroral zone, irregular precipitation of energetic electrons occurs during substorm events - resulting in optical and UV emissions (Northern/

1503)http://www.oulu.fi/~spaceweb/textbook/solarwind.html
Southern Lights). During such events, structured depletions/enhancements of total electron content (TEC) can occur in the auroral ionosphere (at E-region altitudes of 110 km). Auroral activity is a major concern for reliable operation of GPS positioning applications at high latitudes. Auroral substorms are characterized by increased spatial and temporal decorrelations of ionospheric range delay, and loss of signal availability can occur during periods of ionospheric scintillations.  

Background on the early history of the solar wind: The first indication that the sun might be emitting a “wind” came from comet tails, observed to point away from the sun, whether the comet was approaching the sun or whether it was moving away. Kepler in the early 1600s guessed that those tails were driven by the pressure of sunlight, and his guess still holds true for the many comet tails which consist of dust. - The phenomenon and mechanism of so-called “particle bursts” from the sun was first discussed by S. Chapman and V. Ferraro in 1931. These particle bursts would cause a compression of the geomagnetic field. According to their model (now known to be erroneous) a solar wind would only occur temporarily in connection with flares or other specific solar phenomena. - In 1951, Ludwig F. Biermann (1907-1986, of the Max-Planck-InstitutfürPhysikundAstrophysikatGöttingen,Germany) studied tails of comets as they passed near the sun and showed that the pressure of solar radiation alone can not explain his observations.  

As a consequence, he suggested the concept of a continuous solar wind that exists always and essentially affects (bends) the formation of cometary tails (he explained that the motion of the ions was due to their being entrained in a flow of particles being given off by the sun and moving radially outwards). Biermann also estimated the velocity of the solar wind to be in the range 500-1500 km/s. However, the name “solar wind” was coined by Eugene N. Parker at the Enrico Fermi Institute of the University of Chicago in 1958, when developing the theory of the (continuous) solar wind. He predicted that the solar corona must expand (due to the fact that the corona emits a supersonic flow of plasma) he called the outward streaming coronal gas “solar wind.”

- The ISEE-3 (International Sun-Earth Explorer-3) mission, with a launch in 1978, orbited the Earth for nearly four years. It was then directed to study the geomagnetic tail for a first-ever exploration of that region. This resulted in the discovery of gigantic plasmoids that were ejected from the near-Earth magnetosphere. After exploring the nature of the geomagnetic tail, ISEE-3 was sent off for the first spacecraft encounter with a comet in September 1985. When ISEE-3 was near Comet Giacobini-Zinner, first measurements of the solar wind’s interaction with a comet were obtained.

- The Ulysses S/C (launch Oct. 6, 1990, K.30) of ESA/NASA is the first S/C having left the ecliptic plane to observe the polar regions of the sun using a slingshot past Jupiter (a gravity assist maneuver) to obtain such a sun-centered, out-of-ecliptic orbit.  

With a period of 6.2 years, the orbit is inclined at 80.2° to the solar equator. The perihelion (point of closest approach to the sun) is at 1.3 AU, and the aphelion at 5.4 AU (the most distant point in the orbit). The three major objectives are to study the sun, the solar wind characteristics (speed, temperature and composition), and interstellar space. Although Ulysses is the first

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1507) http://www--istp.gsfc.nasa.gov/Education/wsolwind.html
S/C to probe the sun’s polar regions, it does not travel near the sun. The long duration of the Ulysses mission enabled comprehensive observations to be made over the sun’s poles at both solar maximum and solar minimum. In 1994, it was reported that near the south pole the solar wind is flowing away from the sun at nearly twice the speed that is typically observed near the sun’s equator (great variability of the solar wind configuration during solar maximum and solar minimum).

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instruments</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE, launch Aug. 25, 1997 positioned at L1</td>
<td>SWIMS, SWICS, SWEPAM</td>
<td>Focus on solar wind composition and acceleration</td>
</tr>
<tr>
<td>AMPTE, launch Aug. 16, 84</td>
<td></td>
<td>Release of trace gases into the solar wind</td>
</tr>
<tr>
<td>Cluster-2, launch Jul. 16, 00</td>
<td>CIS, HIA, STAFF</td>
<td>Study of solar wind bow shock</td>
</tr>
<tr>
<td>DSI, launch Oct 24, 1998</td>
<td>PEPE</td>
<td>Solar wind energy spectrum</td>
</tr>
<tr>
<td>DSP (Double Star Project), launch in 2003, China, ESA</td>
<td>HIA, LEID, LFEWD, PEACE</td>
<td>Study of solar wind with magnesosphere</td>
</tr>
<tr>
<td>Equator-S, launch Dec. 2, 1997</td>
<td>Collector Array, Solar Wind Concentrator</td>
<td>Solar wind measurements with WIND and SOHO</td>
</tr>
<tr>
<td>Genesis, launch Aug. 8, 2001</td>
<td></td>
<td>Solar wind measurement, collection and return of solar wind samples. Halo orbit at L1, Return to Earth on Sept. 8, 2004</td>
</tr>
<tr>
<td>GEOTAIL, launch Jul. 24, 1992</td>
<td>LEP, CPI</td>
<td>Measurement of fluctuations in the solar wind</td>
</tr>
<tr>
<td>IMAGE, launch Mar. 25, 2000</td>
<td>LENA, MENA, HENA</td>
<td>Response of magnetosphere with solar wind</td>
</tr>
<tr>
<td>IMP-8, launch Oct. 26, 1973</td>
<td>GAF, MAP</td>
<td>Plasma field environment for magnetospheric studies</td>
</tr>
<tr>
<td>INTERBALL, launch Aug. 3, 1995 and Aug. 29, 1996</td>
<td>Monitor-3, etc.</td>
<td>Solar wind energy and interaction with the Earth's magnetosphere</td>
</tr>
<tr>
<td>ISEE-1, -2, launch Oct. 2, 77</td>
<td>SWE, EGD, OGM, SHM</td>
<td>Study of Earth’s bow shock</td>
</tr>
<tr>
<td>NOAA-15, launch May 13, 1998</td>
<td>SEM-2 package</td>
<td>An operational space weather warning system</td>
</tr>
<tr>
<td>POLAR, launch Feb. 24, 1996</td>
<td>MFE, TIMAS</td>
<td>Coupling of the solar wind and magnetosphere, study of particle populations</td>
</tr>
<tr>
<td>SOHO, launch Dec. 2, 1995</td>
<td>UVCS, SWAN, CELIAS</td>
<td>Study of solar wind and energetic particles, interaction with the Earth. First tracing of the slow-speed solar wind</td>
</tr>
<tr>
<td>STEREO, launch Oct. 26, 2006</td>
<td>IMPACT, SWEA, PLASTIC, SWAVES,</td>
<td>Measurements of solar wind in a heliocentric elliptical orbit in the ecliptic plane at 1 AU</td>
</tr>
<tr>
<td>TIMED, launch Dec. 7, 2001</td>
<td>TIDI</td>
<td>Solar wind structure in MLTI (Meso- sphere and Lower-Thermosphere/Ionosphere) region</td>
</tr>
<tr>
<td>Triana (the mission was cancelled as of 2006)</td>
<td>PlasMag</td>
<td>Study of solar wind in halo orbit at L1</td>
</tr>
<tr>
<td>Ulysses, launch Oct. 6, 1990</td>
<td>SWICS, SWOOPS, UARP</td>
<td>Study of the solar wind</td>
</tr>
<tr>
<td>Viking, launch Feb. 22, 1986</td>
<td>V1, V2, V3, V4L</td>
<td>Solar wind interaction with the magnetosphere</td>
</tr>
<tr>
<td>WIND, launch Nov. 1, 1994</td>
<td>MFI, WAVES, SWE, SMS, EPACT, PLASMA</td>
<td>Study of solar wind mass momentum and energy. Halo orbit at L1</td>
</tr>
</tbody>
</table>

Table 77: Some solar wind experiments/studies (alphabetic order of missions)

- Monitoring of the solar wind (i.e. of space weather parameters) is being conducted from several spacecraft located at the Lagrangian point L1 in the in the Earth-Sun system, about 1.5 million km from Earth. The solar wind reaches L1 about one hour prior to reaching Earth; this vantage position is being used to provide early warning in space weather.
monitoring services (geomagnetic storms, etc.). Some spacecraft with solar wind instruments at L1 are:

- **WIND** of NASA/GSFC (launch Nov. 4, 1994)
- **ACE** (Advanced Composition Explorer) of NASA (launch Aug. 25, 1997)
- **SOHO** (Solar and Heliospheric Observatory) of ESA/NASA (launch Dec. 2, 1995). The SOHO spacecraft is a major contributor to space weather forecasts, by observing solar flares and CMEs (both are aspects of the same event).
- **Genesis** of NASA (launch Aug. 8, 2001). The Genesis mission has the objective to collect solar wind particles at L1 (outside the Earth’s magnetosphere) for at least 22 months and return these particles to Earth (by a sample return capsule) after mission completion in Sept. 2004. The L1 location was reached May 22, 2002. The sample collection period ended on April 1, 2004. This has been followed by a 5 month return mission to Earth. On Sept. 8, 2004, the sample return capsule of Genesis crashed into the desert of Utah (at an estimated speed of 310 km/h) due to the failure of a parachute deployment (its drogue and parafoil systems failed to deploy — a design flaw in the re-entry system has been identified as the most likely cause of the spacecraft’s free fall onto the surface of Earth). After inspection of the damage, NASA is optimistic that a portion of the solar wind samples can still be salvaged from the Genesis capsule. Preliminary findings point to an incorrectly installed accelerometer, which was unable to sense the deceleration upon reentry and initiate the parachute deployment sequence.

- The **IMAGE S/C** (launch March 25, 2000, K.16) of NASA carries three ENA (Energetic Neutral Atom) imagers (LENA, MENA, and HENA) whose combined energy coverage permits the detection of ENAs with energies ranging from 1 eV to 500 keV per atomic mass unit (amu). Each neutral atom instrument generates images showing the intensity and spatial distribution of ENA radiation emissions produced in the inner magnetosphere through charge-exchange reactions between geocoronal neutral hydrogen and various magneto-spheric ion populations. Neutral atom imaging of the ionosphere and magnetosphere is possible because the Earth’s geocorona acts like an imaging screen for magnetospheric and ionospheric ions. [The neutral atoms in the space environment are measured against the large and ubiquitous UV background which can produce high noise count rates in MCP detectors. To date, four different techniques have been developed to allow neutral atom detection and imaging against the UV background:
  - A thick foil which blocks the UV
  - An ultra thin charge conversion foil to ionize ENAs (which are then passed through an electrostatic analyzer)
  - A charge exchange surface from which ENAs can reflect as ions which are then analyzed
  - Transmission gratings which block UV but allow ENAs to pass.

The IMAGE spacecraft and its sensor complement represent a new era of magnetospheric observation capability. While traditional instruments provide in-situ observations of the magnetospheric plasma environment, the new ENA devices are able to image the plasma motions by detecting the particles and their traveling directions (the imaging is done using “electromagnetic wave sounding”).

Data of the IMAGE sensors made space storms visible for the first time [HENA has provided the first—ever images (2—min cadence) of geomagnetic storm ring current growth, main phase, and recovery with full particle energy resolution, finally capturing the dynam-
ics of Earth’s reaction to solar and solar wind storms]. Regarding the solar wind, the IMAGE data show that the Earth atmosphere plays an active but ever-changing role in diverting and absorbing the solar wind. The ionosphere dissipates great amounts of energy flung at Earth by ejecting about 100 tons of hydrogen and oxygen into space during each solar storm. 1515)

Background: Energetic neutral atoms (ENAs) are produced when energetic magnetospheric ions undergo charge-exchange collisions with the thermal neutral atoms (hydrogen, helium, oxygen) that make up the Earth’s extended atmosphere (the geocorona). This type of interaction can take place in the “ring current”, the mid and auroral latitude energetic particle precipitation zones, and within the low altitude equatorial ion belt that is itself formed by ionization of earthward directed ENAs via collisions in the low altitude equatorial atmosphere. Since ENAs are unaffected by the Earth’s magnetic field, these energetic neutrals travel away in straight line trajectories from the points of charge exchange. The remote detection of these particles provides a powerful means through which the global distribution and properties of the geocorona and ring current can be inferred. 1516)

The first suggestion that ENAs emitted from the radiation belts and ring current could be used to remotely sense the magnetospheric energetic ion population was made by D. Hovestadt et al., 1517) in 1972, and the first global image of ENA emissions was produced by E. C. Roelof in 1987 from data acquired by the ISEE-1 (International Sun-Earth Explorer-1) spacecraft of NASA/ESA (launch Oct. 2, 1977). 1518) 1519)

<table>
<thead>
<tr>
<th>Mission</th>
<th>ENA Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS-1 of NASA on STS-45 (launch Mar. 24, 1992)</td>
<td>ENAP (Energetic Neutral Atom Precipitation), of the University of Texas, Dallas</td>
</tr>
<tr>
<td>Astrid-1 of IRF-K, Kiruna, Sweden (launch Jan. 24, 1995)</td>
<td>PIPPI (Prelude in Planetary Particle Imaging), a neutral particle imager</td>
</tr>
<tr>
<td>POLAR of NASA, (launch Feb. 24, 1996)</td>
<td>CEPPAD/SEPS (Comprehensive Energetic-Particle Pitch Angle Distribution / Source Loss Cone Energetic Particle Spectrometer)</td>
</tr>
<tr>
<td>SAC-B of CONAE (launch Nov. 4, 1996), the 3rd stage failed to separate from the S/C</td>
<td>ISENA (Imaging Spectrometer for Energetic Neutral Atoms) of CNR/IFSI, Italy</td>
</tr>
<tr>
<td>IMAGE of NASA (launch March 25, 2000)</td>
<td>LENA, MENA, HENA</td>
</tr>
<tr>
<td>Mars Express (launch June 2, 2003) of ESA</td>
<td>ASPERA (Analyzer of Space Plasmas and Energetic Neutral Atoms), of NASA built by SwRI</td>
</tr>
<tr>
<td>TWINS of NASA, LANL, etc. (launch of 1st S/C in 2004, launch of 2nd S/C in 2006)</td>
<td>TEI (TWINS ENA Imager)</td>
</tr>
</tbody>
</table>

Table 78:  Overview of some early ENA instruments flown on various missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Objective or Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-C (NASA), Launch Dec. 16, 1973</td>
<td>VAE (Visible Airglow Experiment)</td>
<td>Measurement of airglow and aurora features</td>
</tr>
<tr>
<td>APEX (Active Plasma Experiment), launch Dec. 18, 1991</td>
<td>Suite of sensors</td>
<td>Study of auroral-ionospheric relationships</td>
</tr>
<tr>
<td>ARGOS (DoD), launch Feb. 23, 1999</td>
<td>EUVIP, HIRAAS, LORAAS, GIMI</td>
<td>Characterization of the aurora</td>
</tr>
<tr>
<td>Astrid-1 (IRF-K), Sweden, launch Jan. 24, 1995</td>
<td>MIO (Miniature Imaging Optics)</td>
<td>Auroral emissions</td>
</tr>
<tr>
<td>Astrid-2, launch Dec. 10, 1998</td>
<td>PIA of MPAe</td>
<td>Auroral imaging</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Objective or Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS-1 (NASA) STS-45, launch March 24, 1992</td>
<td>AEPI (Atmospheric Emissions Photometric Imaging)</td>
<td>Images of natural and induced aurorae and airglow</td>
</tr>
<tr>
<td>DE-1 (Dynamic Explorer) of NASA, launch Aug. 3, 1981</td>
<td>EICS (Energetic Ion Mass Spectrometer), SAI (Spin-Scan Auroral Imager)</td>
<td>Coupling of magnetosphere/ionosphere, auroral images in UV and VIS</td>
</tr>
<tr>
<td>DMSP series of DoD</td>
<td>OLS (Operational Linescan System), SSULI (Special Sensor Ultraviolet Limb Imager), SSUSI (Special Sensor Ultraviolet Spectrographic Imager)</td>
<td>OLS auroral images (nighttime) since the mid-1970s, SSULI and SSUSI starting with F-16 in 2003</td>
</tr>
<tr>
<td>DODGE (DoD) launch July 1, 1967</td>
<td>Dual Vidicon Cameras</td>
<td>Some measurement of airglow and aurorae</td>
</tr>
<tr>
<td>FREJA (Sweden), Oct. 6, 1992</td>
<td>F5 (Auroral UV Imager)</td>
<td>Study of aurorae</td>
</tr>
<tr>
<td>GERTAIL (ISAS/NASA), launch July 24, 1992</td>
<td>CPI (Comprehensive Plasma Investigation) AIM (Auroral Ionospheric Mapper) built by APL</td>
<td>Auroral imaging for magnetotail plasma dynamics Imaging of the sunlit aurora</td>
</tr>
<tr>
<td>HILAT (DoD) or P83-1, launch Jun. 27, 1983</td>
<td>WIC (Wideband Imaging Camera), SI (Spectrographic Imager), MENA (Medium-Energy Neutral Atom Imager), HENA, EUV</td>
<td>Broadband auroral imaging, different types of aurorae, etc. Imaging of ENAs, substorms, and ion populations of the cusp</td>
</tr>
<tr>
<td>IMAGE (NASA), launch May 25, 2000</td>
<td>UFSIPS, UVAI</td>
<td>Study of aurorae</td>
</tr>
<tr>
<td>INTERBALL (Russia, etc.), launch of Auroral Probe Aug. 29, 1996</td>
<td>LEISA</td>
<td>Study of nightglow aurorae</td>
</tr>
<tr>
<td>Lewis (NASA) launch Aug. 23, 1997, contact to Lewis was lost on Aug. 26, 1997</td>
<td>UVISI with 4 cameras and 5 imaging spectrometers</td>
<td>Study of aurorae in FUV-VIS, topographic imagery</td>
</tr>
<tr>
<td>POLAR (NASA), launch Feb. 24, 1996</td>
<td>UVI (UV Imager), VIS (Visible Imaging System)</td>
<td>Study of dayside and nightside aurorae</td>
</tr>
<tr>
<td>ROCSat-2 (NSPO), launch May 20, 2004</td>
<td>ISUAL (Imager of Sprite Upper Atmospheric Lighting)</td>
<td>Study of aurorae and airglow</td>
</tr>
<tr>
<td>STS-39, launch Apr. 28, 1991</td>
<td>CIRRIS (DoD)</td>
<td>Study of aurorae and airglow</td>
</tr>
<tr>
<td>TIMED (NASA), launch Dec. 7, 2001</td>
<td>GUVI (Global UV Imager)</td>
<td>Horizon-to-horizon imagery in five bands with coverage of one limb (away from the sun)</td>
</tr>
<tr>
<td>TWINS (NASA, LANL, APL, SwRI, USC, etc.), planned launches in 2004 and 2006</td>
<td>TEI (TWINS ENA Imager)</td>
<td>3-D visualization of large-scale structures in the magnetosphere, study of geomagnetic storms, etc.</td>
</tr>
<tr>
<td>Viking (Sweden), launch Feb. 22, 1986</td>
<td>V5 (Auroral Imaging Experiment)</td>
<td>Study of dynamic behavior of aurorae</td>
</tr>
</tbody>
</table>

Table 79: Some space science missions/instruments relating to auroral imaging

- The TWINS two-spacecraft mission of NASA (launch of TWINS-A in 2005) has the objective to demonstrate the new capability of stereoscopic imaging of the magnetosphere. By imaging the ENAs (produced by charge-exchange reactions between the geocoronal neutral hydrogen and the plasma) over a broad energy range (about 1-100 keV) using two identical instruments [TEI (TWINS ENA Imager)] on two widely spaced high-altitude and high-inclination spacecraft, TWINS will enable the three-dimensional visualization and the resolution of large scale structures and dynamics within the magnetosphere for the first time.
1.7.4 Earth’s Magnetosphere

The Earth is a huge magnet, and its magnetic influence extends far into space. Magnetic fields play an important role in many of the physical processes throughout the Universe. The Earth in particular has a large and complicated magnetic field, the major part of which is produced by a self-sustaining dynamo, operating in the fluid outer-core. It turns out that measurements, taken at or near the surface of the Earth, are the superposition of magnetic fields originating from the outer core as well as the fields caused by magnetised rocks in the Earth’s crust, electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in the Earth by time-varying external fields. On Earth, we’re protected by our planet’s magnetic field from harmful radiation (cosmic rays, solar wind), but out in space, it gets a lot more dangerous. A particular dangerous region are the Earth’s Van Allen belts.\(^{1520}\)

The magnetosphere is the region of space to which the Earth’s magnetic field is confined by the solar wind plasma blowing outward from the sun, extending to distances in excess of 60,000 km from Earth in the so-called magnetotail.

Close to Earth, the magnetic field is roughly a magnetic dipole that is tilted 11.5º from Earth’s rotational axis and offset from the center of the planet. For most purposes, the dipole approximation is poor, and there are more sophisticated models that account for the steady changes of the central field as well as the dynamic outer boundaries.

The Earth’s magnetosphere is formed from two essential ingredients.\(^{1521}\)\(^{1522}\)\(^{1523}\) The first is the Earth’s magnetic field (or geomagnetic field), generated by currents flowing in the Earth’s core. More than 90% of the geomagnetic field is generated in Earth’s outer core. Outside the Earth this field has the same form as that of a bar magnet, a dipole field, aligned approximately with the Earth’s spin axis. The second ingredient of the geomagnetic field is the solar wind, a fully ionized hydrogen/helium plasma that streams continuously outward from the sun into the solar system at speeds of about 300-800 km/s [the average speed is 1.5 million km/h - with a distance of 150 million km away from Earth this translates to about 100 hours of travel time]. There is a third ingredient that also plays an important role: the Earth’s ionosphere. The upper atmosphere is partially ionized by far-ultraviolet (FUV) and X rays from the sun above altitudes of about 100 km. The resulting ionosphere forms a second source of plasma for the magnetosphere, mainly of protons, singly charged helium and oxygen, and the requisite number of electrons for electric charge neutrality.

Chapman-Ferraro magnetosphere. The basic nature of the interaction between the solar wind and the Earth’s magnetic field, leading to the concept of the Earth’s magnetosphere, was first deduced by Sydney Chapman (English scientist, 1888-1970) and his student Vincenzo C. A. Ferraro in the early 1930s. It is based on two theoretical principles. The first concerns the way in which plasmas and magnetic fields interact; they behave, approximately, as if they are "frozen" together. As a result of this freezing together, magnetic fields are transported by flowing plasmas; the field lines are bent and twisted as the flow bends and twists. An important example is the interplanetary magnetic field. It is wound into a large spiral structure by the sun’s rotation, and near the Earth it has a strength of about 5 nT. This is a rather weak field, about one ten thousandth of the field at the Earth’s surface, but nevertheless, it plays a crucial role in the Earth’s interaction with the solar wind. The second principle concerns the force that the magnetic field exerts on the plasma, which usually opposes the bending and twisting of the field, or its compression, in the frozen-in flow.


\(^{1521}\)Note: The name “magnetosphere” was first proposed in 1959 by Thomas Gold of Cornell University (Ithaca, NY), defining the magnetic environment around Earth. Eventually, the meaning of “magnetosphere” encompassed all phenomena affected by the interaction of Earth’s magnetic field with the solar wind and the cosmic plasma flux.

\(^{1522}\)http://www.agu.org/sci_soc/cowley.html

One of the most important processes for transferring energy and momentum from the solar environment to Earth’s magnetosphere is the concept of magnetic reconnection.  

The Earth’s magnetosphere is actually controlled by reconnection; it is electromagnetically coupled to the solar wind and reconnects in the tail (multiscale coupling phenomenon). This process changes magnetic energy into particle (plasma) energy; it changes the topology of magnetic fields by breaking magnetic lines of force and reconnecting them in a different way. Reconnection plays a role in three distinct regions in Earth’s magnetosphere: on the dayside magnetopause at low latitudes, near the polar cusp, and in the magnetotail.

Background:  

The complex phenomenon/process of magnetic reconnection has its origins in the 1940s. R. G. Giovanelli proposed a theory of solar flares according to which electrons accelerated by induction electric fields near magnetic neutral points excite the optical emissions of chromospheric atoms. He suggested that magnetic X-type null points can serve as locations for plasma heating and acceleration in solar flares and magnetic substorms. In 1961, J. W. Dungey (Cambridge University, UK) was instrumental in proposing the idea of an open reconnecting model and mechanism for transmitting solar wind energy to the magnetosphere by direct magnetic linkage between the two. Dungey proposed that an X-type neutral point (or line) at the front of the magnetosphere enabled terrestrial field lines to link up with interplanetary ones and produce “open” field lines, with one end on earth and the other in distant space. - The search for reconnection continues at the start of the 21st century, the overall model of the geomagnetosphere is known, but the specific understanding of the reconnection process and its complex features (of how the magnetosphere interacts with the solar environment, substorms in the magnetosphere, coronal mass ejections) require continued research into the Earth-space environment.

Note: In June 2007, ESA is reporting that scientists have obtained for the first time ever a 3-D picture of magnetic reconnection events with data of the Cluster mission analyzing an event in Oct. 2001 when the four Cluster spacecraft were flying in formation at approximately 110 000 km from Earth in the magnetotail. The satellites meandered around a reconnection region over a period of nearly 15 minutes. During reconnection, the geometry of the magnetic field forms an X–shape, also called a ‘magnetic null’. Analysed in 2–D, the magnetic field, plasma density and flow velocity data collected during this event showed that only one reconnection region with an X–shape, or a magnetic null, was seen by the satellites. – By analysing a subset of the same data in 3–D with a higher temporal resolution, the scientists found what they were looking for. Two magnetic reconnection sites jumped out, along with the null–null line which connects two magnetic nulls, a previously unobserved phenomenon.

The magnetosphere has a complicated internal structure, consisting of the Van Allen belts, the plasma sheet, and the magnetotail. Chapman and Ferraro predicted the outer boundary of the Earth’s magnetosphere being compressed on the sunward side by solar radiation, and they predicted also that there would be radiation belts (the Van Allen belts were discovered with Explorer-1, launch Jan. 31, 1958).

The geomagnetic main field can be modeled mathematically. Two such models are:

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1529) http://www--istp.gsfc.nasa.gov/Education/bh2_5.html
1531) “Pioneering 3D view of near—Earth magnetic ‘dance’,” June 29, 2007, URL: http://www.esa.int/esaSC/SE-MUOP9OY2P_index_0.html
- **IGRF (International Geomagnetic Reference Field).** IGRF models the field and its secular variation using a set of harmonic coefficients in a truncated series expansion of a geomagnetic potential function and its time derivative. The magnetic field is the gradient of this potential. The current model is known as IGRF2000. Updates occur generally every 5 years.

- **WMM (World Magnetic Model).** The WMM model, produced by the British Geological Survey and by USGS (United States Geological Survey), is similar to that of IGRF.

Satellites observing magnetic forces in space have found that lines from most points on Earth are confined inside a fairly well-defined cavity, the magnetosphere of the Earth. The space outside it is dominated by the sun, and by the fast “solar wind” of free ions and electrons emitted by the sun. The solar wind pushes back the Earth’s field somewhat, but ultimately is forced to detour, leaving the Earth’s lines enclosed in a bullet shaped cavity, which on the night side continues as a long cylinder, like the tail of a comet. The boundary surface between interplanetary field lines and those of the Earth is called the magnetopause.

![Characteristic model of the Earth’s magnetosphere](image)

**Figure 35:** Characteristic model of the Earth’s magnetosphere
The offset of Earth’s magnetic dipole from the geometric center of the planet causes a weaker field region over the South Atlantic Ocean and an opposing region of stronger field over northern Asia. As the trapped inner-zone particles execute their bounce motion along field lines, they can reach lower altitudes at a region known as the “South Atlantic Anomaly”. All spacecraft in low Earth orbit penetrate the inner zone in the South Atlantic Anomaly even if their altitude is below the belt at other positions in the orbit.

While relative stability is one key property of the inner zone, variability is the outstanding characteristic of the outer radiation belt. The solar wind and interplanetary magnetic field affect this weaker field region of the magnetosphere more than the inner zone, leading to shorter lifetimes of trapped particles and more dynamics. Details of how the magnetosphere accelerates electrons to millions of electron volts in a few seconds have been recently glimpsed; however, the mechanism that accelerates the electrons more routinely in geomagnetic storms has not been established even after 40 years of research. Observations over many years with well understood space environment instruments will be needed before researchers can understand the outer zone’s variability and its extreme behavior. 1532)

Background: Most early space age magnetosphere discoveries are reported in chapters 1.7.3 (Solar Wind Observations) and O.17. Newer missions in this context are:

- The Ørsted microsatellite mission of Denmark was launched Feb. 23, 1999, providing highly accurate and sensitive measurements of the geomagnetic field. The Ørsted observations opened a decade of geopotential field research by an international team (the first satellite to measure the three components of the Earth’s magnetic field since MagSat). The Ørsted data are a major source to update the IGRF (International Geomagnetic Reference Field) model. For instance, the IGRF2000 field model was based entirely on Ørsted data. The Ørsted mission is operational as of 2007.

- IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) of NASA (launch March 25, 2000). IMAGE is the first satellite mission dedicated to imaging the Earth’s magnetosphere (investigating the response of the magnetosphere with the solar wind).

- DSP (Double Star Project), a cooperative mission of CNSA (Chinese National Space Administration) of Beijing and ESA (launch of DSP-1 Dec. 29, 2003, launch of DSP-2, July 25, 2004). The overall objective is to explore the Earth’s magnetosphere. The two spacecraft are called TC-1 and TC-2, where TC stands for ‘Tan Ce’ which means ‘Explorer’. The DSP payload includes 8 ESA instruments (identical to those on the Cluster mission) and some Chinese instruments.

- THEMIS (Time History of Events and Macroscale Interactions during Substorms) is a five microsatellite constellation of NASA (launch Feb 17, 2007, launch mass of 126 kg/S/C). The objective is to provide answers to critical questions about the magnetosphere (tail region) and related space weather to determine the causes of the global reconfigurations of the Earth’s magnetosphere that are evidenced in auroral activity. Auroral eruptions are a manifestation of the magnetospheric substorms. THEMIS is considered a complementary program to NASA’s MMS mission.

- Swarm, a geomagnetic LEO constellation of ESA (launch of 3 minisatellites in 2010). The overall objective is to provide the best ever survey (multi-point observations) of the geomagnetic field and its temporal evolution, to gain new insights into the Earth system by improving our understanding of the Earth’s interior and climate. – As it turns out, accurate measurements of the geomagnetic field are one of the very few ways by which the Earth’s interior properties, especially concerning dynamic processes in the core and the mantle, can be deduced. In addition, the geomagnetic field and its interaction with the solar wind plays an important role in forming the external environment of the Earth in a way that also affects space weather and atmospheric processes related to climate and weather.

• MMS (Magnetospheric MultiScale) mission of NASA (planned launch in 2013). The objective is the study of magnetic reconnection, charged particle acceleration, and turbulence in regions of the Earth’s magnetosphere.
1.7.5 **Space Weather**

The time-variable response of the Earth's space environment to the solar wind (including solar eruptions and flares) is termed ‘space weather.’ Space weather is a consequence of sun behavior (solar activity), the nature of Earth’s magnetic field and atmosphere (in particular the ionosphere and magnetosphere), and Earth’s location in the solar system. The solar wind, propagating against the Earth’s magnetic field and interacting with it, shapes the near-Earth space environment.

When energetic electrons and protons from the sun reach Earth, they interact with components of the upper atmosphere. In addition to producing the luminescent aurora borealis, this interaction can generate winds and push atmospheric constituents to higher altitudes, where they can increase the drag on satellites. The energetic particles can also ionize the molecular nitrogen and atomic oxygen in the upper atmosphere, which can radically alter the ionosphere and interfere with satellite—based communications.

Space weather can influence the performance and reliability of spaceborne/airborne electronic systems as well as of groundbased systems (communication systems, the grid infrastructure of electric power utility companies, commercial airlines, navigation systems like GPS and LORAN, satellite launches and operations, etc.) and can endanger human life and health (spacewalks of astronauts). The effects of a sudden ionospheric disturbance are an increase in the local electron concentration in the ionosphere, which can cause a total radio-communication blackout. The more we depend upon space systems for our everyday lives, such as when we use mobile phones and GPS navigation, the more susceptible we become to space weather. - Other effects of space weather are: aurorae (beautiful atmospheric displays in the polar regions caused by high-energy electrons and protons striking the upper atmosphere) and changes of climate. The space environment hazards that spacecraft and mission designers and operators need to be concerned with are: 1533) 1534)

- Solar environment. The solar environment, directly or indirectly, effects all the other hazard environments. The solar activity level, which follows an 11-year cycle, is a directly contributing factor which interacts to the radiation, thermal and plasma environments. The increased energy output from the sun during its active periods heats the Earth’s atmosphere and causes it to expand, which can effect the impact and neutral atmosphere environments, as well.

- Magnetic environment. The fields generated by the magnetic environment can directly interact with spacecraft. This is often taken advantage of in the attitude control subsystems, which can employ magnetometers and magnetic torque rods. The magnetic environment is also a major factor in determining the radiation and plasma environments around the Earth. There are two classic uses of magnetic torque rods in attitude control. One is for momentum management of wheel-based systems. The other is for angular momentum and nutation control of spinning, momentum-biased, and dual-spin spacecraft.

- Radiation environment. The radiation environment is principally composed of naturally occurring charged particles trapped in the Earth’s magnetic field (also known as the Van Allen belts). Energetic solar particles and galactic cosmic rays also contribute to the natural radiation environment.

- Thermal environment. The thermal environment consists of thermal energy flux from the sun, the solar energy reflected back into space (and towards the spacecraft) from the Earth, referred to as albedo and the direct longwave thermal emission of the Earth due to its temperature, sometimes referred to as Earthshine.

- Impact environment. The impact environment consists of material from natural occurring micrometeoroids and from man-made debris flux. Due to the high relative veloci-

1534) Note: The first journal dedicated to the theme of space weather is: “Space Weather - The International Journal of Research and Applications,” published by AGU as of fall 2003, URL: http://www.agu.org/journals/sw/
ties, even tiny particles can cause direct physical damage to the satellite structure and solar panels and can also induce damaging electrostatic discharges.

- Plasma environment. The plasma environment is mostly composed of charged particles (electrons) with energies too low to be a radiation hazard. However, these particles can strike and deposit themselves on external surfaces of the spacecraft or penetrate through the surface and deposit on internal components, causing electrostatic charge build-up. This charge can build up to high enough levels to create electrostatic discharge hazards that can damage spacecraft electronic components.

- Neutral atmosphere environment. The neutral atmospheric environment is the residual atmosphere remaining at spacecraft altitudes. The neutral atmosphere can contain atomic oxygen, which can damage the materials used on spacecraft in LEO. Other residual atmospheric chemicals can also react with materials or be a source of contamination for optical systems.

The development and introduction of suitable instruments and systematic space weather observations started in the 1970s from spacecraft.

- SEM (Space Environment Monitor). SEM is an operational NOAA instrument package with the objective to provide “space weather” on a regular basis to the user community by measuring the solar wind particle flux and its variations. The package is provided by NOAA/SEC (Space Environment Center) in Boulder, CO. SEM-1 instruments were initially introduced on satellites in geostationary orbit starting in 1974. SMS-1 (launch May 17, 1974), a predecessor of the NOAA-GOES series, was the first satellite to carry SEM. NOAA introduced SEM on the POES series (G.14.1) as well starting with TIROS-N in 1978. An upgraded instrument package, SEM-2, was introduced into the POES series spacecraft with the launch of NOAA-K (NOAA-15) on May 13, 1998 (G.15.2).

The SEM package of the GOES series was upgraded with the introduction of SXI (Solar X-ray Imager) instrument on GOES-12 (launch July 23, 2001) and the follow-up spacecraft of the series (see GOES-12 under 1.7.6). SXI obtains a continuous sequence of corona X-ray images from the sun to monitor solar activity for its effects on the Earth’s upper atmosphere. NOAA/SEC is planning in addition a new SEM suite for the next-generation GOES series, starting with GOES-R (projected launch in 2014).

- As of 2002, analysis of the IMAGE satellite data (NASA S/C, launch Mar. 25, 2000) revealed that a layer in the Earth’s outer atmosphere acts like a heat shield by absorbing energy from space storms, which reduces their ability to heat the lower atmosphere. However, it imposes a heavy toll for its services by creating a billion-degree cloud of electrified gas, or plasma, that surrounds our planet.

- The DMSP—F16 weather satellite of DoD (launch Oct. 18, 2003) is flying the SSUSI (Special Sensor Ultraviolet Spectrographic Imager) instrument that measures UV radiation from the Earth’s atmosphere and ionosphere, it also measures visible radiation (airglow and terrestrial albedo). The instrument provides the NOAA—5D—3 satellite series with the ability to obtain photometric observations of the nightglow and nightside aurora.

- The TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) mission of NASA (launch Dec. 7, 2001) is flying the GUVI (Global Ultraviolet Imager) instrument, actually of SSUSI heritage (flown on the DMSP F-16) and a joint collaboration between JHU/APL and The Aerospace Corporation, El Segundo, CA. The objective is to monitor three general regions: the daytime low- to mid-latitude thermosphere, the nighttime low- to mid-latitude ionosphere, and the high-latitude auroral zone. The goal is to obtain a detailed quantitative and predictive understanding of auroral phenomena.

NOAA/SEC in partnership with the USAF is providing a comprehensive online (near real-time) space weather monitoring service offering a spectrum of parameters and forecasts of solar and geophysical events to all parties of interest. In addition, a lot of background information is provided. SEC is the national and world warning center for disturbances in the space environment that can affect people and equipment. Note: The SEC web server began in December 1993, the Gopher/FTP servers in July 1994. 1537) 1538) 1539)

At the start of the 21st century, ESA is also considering a space weather applications service program (network) of its own, complementing the NOAA/SEC-provided service with emphasis on European applications. 1540) 1541) 1542) 1543) 1544)

1.7.6 X-ray imaging

X-rays are the natural signatures of the high-energy universe, a high-frequency electromagnetic radiation. Any object heated to more than a million degrees Celsius begins to give off significant quantities of X-rays (electromagnetic radiation is produced whenever high-speed collisions between electrons and protons occur). 1545) 1546) This is around the temperature of the sun’s outer atmosphere, known as the corona. It is therefore no surprise that X-ray astronomy began with studies of the sun before detections of other X-ray objects elsewhere in the universe were made. The sun appears completely different in the X-ray region of the spectrum than in the visible region. X-rays are emitted by very hot gases in the outer solar atmosphere, the corona, where the temperature reaches a few million degrees; the much cooler surface of the Sun, at 6,000º C, is not hot enough to emit X-rays. As a result, an X-ray image reveals a bright glow for the corona and a black disk for the surface of the sun. The EUV (Extreme UltraViolet) and X-ray regions of the spectrum have been especially significant in solar studies from space because these wavelengths are produced directly by solar activity. At the end of the 20th century it became known that nearly every astronomical object, from nearby comets to stars and distant quasars, emits X-rays. These findings were produced by the instruments of such astronomy missions as:

- Uhuru (Swahili word for “freedom”), also known as SAS-1 (Small Astronomical Satellite 1) was the first Earth-orbiting mission dedicated entirely to celestial X-ray astronomy. Uhuru of NASA was launched on 12 December 1970 from the San Marco platform in Kenya (energy range: 2 – 20 keV).
- HEAO-1 (High Energy Astronomy Observatory) of NASA with a launch Aug. 12, 1977 (energy range: 0.2 keV - 10 MeV)
- HEAO-2 (or Einstein Observatory) of NASA with a launch Nov. 12, 1978 (energy range: 0.2 - 20 keV); the first X-ray telescope in space imaging cosmic sources
- EXOSAT (ESA X-ray Observatory) with a launch May 26, 1983 (energy range: 0.05 - 50 keV). S/C in HEO orbit of 90 hour period
- ASTRO-C (Ginga) of Japan with a launch Feb. 5, 1987 (energy range: 1 - 500 keV)

1537) http://www.sec.noaa.gov/SWN/
1538) http://www.windows.ucar.edu/spaceweather/
1539) http://www.spaceweather.com/
1541) http://www.estec.esa.nl/wmww/wma/spweather/workshops/spw_w4/index.html
1542) http://www.estec.esa.nl/wmww/wma/spweather/esa_initiatives/spweatherstudies/public_doc.html
1545) http://www.esa.int/export/esaSC/SEMTA2T1VED_index_0.html
1546) http://heasarc.gsfc.nasa.gov/docs/corp/observatories.html
• Granat a Russian X-ray/gamma-ray astronomy mission in collaboration with other European countries. Launch Dec. 1, 1989 (energy range: 2 keV - 100 MeV).

• ROSAT (Röntgen Satellit), a collaboration of Germany, USA, and UK with a launch June 1, 1990 (energy range: X-ray 0.1 - 2.5 keV, EUV 62-206 eV); all sky-survey in the soft X-ray band. The ROSAT X-ray imaging telescope detected more than 60,000 new X-ray sources. The instrument had the capability to locate these sources with an accuracy of < 10 arcsec while operating in pointing mode.

• ASCA (Advanced Satellite for Cosmology and Astrophysics) of Japan with a launch Feb. 20, 1993 (energy range: 0.4 - 10 keV). First X-ray mission to combine imaging capability with broad passband, good spectral resolution, and a large effective area.

• RXTE (Rossi X-ray Timing Explorer) of NASA with a launch Dec. 30, 1995 (energy range: 2 - 250 keV); Very large collecting area and all-sky monitoring of bright sources. RXTE had 3 instruments: 1) PCA (Proportional Counter Array) to detect the lower part of the X-ray energy range, 2) HEXTE (High Energy X-ray Timing Experiment) to observe the upper energy range, and 3) ASM (All Sky Monitor). HEXTE demonstrated the capability to time tag X-ray photons (15 - 250 keV) with an accuracy of 8 µs.

• Chandra of NASA with a launch July 23, 1999 (energy range: 0.1 - 10 keV); highly-eccentric Earth orbit of 64 hour period. Spatial resolution < 1 arcsec.

• XMM-Newton (X-ray Multi-Mirror Mission) of ESA with a launch Dec. 10, 1999 (energy range: 0.1 - 15 keV). Very large collecting area; simultaneous X-ray and optical (170-650 nm of UV, VIS) observations. HEO (Highly Elliptical Orbit) of 19,200 km x 101,900 km, inclination of 52.97º.

• The introduction of X-ray interferometry technology represents the next step in providing a high-angular-resolution imaging capability of celestial X-ray sources. Proposals in this direction are: the NASA MAXIM Pathfinder and the follow-up MAXIM (Micro-Arcsecond X-ray Imaging Mission) satellite concepts. The goal is to achieve µarcsec pointing accuracies in the X-ray spectrum. 1547)

Within Earth’s environment, X-rays are also being generated by precipitating energetic electrons (energetic electrons precipitating into the Earth’s upper atmosphere cause the auroral emissions from exited atoms and molecules, but X-ray bremsstrahlung is also generated when the electrons are decelerated). 1548) In the context of spaceflight, X-ray radiation causes considerable damage to the performance of electronic spacecraft components. This applies for instance to imaging detectors, such as CCDs.

• X-ray sensor applications. Devices measuring in the x-ray spectrum are being used in a variety of applications. Examples are: to observe x-ray sources in the universe (astronomy, study of particle transport mechanisms in the interplanetary medium), to measure the sun’s x-ray radiation (study of solar flares, warning services of solar flares for possible S/C damage, etc.), to diagnose the chemistry of a planet’s surface, to monitor the Earth’s atmosphere for nuclear explosions in support of the Nuclear Non-proliferation Treaty and the Atomic Test Ban, and to monitor the morphology and spectra of energetic electron precipitation and its effect on the Earth’s atmosphere.

Background: X-rays were discovered in Nov. 1895 by the German physicist Wilhelm Conrad Röntgen (1845-1923). His experiments at the University of Würzburg focused on light phenomena and other emissions generated by discharging an electric current in a cathode ray glass tube (he evacuated the tube of all air, filled it with a special gas, and passed a high electric voltage through it). In the experimental setup, Röntgen’s attention was drawn to a glowing fluorescent screen on a nearby table. He realized that the fluorescence was caused

1547) http://maxim.gsfc.nasa.gov/pathfinder.html
by invisible rays originating from the tube. The new type of radiation had the ability to penetrate matter, like human tissue; Röntgen saw the bones of his hand clearly displayed in an outline of flesh. The mysterious radiation was soon referred to as “X-ray radiation” because “X” stood for the “unknown” (however, in Germany, the new radiation was called “Röntgenstrahlung” in honor of the discoverer). The first ever Nobel Prize for physics was awarded to Wilhelm Röntgen in 1901 for his discovery of X-rays.

Some basic characteristics of X-ray radiation: 1549) 1550)

- The X-ray spectrum is generally considered from 60 nm (EUV) to about 3 pm in wavelengths (see Table 80).
- X-ray radiation penetrates solid matter. The degree of penetration is least in materials containing elements of high density and high atomic number. A sheet of lead (Pb) absorbs X-ray radiation completely.
- The Earth’s atmosphere is completely opaque to X-ray radiation, i.e. to photons with energy levels above about 100 eV. [Note: the Earth’s atmosphere absorbs radiation over a large portion of the electromagnetic spectrum.] Hence, observations of incoming X-ray radiation can only be done by instruments on satellites. This is the reason why the field of spaceborne X-ray (as well as UV and gamma-ray) astronomy is relatively young, starting in the 1970s.
- X-ray radiation interacts with matter by ejecting electrons from matter by the photoelectric effect and other mechanisms. In photo-electric absorption, a photon is absorbed in the process of removing an electron from an atom. The high energy of the X-ray is necessary for it to take place.
- X-ray radiation ionizes a gas - permitting it to conduct. This effect may for instance be used to measure the energy of x-ray radiation.
- X-ray radiation causes certain substances to fluoresce (e.g. barium). In x-ray fluorescence of trace elements, the filter deposit is irradiated by high energy x-rays that eject inner shell electrons from the atoms of each element in the sample. When a higher energy electron drops into the vacant lower energy orbital, a fluorescent x-ray photon is released. The energy of this photon is unique to each element, and the number of photons is proportional to the concentration of the element.
- X-ray radiation exhibits also diffraction characteristics. 1551) 1552) 1553) In 1912, the physicists Max von Laue, Walter Friedrich and Paul Knipping (all at the University of Munich) succeeded in the first demonstration of x-ray diffraction in crystal structures, thus rendering proof of the wave-like nature of x-ray radiation (phenomenon of constructive interference).
- X-ray detection technology: High-energy radiation (X-ray, gamma-ray) observations require in general special detection techniques. These are due to the difference in the way high-energy electromagnetic radiation interacts with matter compared to wavelengths longer than the ultraviolet. In the optical and microwave wavelength regions the methods and instruments are basically similar to those in ground-based astronomy.
- X-rays are capable to expose photographic film (integrating detector)
- X-ray sources generally emit fewer high-energy photons (as compared to photons of the optical spectrum) so that X-ray detectors can detect and measure individual X-ray photons, and accumulate enough photons to make an accurate picture of the total source. - A flux of one photon/(cm²s) in the 1-10 keV range observed at Earth constitutes a bright cosmic X-ray source.

1550) http://ihome.cuhk.edu.hk/~s016969/physproj/Spectrum/Xrays/astronomy1.htm
The interpretation of x-ray emissions from astrophysical objects relies on the detailed spectral information, and on the morphology of the emission. The emission lines carry information on the physical state of the emitting plasma (density, temperature, state of ionization, thermal versus non-thermal emission process), whereas the morphology of the emission allows deep insights into the physics of the objects studied.

**Some background on X-ray instrumentation:**

The design of an X-ray imaging system (optics) poses some difficulties due to the constraints imposed by the interaction of X-rays with matter. First, X-rays impinging at normal incidence on any material are largely absorbed rather than reflected. Secondly, the index of refraction, n, is about 1 at X-ray wavelengths for all materials. Any refracting system (i.e., lens) sufficiently thin to transmit X-rays must therefore possess a long focal length. For most materials, however, the index of refraction is slightly less than unity at X-ray wavelengths. This property offers the possibility of using "total external reflection" of X-rays incident on a surface near grazing incidence. As long as the grazing angles are very shallow, about one degree, the X-rays do not penetrate the surface but are reflected, just like visible light.

<table>
<thead>
<tr>
<th>Radiation spectrum</th>
<th>Photon energy range</th>
<th>Spectral range</th>
<th>Frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV</td>
<td>0.02 - 0.2 keV</td>
<td>60 - 6 nm</td>
<td>5 x 10^{16} - 5 x 10^{18} Hz</td>
</tr>
<tr>
<td>Low-energy (soft) x-rays</td>
<td>0.2 - 2 keV</td>
<td>6 - 0.6 nm</td>
<td>5 x 10^{18} - 5 x 10^{19} Hz</td>
</tr>
<tr>
<td>Medium-energy x-rays</td>
<td>2 - 10 keV</td>
<td>0.6 - 0.1 nm</td>
<td>5 x 10^{19} - 3 x 10^{19} Hz</td>
</tr>
<tr>
<td>High-energy (hard) x-rays</td>
<td>10 - 400 keV</td>
<td>0.1 - 0.003 nm</td>
<td>3 x 10^{19} - 1 x 10^{22} Hz</td>
</tr>
<tr>
<td>Gamma-rays</td>
<td>&gt; 400 keV</td>
<td>&lt; 0.003 nm (&lt; 3 pm)</td>
<td>&gt; 1 x 10^{22} Hz</td>
</tr>
</tbody>
</table>

Table 80: Overview of high-energy spectral ranges

Prior to the introduction of imaging optics into X-ray astronomy, the most sensitive X-ray instruments consisted of collimated detectors with large collecting areas. A large collecting area was required in order to obtain a sufficiently strong signal from the relatively weak X-ray sources, in the presence of a large background signal. Placing a collimator in front of a large-area detector restricted the size of the sky from which a signal was collected at any time, and thus reduced the background signal when the detector was pointed at a source. For very bright X-ray sources, this approach is still adequate. 1555) 1556)

A complete spaceborne X-ray imaging instrument consists of the following elements: telescope, dispersing element, detector, a processing and telemetry unit, and a background rejection system.

**Telescope:** A concept for increasing the ability to detect weaker sources is the use of an X-ray telescope to create an image of a portion of the X-ray sky. - The instrument system can either be with or without the capability to sense the direction of incoming radiation. There are all-sky monitors and active radiation shields which haven’t any or have only very rough directional sensitivity, but the majority of systems include a telescope or at least a collimator. The structure of a focusing telescope is determined by the ability of effectively reflecting the incoming radiation. In modern astronomical telescopes lenses (refracting systems) are hardly ever used as the main focusing elements. This is due to the fact that high-energy photons (X-ray, gamma-ray) are effectively absorbed in mirror surfaces, and therefore large incidence angles and designs similar to optical telescopes cannot be applied.

The utilization of X-ray mirrors for extra-solar X-ray astronomy had to await the development of electronic detectors with both high quantum efficiency and the ability to determine

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1554) Note: A very useful formula which helps converting from wavelengths to energies, and vice versa, is the following: 
Energy (keV) = 1.24 / Wavelength (nm)
1556) http://www.astro.helsinki.fi/education/spaceastro/observ.html
the location of the arrival of an X-ray photon in two dimensions. The first such detectors were the Imaging Proportional Counter (IPC) and the MCP (Microchannel Plate) detector. Subsequently, more sensitive detectors including CCD spectrometers and imaging gas scintillation proportional counters have been employed.

Metal surfaces are capable of reflecting high energy photons if very small reflection angles (a few degrees or less) are used. Telescope designs of this type are called grazing incidence telescopes, and they have been used in XUV to X-ray astronomy (up to photon energies of a few tens of keV) starting from the 1970’s.

X-ray imaging techniques below 10 keV (soft X-ray imaging): One difficulty of x-ray instrumentation is that x-ray photons cannot be focussed as lower wavelength ones, since they are absorbed by matter under normal incidence conditions. Reflection on a surface can occur only under grazing incidence angles, the cut-off angle decreasing when the energy increases. This has been the major problem in building X-ray telescopes, and is the reason why X-ray instruments imaging characteristics look poor compared to optical astronomy. Below ~ 10 keV, astrophysics missions are flying with focussing X-ray mirrors built on this grazing incidence reflection property. The x-ray instruments of the Chandra mission of NASA (launch Jul. 23, 1999) and of the XMM-Newton mission of ESA (Dec. 10, 1999) operate on this principle.

[At about 0.5 arcsecond resolution, Chandra cannot quite achieve the clarity of Hubble. But Chandra is seeing a huge slice of the universe that Hubble cannot see due to the limitations of optical light. In fact, after just six months in space, Chandra was detecting new types of galaxies and black hole activity so distant and faint that Hubble couldn’t even follow-up with optical observations.]

X-ray imaging techniques above 10 keV: Hard X-ray imaging instrumentation relies on the following techniques:

- Use of a simple collimator to select a part of the sky, with photons detected by a non imaging detector system. First applications to guide X-ray and gamma-ray photons were actually pure collimator systems, which do not apply any focusing, but merely block out the radiation from unwanted directions. These have very limited imaging capability, and require large detectors if large effective areas are desired. Pure collimator systems were used in e.g. the first astronomical X-ray observations in 1970’s. The first spaceborne focussing X-ray telescope flew on Skylab in 1973 (launch May 14, 1973) and recorded over 35,000 full-disk images of the sun over a 9-month period (see L.5).

- The modern technique of hard X-ray imaging employs a coded mask, which for each point source in the sky projects an unambiguous pattern onto an imaging detector system. The sky image is reconstructed by unfolding the mask motives from the image measured by the detector. This technique, which allows to reach angular resolutions of about 5-15 arcminutes, is employed in ESA’s Integral mission launched Oct. 17, 2002. Note: A coded mask is placed in front of the detector usually together with a mechanical collimator. The mask is basically a plate with a well defined pattern of equally sized holes (normally thousands) in the plate. The holes pass a radiation pattern to the position-sensitive focal plane detector, and the pattern can be decoded to produce a unique solution of the original image of the sky.

**Dispersive element filters:** There can then be a dispersive element and/or filters which determine the spectral interval passing further. The dispersive element may be a prism, a diffraction grating, or a crystal, whichever is suitable for the wavelength region and the desired spectral resolution.

**Detectors:** The detector collects the incoming radiation and responds in an accurately determined manner, the output being some physically measurable signal (e.g., electric charge, current or voltage). In some cases, the energy of the X-ray radiation (photons) is so high that it interacts with solids and liquids via the photoelectric effect.
X-ray imaging detectors are being used from astronomy to material science and to clinical radiology applications. The first x-ray detector used was photographic film; it was found that silver halide crystallites would darken when exposed to x-ray radiation. The majority of conventional x-ray detection techniques rely on film and phosphor storage screens. Commercially available systems generally utilize secondary detection media, such as phosphor plates or scintillator conversion layers. All of the above methods have some shortcomings, such as in resolution, radiation collection efficiency, or in the provision of multispectral (color) imagery. The semiconductor approach offers better detection solutions; hence, they are extensively being used in x-ray detection schemes.\textsuperscript{1557}

- Semiconductor detectors based on silicon (CCDs) are suitable for soft x-ray energies \(<10\) keV (spectral range of 0.1 nm to 60 nm). In the soft x-ray range, energy resolutions of \(<1\) keV are obtained. Germanium detectors are more suitable for the hard x-ray region with energies between 10 keV and about 1000 keV (or 1 MeV).
- Low-temperature bolometers are also used as high-resolution x-ray detectors. In these designs, x-rays are detected by semiconductors and cooled to very low temperatures (about 0.1 K) for high energy resolutions.
- MCP (Microchannel Plate), coupled with a scintillator, a film, or a CCD array, can provide x-ray imaging (suitable from UV to x-ray to \(\gamma\)-ray range). MCPs are used for plasma particle, ion, photon, and/or electron counting applications (measurement of ionospheric fluxes in the solar wind, etc.).
- At the start of the 21 century, x-ray detection can probably be best served with a compound semiconductor, in particular of the type GaAs (gallium arsenide), according to the ESA GaAS sensor development program.\textsuperscript{1558} It offers the following system requirements:
  - High density to provide a high detection efficiency
  - A wide enough bandgap to ensure room-temperature operation
  - A time response matched to the expected photon fluxes
  - A uniformity in spatial response in excess of 99.99%

The band-gap of GaAs detectors is high enough that it does not need cryogenic cooling, and low enough that sub-keV spectral resolution is achievable at hard x-ray energies. Room-temperature operation is an important consideration for x-ray systems.

Example of X-ray CCD detector: The ACIS (AXAF CCD Imaging Spectrometer) X-ray instrument of NASA's Chandra spacecraft features high-sensitivity CCDs with excellent charge-transfer characteristics. The flight assembly (Figure 36) shows two distinct arrays:

\textsuperscript{1558} http://astro.estec.esa.nl/SA-general/Research/Detectors_and_optics/home.html
a square imaging array and a linear spectrometer array. The angular resolution of the detectors is better than 0.5 arcseconds, a factor of 10 greater than other X-ray observatories. The energy resolution is a factor of 10 greater, and the sensitivity is a factor of 20 greater than that of any other X-ray detectors in orbit. 1559)

The ACIS CCD instruments were constructed jointly by the MIT Center for Space Research and the Department of Astronomy at the Pennsylvania State University.

**Background rejection system:** There are several other aspects which have to be accounted for in the high-energy detector system design. Perhaps the most important is the external and internal background radiation of the system. External background is of profound importance in space environment where the system is exposed to primary cosmic radiation. Internal background may be a problem especially for the infrared detectors, where some parts of the system may radiate in the same wavelength band as observed by the detector. Radiation shields, either passive which just block off the unwanted radiation, or active which also measure the radiation when it is absorbed by or passing through the shield, are used in spaceborne instruments.

- Solar observations in the high-energy spectrum are performed by a number of dedicated satellite missions, normally with strong international cooperation (see Section K). Prominent examples in this class are SOHO of ESA/NASA (launch Dec. 2, 1995) and the STEREO mission of NASA with a launch on Oct. 26, 2006 (K.28) with the objective to study CMEs (Coronal Mass Ejections) of the sun. - There are also some Earth-observation missions with instruments dedicated for sun observations. Examples:
  - Coriolis of NRL with SMEI (Solar Mass Ejection Imager), launch Jan. 6, 2003 (see A.12).
  - GOES-12 of NOAA (launch July 23, 2001). It is the first GOES-series satellite to carry a solar X-ray imager in addition to its standard imager. The instrument is called SXI (Solar X-ray Imager). It images the solar atmosphere once per minute, giving virtually continuous updates on solar flare occurrences, which can disrupt communications on Earth (see F.4.2). The SXI instrument is providing space weather forecasters with near real-time imagery of the sun’s explosive atmosphere, helping them issue timely warnings when solar activity might harm spaceborne and/or ground-based assets (see also 1.7.5). The SXI employs a small telescope that makes use of advanced technology and grazing incidence optics to allow it to see the sun’s outer atmosphere or corona in X-rays.

<table>
<thead>
<tr>
<th>S/C Mission</th>
<th>X-Ray Instruments</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGILE (launch Apr. 23, 2007)</td>
<td>GRID (Gamma Ray Imaging Detector), Super-AGILE, Mini-Calorimeter</td>
<td>Gamma rays in 30 MeV – 50 GeV range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard X-rays in 10–40 keV range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250 keV – 100 MeV range</td>
</tr>
<tr>
<td>ALEXIS (launch Apr. 25, 1993)</td>
<td>ALEXIS</td>
<td>Soft X-ray monitor (6 telescopes)</td>
</tr>
<tr>
<td>ARGOS (launch Feb. 23, 1999), DoD</td>
<td>USA (Unconventional Stellar Aspect)</td>
<td>X-ray timing, time-resolved spectroscopy, Feasibility tests of X-ray S/C navigation</td>
</tr>
<tr>
<td>Astro-E2/Suzaku (launch July 10, 2005)</td>
<td>XRS (X-ray Spectrometer), 4 XIS (X-ray Imaging Spectrometer), HXD (Hard X-ray Detector)</td>
<td>JAXA astronomy mission in collaboration with NASA. Astro-E2 covers the energy range 0.2–600 keV with 3 instruments. Note: In Aug. 2005, JAXA discovered that all liquid helium had evaporated making the XRS observations useless.</td>
</tr>
<tr>
<td>Bhaskara (launch Nov. 20, 1981)</td>
<td>X-ray monitor experiment</td>
<td>Study of transient and long-term X-ray sources (ISRO)</td>
</tr>
<tr>
<td>Chandra X-ray Observatory of NASA, formerly AXAF (launch July 23, 1999 on STS–93)</td>
<td>ACIS, HRC, HETGS, LETGS</td>
<td>The telescope features 4 nested pairs of grazing incidence paraboloid and hyperboloid mirrors, diameter 1.2 m, focal length of 10 m, collecting area of 400 cm$^2$ at 1 keV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission/Date</th>
<th>Instruments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORONAS-I (Mar. 2, 1994)</td>
<td>TEREK-C, RES-C, DIOGENESS, HELICON, IRIS</td>
<td>Study of the solar atmosphere structure</td>
</tr>
<tr>
<td>CORONAS-F (Jul. 31, 2001)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMSP series</td>
<td>SSB, SSB/X-2,</td>
<td>Array-based systems for the detection of x-rays emitted by the atmosphere</td>
</tr>
<tr>
<td>GOMS (launch Oct. 31, 1994)</td>
<td>RMS</td>
<td>Study of solar x-ray radiation</td>
</tr>
<tr>
<td>GPS/Navstar (Block-II satellites)</td>
<td>IONDS, CXD is follow-up sensor</td>
<td>Monitoring of nuclear explosions, CXD (Combined X-ray detector and Dosimeter)</td>
</tr>
<tr>
<td>RHESSI (launch Feb. 5, 2002) initially referred to as “HESSI”</td>
<td></td>
<td>Study of solar flares in X-ray and gamma-ray region (3 keV to 20 MeV) covering soft and hard x-rays</td>
</tr>
<tr>
<td>IMP-8 (launch Oct. 26, 1973)</td>
<td>CPME, EPE</td>
<td>Solar x-rays</td>
</tr>
<tr>
<td>Integral (launch Oct. 17, 2002), ESA</td>
<td>JEM-X (Joint European X-ray Monitor) SPI (Spectrometer on INTEGRAL)</td>
<td>Study of X-ray sources in the energy range 3–35 keV, angular resolution of 1 arcmin. Gamma-ray sources in the energy range 20 keV–8 MeV</td>
</tr>
<tr>
<td>Interball (launch Aug. 3, 1995)</td>
<td>SKA-2, DOK-2X, RF-15, SNSA-2</td>
<td>Tail Probe instruments</td>
</tr>
<tr>
<td>IRS-P3 (launch March 21, 1996)</td>
<td>XRAP (X-Ray Astronomy Payload)</td>
<td>Study of x-ray sources</td>
</tr>
<tr>
<td>ISEE-3 (launch Aug. 12, 1978)</td>
<td>ANH,</td>
<td>Study of solar flares</td>
</tr>
<tr>
<td>MTI (launch March 12, 2000)</td>
<td>HXRS</td>
<td>Measures solar x-ray emissions in 8 bands</td>
</tr>
<tr>
<td>Kibo, the JAXA module on ISS, planned launch in 2008</td>
<td>MAXI (Monitor of All-sky X-ray Image)</td>
<td>MAXI monitors the X-ray spectrum of extra-galactic objects</td>
</tr>
<tr>
<td>POLAR (launch Feb 24, 1996)</td>
<td>PIXIE (pinhole camera concept)</td>
<td>Study of energetic electron precipitation on and its effect on the atmosphere</td>
</tr>
<tr>
<td>Skylab (launch May 14, 1973)</td>
<td>S-054 and S-056</td>
<td>First study of the sun in x-ray range</td>
</tr>
<tr>
<td>SMART-1 (launch Sept. 27, 2003)</td>
<td>D-CIXS, XSM</td>
<td>Moon surface chemistry, swept charge detector design, instrument mass of 3 kg</td>
</tr>
<tr>
<td>SMM (launch Feb 14, 1980)</td>
<td>GRS, HXBRs (study of electron acceleration of solar flares), HXIS, XRP</td>
<td>GRS made important contributions to the international study of Supernova 87A, which in Feb. 1987 provided astronomers with their first opportunity to study such an explosion</td>
</tr>
<tr>
<td>SNOE (launch Feb. 26, 1998)</td>
<td>SXP</td>
<td>Monitoring of soft x-ray flux from the sun</td>
</tr>
<tr>
<td>SOHO (launch Dec. 2, 1995)</td>
<td>CDS, EIT, UVCS, LASCO</td>
<td>Study of the composition of the solar corona, etc.</td>
</tr>
<tr>
<td>Solar-A (launch Aug. 30, 1991)</td>
<td>HXT, SXT,</td>
<td>Study of high-energy solar phenomena</td>
</tr>
<tr>
<td>Solar-B (launch Sept. 23, 2006)</td>
<td>XRT</td>
<td>Study of high-energy solar phenomena</td>
</tr>
<tr>
<td>SOLRCE (Jan. 25, 2003)</td>
<td>XPS (SXP heritage)</td>
<td>Solar EUV measurement</td>
</tr>
<tr>
<td>STS–35 (Dec. 2–11, 1990), Shuttle mission of NASA</td>
<td>BBXRT (Broad Band X-ray Telescope)</td>
<td>BBXRT (first focusing X-ray telescope) was part of the ASTRO–1 payload operating in the energy range 0.3–12 keV</td>
</tr>
<tr>
<td>TRACE (launch Apr. 2, 1998)</td>
<td>TRACE</td>
<td>Study of coronal mass ejections, etc.</td>
</tr>
<tr>
<td>UARS (launch Sept 12, 1991)</td>
<td>AXIS,</td>
<td>Measurement of Bremsstrahlung x-rays from Earth</td>
</tr>
<tr>
<td>Ulysses (launch Oct. 6, 1990)</td>
<td>GRB</td>
<td>X-ray and gamma-ray measurement of solar and cosmic origin</td>
</tr>
<tr>
<td>XMM–Newton (Dec. 10, 1999)</td>
<td>EPIC (3), RGS (2)</td>
<td>EPIC can register extremely weak X-ray radiation</td>
</tr>
</tbody>
</table>

Table 81: Overview of some missions flying X-ray instruments (alphabetical order) ¹⁵⁶⁰

¹⁵⁶⁰) Note: The NASA mission HESSI was formally renamed in April 2002 to RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager). This renaming is in recognition of the enormous contribution that Reuven Ramaty made to gamma-ray astronomy in general and to the HESSI program in particular. Reuven Ramaty died in 2001, after a long and distinguished career in the Laboratory for High Energy Astrophysics at NASA/GSFC.
1.8 Navigation - Geodesy in Action

Navigation is the art of establishing position and direction (orientation and heading) of an object in space (or elsewhere), generally involving distances, angles and time to known references - all based on geodetic principles. The object (platform) attitude is also of fundamental importance, since it serves in general as a reference for most sensor observations. Of particular interest are the ground-based and onboard instruments which provide inputs for orbit and/or attitude determination. In general, orbit determination is an iterative process, building upon the results of previous solutions, and on tracking data inputs from various sources over significant time periods. In spite of these obstacles, orbit determination is becoming an increasingly automated process due to better real-time computing capabilities and ever-improving algorithms (and filters) in the latter 1990s.

The functions of satellite orbit and attitude determination have traditionally been performed on the ground. Commands were then uplinked to the satellite to relay the precomputed information. Historically, the lack of onboard processing power and the complexity of required algorithms have precluded the application of onboard orbit and attitude determination. – However, at the start of the 21st century, there is a trend to automate the orbit and attitude determination functions and to move them onboard the spacecraft. The benefits are savings in operational manpower as well as improved functionalities (ability to locate targets of opportunity, etc.). An onboard automation process is also a natural consequence of constellation and formation flight requirements, to coordinate all real-time functions in support of the planned constellation and formation-flying projects. 1561)

In spaceflight, the term “navigation” is often a synonym for GNC (Guidance Navigation & Control) or GN&C, involving a) the knowledge and prediction of spacecraft position and velocity, referred to as orbit determination, and b) the execution of orbit maneuvers (station keeping, orbit raising, etc.), referred to as flight path control. In addition, the attitude of a vehicle is of importance as it performs its observation mission. A short definition of each function is: 1562)

- Navigation is the subject of computing the position and orientation of the spacecraft platform with respect to either some inertial coordinate system (such as a star or several stars) or a rotating reference system (such as the Earth).
- Guidance is the process of propagating the current state of the spacecraft forward in time to predict the future behavior of the spacecraft and to compare it to the desired profile.
- Control is the process of orienting and moving the spacecraft platform in the desired direction required by the guidance. This includes attitude stabilization (maintaining the attitude in a desired state), attitude maneuver control (changing the attitude from one orientation, or the old state, to another orientation, the new state), and firing engines to move the spacecraft to the desired trajectory.

Background: 1563) The history of navigation, of finding the way, is as old as humankind. The Latin roots of “navis” (ship) and “agere” (to move or direct) indicate that navigation was mainly used in the past to guide ships across the seas. In the modern world, the term navigation encompasses the guidance generally: on the seas, on land, in the air, as well as in inner and outer space. - Of particular interest to all navigators are navigation aids. Conventional “way finding methods” included the observation of landmarks on the Earth’s surface (light-houses, beacons, buoys, prominent rocks and cliffs, sounding of water depths, shorelines, etc.), and of celestial navigation, finding position and heading (keeping course) by observation of the stars, the sun, and the moon. However, the art of celestial navigation was in particular in need of an accurate time standard. Even two centuries after Columbus, no clock

1563) http://isa.dknet.dk/~janj/navigation.html
could keep time well enough to aid in fixing longitude (the problem of fixing longitude was solved, when John Harrison in England produced several chronometers between 1730 and 1763). Harrison’s chronometer lost or gained only about one second a day - incredibly accurate for the time. For the next two centuries, sextants and chronometers were used in combination to provide latitude and longitude information. - Plausible records indicate that the Chinese were using the magnetic compass (a heading or bearing device) around AD 1000, western Europeans by 1187, Arabs by 1220, and Scandinavians by 1300.

It took a while until humankind obtained a proper perception of Earth as a planet in the solar system and later on of its true dimensions and shape (Earth observation from space was a great help in this venture). Within the last century there have also been great strides in the observation and discovery of the surrounding universe. The early space age permitted also the first excursions into our solar system by unmanned probes with truly great achievements in navigation. However, the vastness and true greatness of the universe has been and remains to be observed by astronomy (ground-based and spaceborne).

Geodesy is the discipline of measuring and mapping the dynamic shape (and size) of the Earth’s surface (the geoid representation), including the Earth’s gravity field and its rotation - and the establishment of general reference systems. This definition includes the orientation of the Earth in space, and temporal variations of the Earth’s orientation, its surface and its gravity field. Space geodesy (also referred to as satellite geodesy) is an interdisciplinary science which uses spaceborne and airborne remotely sensed, and ground-based measurements to study the shape and size of the Earth, the planets and their satellites, and their changes; to precisely determine position and velocity of points or objects at the surface or orbiting the planet, within a realized terrestrial reference system. Positioning (or point position determination) is a subdiscipline of geodesy. In short, the three pillars of geodesy are: 1. Geometry and kinematics 2. Earth orientation and rotation 3. Gravity field and dynamics

Modern geodetic tools such as GPS, radar and laser altimetry, interferometric SAR observations, and SST (Satellite-to-Satellite Tracking) techniques are accurate enough to monitor time variations in the Earth related to plate tectonics, post-glacial, ocean circulation and atmospheric circulation. Geodesy attempts to solve geophysical problems by assimilating observable phenomena (such as variations in the Earth’s rotation, gravity, geocenter, and surface deformations) into models. Today, these observations come from a variety of sources including SLR (Satellite Laser Ranging), VLBI (Very Long Baseline Interferometry), GPS, DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) and PRARE (Precision Rate and Range-Rate Equipment).

Note: Actually, the discipline of geodynamics is studying the processes involved in the rotation and deformation (plate tectonics, crustal motion and deformation of the surface and sea level caused by glacial loading and unloading, etc.) of the Earth. In this context, geodesy is being used to monitor these effects. Geodesy has, in a real way, been reinvented to meet the extraordinary accuracy requirements of geodynamics.

### 1.8.1 Some background on datums and reference systems

Today’s Earth navigation is based on a geodetic coordinate system (providing a dense global coverage by using latitude and longitude to fix position) and on commonly used datums (standards) to permit proper referencing of locations in various coordinate systems, to sup-

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1564) In general relativity the terms geodesic (noun) and geodetic (adjective) refer to paths followed by massive bodies ("geodesics") and light rays ("null geodesics") in curved four dimensional space-time. This usage is an outcome of the history of tensor analysis, the mathematical machinery applied in Einstein’s theory.

port a multitude of map projections, to determine distances between any two points, as well as for a multitude of other functions and services. Central to almost all navigation and positioning tasks is the notion that a map coordinate is of little value without reference to recognizable features on the surface of the Earth.

- So-called ecliptic coordinates were already used by Hipparchos and Ptolemy in their star catalogs, and were the standard of celestial measurement until the Renaissance, when they were replaced by the equatorial coordinate system of the Earth. The equatorial coordinate system is identical to the ecliptic system, except that it uses the celestial equator for horizontal measurement instead of the ecliptic.

- Celestial coordinates. The celestial sphere has a north and south celestial pole as well as a celestial equator which are projected reference points to the same positions on the Earth surface. Right ascension and declination serve as an absolute coordinate system fixed on the sky, rather than a relative system like the zenith/horizon system. Right ascension is the equivalent of longitude, only measured in hours, minutes and seconds (since the Earth rotates in the same units). Declination is the equivalent of latitude measured in degrees from the celestial equator (0 to 90º). Any point of the celestial (i.e. the position of a star or planet) can be referenced with a unique right ascension and declination.

- Historically, horizontal positioning of a point on the Earth’s surface (such as latitude and longitude) evolved from calculations based on celestial observations from that location. Distinct points - or stations - could be linked by measured networks, forming the geodetic basis for mapping systems. Mapping systems in the western tradition were terrestrially based, and were referenced to specific models of the shape and size of the Earth, called reference ellipsoids. These systems were generally called “datums” (from the singular of “data”) in reference to the single specific point where the mapping system was “tied to the ground,” i.e. linked to the reference ellipsoid. 1566)

Determining a vertical position was and is substantially harder than finding a horizontal position. This is because vertical positions, usually height above sea-level, are expressed relative to an equipotential gravitational surface. This can be imagined by mentally extending the plane of the ocean’s surface at the seashore inland running underneath mountains at a height corresponding to the gravitational level of the sea surface. This hypothetical sea level at rest is called the geoid. 1567) However, the Earth’s mass is distributed unevenly, and the oceanic crust is denser than the continental crust. The result is that the real geoid undulates in comparison to the smooth and symmetrical figure of the imaginary reference ellipsoid.

- An important datum in the history of navigation is the “International Meridian Conference of 1884” which took place in Washington D.C. in October 1884 (attended by 41 delegates from 25 nations) on invitation of the President of the United States, Chester A. Arthur. The conference formally adopted the Prime Meridian line (0º longitude) passing through the Greenwich Observatory near London, England. This action of a single world meridian was highly desirable to replace the numerous one’s already in existence by various seafaring nations. It was further established that: 1568)
  - All longitude would be calculated both east and west from this meridian up to 180º
  - All countries would adopt a universal day
  - The universal day would be a Mean Solar Day, beginning at the Mean Midnight at Greenwich and counted on a 24 hour clock.
  - Nautical and astronomical days everywhere would begin at mean midnight
  - All technical studies to regulate and extend the application of the decimal system to the division of time and space would be supported.

1567) Note: The geoid is a surface along which the gravity potential is everywhere equal and to which the direction of gravity is always perpendicular.
1568) http://millennium-dome.com/info/conference.htm
### Geodetic satellites up to 1970

Geodetic accuracy increased rapidly in the decade after the launch of Sputnik (Oct. 4, 1957). Multiple satellites tested three different types of tracking systems (see 1.8.3).

- **Optical tracking** by cameras on the ground observing a series of bright ECHO satellites. These balloon satellites of 30 m diameter (ECHO-1A launch Aug. 12, 1960) were deployed using inflation gas. ECHO (1960) and PAGEOS (Passive Geodetic Earth Orbiting Satellite) of NASA (1966) led to the first models of Earth’s gravity field and of the upper atmosphere density, improving global geodetic accuracy from 200 m to 10---15 m.


Transit allowed oceanographic ships to navigate with 1 km accuracy, a vast improvement over 10---20 km accuracy of celestial—navigation techniques.

- **Satellite Laser Ranging (SLR)**, a corner cube reflector experiment on satellites was first demonstrated on BE-B (Beacon Explorer-B/ or Explorer-22) of NASA/GSFC (Oct. 10, 1964), then on GEOS-1, (launch Nov. 6, 1965), Diademe-1 and -2 (Feb. 1967) of CNES. This led to measurements of a satellite's position with ~ 3 m accuracy (eventually to a few cm accuracy). The measurements produced much new information about Earth’s gravity field.

### Geodetic satellites in the decade 1970—1980

At the same time oceanographers were perfecting altimeters, geodesists were busy refining knowledge of Earth’s gravity field, an Earth reference system, and tracking station locations.

- Starlette of CNES (launch Feb. 6, 1975) was the first satellite with high mass relative to its surface area (the entire S/C surface consisted of corner cube reflectors), making it ideal for geodetic studies and mapping of earth’s gravity field. The satellite was 25 cm in diameter with a mass of 52 kg. It was accurately tracked by SLR techniques.

- Lageos-1 of NASA (launch May 4, 1976) was similar to Starlette, but operated at a higher altitude of 5950 km. It was ideal for studying polar motion and Earth’s rotation. The satellite was 60 cm in diameter with a mass of 405 kg. It too was accurately tracked by laser tracking systems.

### Geodetic satellites in the decade 1980—1990

- **DORIS** (Doppler Orbitography and Radiopositioning Integrated by Satellite). This is a one-way, two-frequency, ground-to-satellite Doppler tracking system developed by CNES, GRGS (Groupe de Recherches de Géodésie Spatiale), and IGN (Institut Géographique National) beginning in 1983. It was flown successfully on SPOT-2 (launch Jan. 22, 1990) and on many later satellites, including Topex/Poseidon. DORIS was designed to produce orbits with 1 cm accuracy when used with the improved gravity fields. The system is based on the ARGOS widely used in oceanography for tracking drifters.

- **PRARE** (Precision Range and Range Rate Equipment) is a compact, spaceborne, two-way, two-frequency microwave satellite tracking system developed by the German GFZ (GeoForschungsZentrum) beginning in 1982. PRARE was initially installed on ERS-1 (launch July 17, 1991), but could not be operated. Further PRARE uses: Meteor-3-7 (launch Jan. 25, 1994, PRARE demonstration operations until March 1995), ERS-2 (launch April 21, 1995).

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The International Date Line is lying along the 180° line of longitude (actually a zigzag line in the Pacific), thus establishing two simultaneous dates on Earth - to the west of this imaginary line is the location of the new day, while to the east of the 180° line there is still the date of the previous day. An explanation: A day lasts 24 hours, but a date lasts 48 hours (going through all time zones)! Two parallel dates of 48 hours each, divided by 2, provides us again our 24 hour day. The introduction of a date line solved also the problem of the circumnavigator’s paradox.

The Greenwich meridian also serves as the basis for the world’s standard time zone system. The mean solar time at Greenwich is now called Universal Time (UT) and was formerly called Greenwich Mean Time (GMT). The introduction of a GMT/UT meant, it is for instance 12 o’clock UT when the sun passes the meridian at Greenwich. The division into 24 time zones was suggested by the Canadian engineer Sandford Fleming in 1883. It is easy to calculate and to project onto Earth. There are 360° of longitude and the Earth takes 24 hours to rotate around its axis thus creating day and night. The time in each zone (15°) differs by one hour from the time in the next, and it differs by a multitude of an hour from the Universal Time. All places within the same zone use the same time. It is up to the individual countries whether they keep to the time zones into which they fall or not.

In this worldwide adopted coordinate system, the baseline for latitude measurement is the equator plane and the baseline for longitude measurements is half of a great circle passing through Greenwich, England. Geodetic latitude and longitude are measured as angles with the origin of the angular measurements at the center of the Earth. The latitude value indicates the angular measurement above or below the equator plane, with a latitude at the equator being zero degrees. Longitude lines (meridians) are the intersection of the Earth’s surface and a plane going through the Earth’s north-south (rotational) axis and the point of interest on the Earth’s surface. Zero degrees longitude is the longitude line passing through Greenwich, England (prime meridian plane).

1.8.1.1 Geodetic reference frames

While the international latitude-longitude reference frame is very suitable for navigation purposes, other geodetic (i.e. terrestrial or surface) reference frames were needed for such applications as cadastral, surveying, map making, and many other practical functions of everyday life. National geodetic reference frames were created in the past (19th century) to suit these needs. At the start of the space age, most of the national reference frames were not identical/compatible for historical reasons. In particular, large existing geodetic systems such as NAD (North American Datum), ED (European Datum) and TD (Tokyo Datum) were quite incompatible to provide a basis for inter-continental geodetic information systems. 

Soon after the first satellites were in orbit, geodesists, by observing the perturbing effect on satellite motion, began to evaluate the Earth’s gravitational field. The photography of satellites with respect to stars was the first type of precise measurements of the angular positions of satellites. These determinations were followed by a rapid succession of more extensive and accurate descriptions of the Earth’s gravity field. Early space geodesy was conducted primarily using optical instruments (photographic processes) adapted from earlier stellar systems.

The visual tracking of the ECHO satellites in the early 1960s put several geodetic institutes in a position, to establish for the first time geodetic intercontinental links. For example, one of the most successful tracking campaigns in this era provided the geodetic connection be-

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1570) Note: A great circle is an imaginary circle on the surface of a sphere whose center is the center of the sphere. Great circles that pass through both the north and south poles are called meridians, or lines of longitude.

1571) Note: A geodetic coordinate system is correctly defined by describing the following: a) reference ellipsoid, b) system origin, and c) axis orientation.

1572) http://www.nima.mil/GandG/geolay/TR80003E.HTM#ZZ11
between Europe and Africa. The PAGEOS (Passive Geodetic Earth Orbiting Satellite) mission of NASA (launch June 24, 1966), represented a more stable balloon satellite in orbit at a higher altitude (2953 km x 5207 km). The existing Wild BC4 cameras from the US Coast Guard and USGS (United States Geological Survey) were deployed in networks occupying some 40 sites — well distributed around the Earth. The geocentric positions of the 40 stations were published and were considered at the time as making one of the first homogeneous global Earth reference systems. However, the best accuracy of these new positions (reference points) was no better than ~2 arcsec which translated to about 10–20 m on Earth. 1573)

The first satellite equipped with laser corner cube reflectors was BE-B (Beacon Explorer-B — also referred to as Explorer-22 mission) of NASA, with a launch Oct. 10, 1964 (see chapter 1.8.3.5). The new technique of round-trip signal measurements between a ground station and the satellite permitted to calculate more precise orbits with accuracies in the 1–1.5 m range.

Radio frequency tracking: With the development of the US Navy Navigation Satellite System (TRANSIT), Doppler satellite geodesy became a cheaper, more rapid technique for space geodesy. One of the striking characteristics of space geodesy in the 1960s and 1970s was the almost complete separation between the optical school and the Doppler school. 1574) 1575) 1576) 1577) 1578)

Satellite navigation systems such as Transit (for Doppler), GPS and GLONASS (for positioning) and other space-based measurement techniques require a single global geodetic datum to fix position. Hence, considerable efforts in global geodetic reference frame standardization were initiated during the last four decades of the 20th century to suit the fundamental requirements on global datum definition and use. It became also apparent to extend the definitions to include more physical models, including, for instance, spherical harmonic models for the Earth’s gravity field. Some of these geodetic coordinate frame efforts are (all with an Earth-centered datum):

- **WGS60** (World Geodetic System 1960). 1579) In 1960, research efforts of the US Army, Navy, and Air Force were combined to create the World Geodetic System of 1960, based on a combination of surface gravity data, astro-geodetic data, and Shoran (Short Range Aid to Navigation) and Hiran (an improved version of Shoran) 1580) geo-positioning surveys to obtain a best-fitting ellipsoid for the most significant datum areas.

- **WGS66** (World Geodetic System 1966). In 1966, DoD formed a World Geodetic System Committee to develop an improved WGS, based on greater surface data and increasing volumes of satellite data. The satellite data came from the Navy’s TRANSIT Doppler navigation system and from four different programs of optical geodetic satellites, referred to as ANNA (Army-Navy-NASA-Air Force). The first geodetic satellite was ANNA-1B, launched in 1962. ANNA systems included geodetic cameras, electronic ranging and

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1580) Note: The Shoran and Hiran systems provided a means for early electronic surveys from an airborne vehicle or a platform.
Doppler. These early systems have made it possible to perform various geodetic measurements to relate known or unknown positions to the Earth’s center, to relate unknown positions to existing triangulation networks, and to relate the triangulation networks to each other. The defining parameters of the WGS66 ellipsoid were the Earth flattening factor (1/298.25), determined from satellite data and the semimajor axis (6,378,145 m), determined from a combination of Doppler satellite and astro-geodetic data. A worldwide 5° x 5° mean free air gravity anomaly field provided the basic data for producing the WGS66 gravimetric geoid.

- **WGS72** (World Geodetic System 1972). A principal objective of WGS is to allow referencing of local geodetic systems to a single geocentric system. WGS72 is the result of an extensive effort (extending over 3 years) to collect satellite, surface gravity, and astrogeodetic data available throughout 1972 [a major data source were Doppler data from DoD (CORONA program) and non-DoD satellites]. These data were combined using a unified WGS solution (a large-scale least squares adjustment). The value for the semimajor axis of the WGS72 ellipsoid is 6,378,135 m (10 m shorter than the one of WGS66, based on several calculations and indicators including a combination of satellite and surface gravity data for position and gravitational field determinations). An Earth flattening factor of 1/298.26 was adopted.

Note: WGS 72, considered to be the standard for about a decade, contained a gravity field represented by about 450 coefficients and could demonstrate a system consistency of about 1 m, while the overall accuracy for tracking station locations was estimated at about 3 m.

- **WGS84** (World Geodetic System 1984). WGS84 was also developed by DoD and is an improvement and a replacement for WGS72. Radar altimeter data from GEOSAT was used to deduce geoid heights from oceanic regions of latitude ±70°. Geoid heights were also deduced from a large number of ground-based Doppler stations and ground-based laser satellite-tracking data, as well as surface gravity data [at the time of WGS 84 development, its reference frame realization was defined by TRANSIT tracking stations; however, to define the most accurate TRANSIT coordinates, external calibration was necessary]. The GPS system uses the WGS84 as coordinate reference frame. The GPS satellites send their positions in WGS84 as part of the broadcast signal recorded by the receivers, all calculations internal to receivers are also performed in WGS84. 1581) 1582) 1583)

Definition: WGS84 is a set of parameters for determining geometric and physical geodetic relationships on a global scale. The system includes a geocentric reference ellipsoid, a coordinate system, and a gravity field model. The ellipsoid is essentially that of the International Union of Geodesy and Geophysics Geodetic Reference System 1980 (GRS80). The coordinate system is a realization of the conventional terrestrial system, as established by the International Earth Rotation Service. 1584)

In 1983 the WGS 84 development committee adopted the BTS (Bureau International de l’Heure Terrestrial System) as the external comparison standard for the WGS 84. The BTS, based on very long baseline interferometry (VLBI) and other observations, was globally distributed and very accurate. The WGS 84 TRANSIT tracking station coordinates were adjusted to match the BTS as well as possible.

Note: In WGS 84, several thousand gravity coefficients were determined, and the separation between “Optical” and “Doppler” satellite measurements was somewhat reduced; however, most major datum parameters were greatly influenced by Doppler satellite mea-

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1582) http://www.wgs84.com/wgs84/wgs84.htm
1584) A coordinate reference frame has to be accomplished by an Earth’s gravity model. For example, the WGS84 uses a spherical harmonic expansion of the gravity potential up to the order and degree 360. For Galileo a similar model must be considered. In that context, the European satellite gravity missions GOCE and CHAMP as well as the US/German mission GRACE are of importance.
measurements. Space geodesy computations performed with WGS 84 demonstrate internal consistency of several tens of centimeters, with an estimated accuracy of about 1 m.

- Parallel to the US efforts of DoD and other organizations, the following framework was defined within the standardization bodies of the international community: 1585) 1586) - GRS (Geodetic Reference System). In geodesy, two distinct reference systems are to be noted:

- An Earth-fixed coordinate system called CTS (Conventional Terrestrial System)
- A space-fixed (quasi) inertial system called CIS (Conventional Inertial System)

Both systems share the Earth’s center of gravity (geocenter) as their origin, and the Earth’s rotational axis as a coordinate axis. The reciprocal connection is through precession and nutation, as well as Earth-rotation (polar motion and time). The ellipsoid called GRS67 (Geodetic Reference System 1967) was recommended by IAG (International Association of Geodesy), one of seven associations within IUGG (International Union of Geodesy and Geophysics) at the Lucerne, Switzerland meeting. 1587) The ellipsoid called GRS80 was approved and adopted at the 1979 meeting of the IUGG held in Canberra, Australia. GRS80 is based on the theory of the geocentric equipotential ellipsoid. In this system the equatorial radius of the Earth is 6,378,137 m [ellipsoid flattening factor: 1/298.257; angular velocity of the Earth: 7292115 x 10^-11 rad/s; the Earth’s gravitational constant (atmosphere included): 3986005 x 10^8 m^3/s^2]. The ellipsoidal parameters of the WGS84 standard are identical with the corresponding values of GRS80. The CIS reference is now realized by extragalactic radio sources, in connection with a limited number of fixed stars. By including the satellites’ orbits into the models, geocentric station coordinates can be determined now with cm accuracy, thus realizing the CIS.

Background: 1588) 1589) 1590) 1591) 1592) 1593) In 1899 the ILS (International Latitude Service) was established to coordinate the observations of the Earth’s rotation pole. These motions are caused by the gravitational forces of sun and moon as well as by geophysical processes within the atmosphere, the oceans and the interior of the Earth. In 1962 the ILS was superseded by the IPMS (International Polar Motion Service). Until 1984 the rotation of the Earth was monitored using a rigid Earth model, by IPMS and BIH (Bureau International de l’Heure) the International Bureau for Time Measurements (Paris), with latitude and time observations from a number of observatories. In 1987, IUGG decided, in cooperation with IAU (International Astronomical Union), to combine the services of IPMS and BIH into the newly established organization called IERS (International Earth Rotation Service), with the Central Bureau at the Paris Observatory. Since January 1, 1988, the Central Bureau of IERS monitors and maintains the international reference frame, referred to as ITRF (International Terrestrial Reference Frame). The ITRF is a set of points with their 3-D Cartesian coordinates which realize an ideal reference system, the ITRS (International Terrestrial Reference System).

1588) http://www.iers.org/iers/products/itrf/
In 1991 at the 20th General Assembly in Vienna, Austria, IUGG (and IAU) defined and adopted a new **CTRS** (Conventional Terrestrial Reference System), with consideration of relativistic effects and of Earth deformation (i.e. long-term geodynamics of plate motions). CTRS replaces the older CTS. In addition, the ITRS, as defined by the IUGG resolution No. 2, was adopted in agreement with IAU. The CTRS characteristics are:

- CTRS is defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system
- The geocentric non-rotating system is identical to the Geocentric Reference System (GRS80) as defined in the IAU resolutions
- The coordinate time of CTRS as well as of GRS is **TCG** (Geocentric Coordinate Time)
- The origin of the system is at the geocenter of the Earth’s masses including oceans and atmosphere
- The system has no global residual rotation with respect to horizontal motions at the Earth’s surface.

CTRS assumes a spherical Earth, it does not take any flattening factors into account. The pole of this system is known as the CIO (Conventional International Origin). The Z-axis is coincident with the Earth’s principal rotational axis, with the positive direction toward the CIO. The X-axis passes through the intersection of the CTRS reference equatorial plane and the CTRS reference meridian. The positive X-axis is in the direction of the CTRS reference meridian. The positive Y-axis completes the rotating right-handed Cartesian system.

An important underlying concept is that reference system definitions are purely definitions and must be realized through some defined process. Particularly relevant realizations of CTRS are:

- **WGS84** as used for GPS. WGS84 is practically also a realization of the ITRS, realized and maintained by the coordinates of the GPS control station network on a global scale. The network is in fact an international collaborative activity (routine activities commenced at the beginning of 1994). The first GPS derivation of WGS 84 coordinates used data collected in 1992 from the ten USAF (United States Air Force) and DMA (Defense Mapping Agency) stations and from a set of globally distributed civilian stations defined in the ITRF. 1594)

- **PZ90** (Parameters of the Earth System 1990) as used for GLONASS since 1993. PZ90 is an Earth-centered and Earth-fixed terrestrial reference frame. PZ90 is realized through a network of geodetic reference stations in Russia. 1595)

- **ITRF** (International Terrestrial Reference Frame). 1596) ITRF is the realization of the ITRS through space-based measurements at specific sites around the globe and is affected by factors in the observation and processing of both the station and satellite positions and their motions. Some ITRF realizations are: ITRF96, ITRF97, ITRF2000, based on a combination of geodetic techniques including SLR and VLBI.

- **GTRF** (Galileo Terrestrial Reference Frame). The European Galileo radionavigation system opted for UTC and ITRF as its time and coordinate references. In practical terms, the GTRF will be an independent realization of ITRS. 1597)

The WGS84 and ITRF reference frames are consistent. The differences between WGS84 (G1150) and ITRF2000 are in the centimeter range, worldwide. This implies for the interoperability of both GNSS systems that the WGS84 and GTRF will be identical within the accuracy of both realizations (i.e. coordinate reference frames are compatible).

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1596) Z. Yang, “Regional geometric changes of the Earth Observed by VLBI, GPS and SLR,” Proceedings of the Weikko A. Heiskanen Symposium in Geodesy, Ohio State University, Columbus, OH, USA, Oct. 1-4, 2002

IERS publishes revised ITRF positions and velocities every few years for a worldwide network of geodetic stations (some 150 sites in 2002). Each IERS solution for these positions and velocities uses observations obtained from various geodetic techniques including GPS, VLBI (Very Long Baseline Interferometry), DORIS, and SLR (Satellite Laser Ranging). New solutions not only incorporate at least an additional year of data, but also the most current understanding of the Earth’s dynamics.

With regard to GPS reference stations, there are a number of national initiatives underway providing services to their user communities. These networks of reference stations serve also for an ever increasing number of applications. One of these involves crustal movements. Some examples:

- NGS (National Geodetic Survey) of NOAA/NOS created a cooperative national network called CORS (Continuously Operating Reference Station), to make data from hundreds of such GPS base stations, located in the United States, freely available to the public via the Internet.\(^{(1598)}\)\(^{(1599)}\)\(^{(1600)}\) In April 2002, CORS comprised over 600 stations in USA with a growth rate of several stations per month. CORS is a composite network of GPS tracking stations or regional sub-networks established by a wide variety of agencies (over 60), institutions and private companies; it provides a reliable flow of GPS data from precisely known positions that can be used to easily access the National Spatial Reference System. CORS is also providing a number of value-added services.

- In the past decade, geodetic measurements (GPS, GNSS)\(^{(1601)}\) have been widely used to monitor crustal motions ranging from tectonic plates to local surveys of active faults, with precision levels on the order of 2-3 mm/yr (horizontally). Starting in the late 1990s, the increasing accuracy and density of space geodetic measurements has also permitted to test plate rigidity at a 2 mm/yr level.

- Japan created GEONET (GPS Earth Observation Network) in 1993 which produced a large amount of crustal movement data (secular, transient, and periodic crustal movements) over the past decade. The GEONET data clarified also various new aspects of crustal dynamics and earthquake physics.\(^{(1602)}\)

- The accuracy for dynamic geodesy and — to a large extent — all space geodesy, is dependent on accurate positioning of the satellite. In turn, satellite orbit computation accuracy (and satellite ephemeris accuracy) is dependent on the accuracy of the space geodesy. Satellite observations made from the ground can be used accurately only if the ground station locations are known accurately, while the orbit itself can be computed accurately only if all of the forces governing the satellite motion are known. The early dynamic geodisists observed satellite prediction errors and made bootstrap corrections to the gravity models. GPS benefited greatly from the existing WGS gravity model. Techniques that eliminate common-mode errors among ground locations provide improved accuracy over limited distances, but they still depend on satellite position accuracy. GPS geodesy, like GPS navigation, relies on the accuracy, quality, and timeliness of the orbit computation and prediction (Ref. 1578).

- The arsenal of geodetic measurement methods has increased considerably in number and accuracy since the early days of space flight. It includes some of the following tech-

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niques (besides the conventional satellite imaging, Doppler satellite surveying, and ground-based triangulation surveys):

- SLR (Satellite Laser Ranging), see chapter 1.8.3.5. There is now the ILRS (International Laser Ranging Service) providing high-accuracy data sets.

- LLR (Lunar Laser Ranging). The first men on the moon in July 1969 deployed a rack structure with an array of 100 fused silica retroreflectors designed to return some of the light of a pulsed laser beam to the telescope to which the laser equipment is coupled. The equipment is referred to as LURE (Lunar Laser Ranging Experiment).

- VLBI (Very Long Baseline Interferometry), see 1.8.3.3. Observations of extragalactic radio sources provide the geodetic information to determine the vector separations between the antennas of two widely separated radio telescopes on Earth. A major goal of VLBI is to reduce the uncertainty in intercontinental baselines to the centimeter level. IVS (International VLBI Service) is used for data set access and for coordination of activities.

- Satellite altimetry, see 1.6.2.

- The GNSS constellations of NAVSTAR/GPS, GLONASS, (and the future Galileo system), see 1.12.6. An IGS (International GPS Service) was established in 1991 to provide GPS measurements from a global network of reference stations. The official IGS service provision by IAG (International Association of Geodesy) was launched in January 1994. At the start of the 21st century, the IGS network IGS) consists of more than 200 stations and was originally set up for geodynamic applications, as determination of tectonic plate motions. The IGS service provides a first order geometric reference worldwide; it employs, maintains and contributes to the ITRF (International Terrestrial Reference Frame). The IGS infrastructure (and regional and local densifications) forms the backbone for GNSS positioning and mapping activities all over the world, and not just only for the class of highest accuracy! The European densification of the IGS is EPN (EUREF Permanent Network). The IGS and EPN infrastructure are considered to play a crucial role in the implementation of the reference system for Galileo.

- SST (Satellite-to-Satellite Tracking), see 1.8.3.2. The GRACE constellation is an example of SST measurements.

- Systems such as: DORIS (Determination Orbite Radiopositionnement Integres Satellite) and PRARE (Precise Range And Range-rate Equipment).

- Inertial surveying (gradiometry and accelerometry), see 1.8.3.7. This refers to inertial navigation by determining the position and velocity of a vehicle solely by means of sensing that vehicle’s accelerations and performing the necessary integrations to determine the position and velocity on a real-time basis. [Note that the technique of inertial surveying does not require inter-station visibility, and does not rely on measurements of external signals, but which can still determine relative position to a high accuracy.] Examples of drag-free missions are CHAMP and GRACE.

- Earth rotation. The services of SLR, LLR, VLBI and DORIS are being used by IERS (International Earth Rotation Service) to monitor the Earth’s polar motion and rotation time. Polar motion consists of two main signal components: the Chandler wobble with a period of 14 months, and the annual oscillation. The Chandler wobble is characterized by a time-varying energy behavior, i.e. the amplitude and the frequency are time-dependent functions. The wobble has diurnal and semi-diurnal variations with amplitudes of a fraction of a milliarcsecond (marsec) that are due to a combination of oceanic tides and atmospheric mass fluctuations; the rate of rotation fluctuates by up to a millisecond per day. \(^{1603}\) \(^{1604}\) Accurate knowledge of the motions of the pole is important for maintenance of reference

\(^{1603}\) Note: The wobbling motion of the Earth was first detected by Seth C. Chandler (US astronomer, 1846-1913) in 1891 and has been under observation ever since. The Earth pole motion phenomenon is also referred to as the “Chandler Wobble.” The pole motion, due to the dynamic flattening of the Earth, appears when the rotation axis does not coincide anymore with the polar main axes of inertia.

frames and understanding of planetary physics. For instance, the causes of temporal variations in the Earth’s gravity field arise in response to changes in the mass distribution both on and beneath the Earth’s surface. It turns out that water movement (both of surface water and groundwater) is one of the major causes of fluctuations in mass on the Earth’s surface. Other causes for Earth’s gravity variations are being attributed to mass changes in the atmosphere, the oceans, postglacier rebound (from the enormous mass of the glaciers), and melting ice in the polar regions.

- Establishment and maintenance of the (four-dimensional) geometric reference frame. This task is primarily solved by the geometry-related IAG (International Association of Geodesy) services, namely IERS (International Earth Rotation Service), IGS (International GPS Service), IVS (International VLBI Service) and ILRS (International Laser Ranging Service). The geometric reference frame is (must be) used for all high-accuracy applications (e. g., precise orbits for LEOs (Low Earth Orbiting satellites).

- WRS (World Reference System). 1605) WRS is simply a global notation system for data of the Landsat program (Note: it should be understood that WRS has nothing to do with a geodetic frame, it is placed here simply for convenience). WRS enables a user to inquire about satellite imagery (ground coverage in any repeat cycle) over any portion of the world by specifying a nominal scene center designated by PATH and ROW numbers. The WRS has proven valuable for the cataloging, referencing, and day-to-day use of imagery transmitted from the sensors of the Landsat program.
  - WRS-1 is being used for the Landsat-1 to -3 mission data. The 18-day ground coverage cycle for Landsat 1-3 is accomplished in 251 orbits. WRS-1 assigns sequential path numbers from east to west to 251 nominal satellite orbital tracks, starting with number 001 for the first track which crosses the equator at 65.48º west longitude.
  - WRS-2 is being used for Landsat-4, -5 and -7 mission data (extension to WRS-1). WRS-2 defines Landsat scenes as 185 km x 180 km rectangular areas on the Earth’s surface designated by path and row coordinates. The 16-day ground coverage cycle for Landsat 4-7 is accomplished in 233 orbits. Hence, the WRS-2 system is made up of 233 paths numbered 001 to 233, east to west, with Path 001 crossing the equator at 64.60º west longitude.
  - All members of the “A—train” (afternoon constellation of NASA: Aqua, PARASOL and Aura) are also using the WRS-2 frame; except CALIPSO and CloudSat.

- Positioning (Ref. 1578): The term absolute positioning, when used in the discipline of geodetic surveying, generally refers to a process that establishes the Earth-centered, Earth-fixed coordinates of a solitary station on the Earth’s surface. Unlike relative positioning (differential positioning), the absolute positioning process does not depend on use of a previously determined reference station position. Instead, a set of satellite positions and clock states are obtained from an existing satellite ephemeris. A position estimation algorithm is employed that uses data collected at the solitary station over some period of time, typically at least a few hours or more.

1.8.1.2 Gravity datums and some measurement concepts

The gravity field of the Earth is variable in both space and time, and is an integral constraint on the mean and time variable mass distribution in the Earth. The study of the Earth’s gravity field leads to the determination of the geoid. The geoid is by definition the main equipotential surface (an ellipsoid) of the Earth’s gravity field — it would coincide with the ocean surface without ocean currents, winds, and other disturbances, i. e., with the hypothetical sea surface. The geoid is used as a datum for gravity surveys (a hypothetical ocean surface at rest). The gravity field is in effect the natural reference to define the vertical position: the height. It is also defined as the physical (or gravimetric) reference system. With its deter-

1605) http://landsat.gsfc.nasa.gov/documentation/wrs.html
mination, the representation of 70% of the Earth’s surface (the oceans) is achieved. \(^{1606}\) The Earth’s gravity field (high resolution and precision) is needed for many applications in the geosciences. In geodesy, for example, the gravity field is needed for levelling with GPS, in oceanography it is important for studying ocean circulation, in geophysics a better knowledge of the Earth’s gravity field provides also better boundary conditions in the study of the Earth’s interior. Also, a precise ocean geoid model is essential to recover dynamic sea-surface topography, and thus ocean circulation, by satellite altimetry.

- **Historical background** on gravity reference systems (gravity models). Traditionally, scientists constructed gravity maps using a combination of land measurements and ship records. However, those measurements weren’t accurate enough to capture the slight changes in water movement that cause gravity to change over time.

In 1900, the so-called “Vienna Gravity System” was adopted by IAG (International Association of Geodesy). A strategy was devised of establishing a global gravity standard by connection with relative measurements to the most accurate possible absolute station. A much improved “gravity datum” was the so-called “Potsdam Gravity System” in 1906. Reversible pendulums were used to measure absolute gravity at Potsdam, Germany. The value measured at this time was later adopted as the initial point for the “Potsdam gravity reference system.” Using relative measurements, several points on each continent were connected to Potsdam, and these served as the fundamental base stations for many relative gravity surveys.

The Potsdam system, however, was found to be in error and, in 1971, was replaced by the IGSN-71 (International Gravity Standardization Net 1971). The IGSN contains 1854 re-occupiable stations distributed worldwide. The acceleration of gravity at each point was determined by a least squares adjustment that included a number of absolute gravity measurements and a multitude of relative gravity measurements that interconnected all stations. The IGSN-71 established the basic “gravity datum” for today’s relative gravity surveys. Since there are variations in the densities of the Earth’s crustal materials as well as terrain variations, the observed gravity of the earth varies irregularly from point to point. As a result the surface known as the geoid is an irregular figure.

- The first spaceborne gravity field of Earth was produced in 1983 derived from altimetric measurements. The necessity of a high-resolution satellite-borne gravity field mission was already defined in 1969 in the so-called “Williamstown Report” by the leading geo-scientists at that time. The idea was to derive the gravity field and positions at the Earth’s surface and in space consistently at the same level of precision. But somehow, such a mission could not be realized due to a lack of funding. \(^{1607}\)

At the start of the 21 century, survey methods for EGMs (Earth Gravity Models) can be obtained from satellite altimetry with spatial resolutions of 2’ x 2’ (arcsec), and an accuracy of 2 - 10 mgal. The accuracy is limited by tide models, troposphere, editing, etc. Many gravity field models (regional and global scale) have been developed since the availability of altimetry data, only a few global models are being listed here for reference. The interested reader is referred to the following reference. \(^{1608} 1609\)

- EGM96 (Earth Gravity Model 1996). Developed in 1996-1998 as a collaborative effort of NASA/GSFC, NIMA and OSU (Ohio State University). It is based on surface gravity data, altimeter-derived gravity anomalies from ERS-1 and from GEOSAT, extensive satel-

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1608) http://www.iges.polimi.it/
1609) Global Gravity Field Models History; URL: http://op.gfz-potsdam.de/iagwg/WG_models.html
Earth Observation History on Technology Introduction

- IFE88E2 (Institut für Erdmessung 1988) University of Hannover, Germany in cooperation with the Kort-og-Matrikelstirelsen, Denmark and the Statens Kartwerk, Norway. IFE88E2 is a tailored model, complete to degree and order 360. IFE88E2 is based on the OSU86F (Ohio State University 1988) coefficients set, which was used as a start model. The low degree coefficients of the OSU86F were not modified due to the limited data collection area and due to the fact that these coefficients are well determined from the analysis of the satellite orbit perturbations.

- OSU91A (Ohio State University 1991 A). The OSU91A potential coefficients model was obtained as a merger of two potential coefficients data sets: 1613)
  - A potential coefficients model up to degree 50, selected on the basis of a combination of the GEM-T2 (Goddard Earth Model-T2) potential coefficients, surface gravity normal equations and one year of GEOSAT altimeter data
  - A potential coefficients model from degree 51 to degree 360, calculated using a global set of adjusted anomalies (combination solution with the GEM-T2 potential coefficients and a recent 30° x 30° mean gravity anomaly data set).

- GEM-T3 (Goddard Earth Model-T3). This model was developed by NASA/GSFC in the early 1990s from tracking data acquired on 31 satellite orbits in combination with surface gravimetry and satellite altimetry (GEOS-3, SEASAT, GEOSAT). It describes the gravity field up to degree and order 50.

- GGM01 (GRACE Gravity Model 01) of 2003. GGM01 has been computed from 111 days of GRACE K-band ranging data (spanning April to Nov. 2002); it is differenced from a global mean sea surface (MSS) computed from a decade of satellite altimetry to determine a mean dynamic ocean topography (DOT). For the first time, all major current systems are clearly observed in the DOT from spaceborne measurements. At wavelengths of 500 km or longer, GGM01 produces a better marine geoid than any previous gravity model. The accuracy of final GRACE geoids is expected to be a few out to a degree/order of 70.

- Earth Gravity Model “EIGEN-GRACE_02S” (from GRACE data only, released Feb. 13, 2004): An Earth gravity field model complete to degree and order 150 from GRACE.

- GGM02 (GRACE Gravity Model 02) is based on the analysis of 363 days of GRACE in-flight data, spread between April 4, 2002 and Dec 31, 2003. GGM02 was released Oct. 29, 2004. GGM02 is an improved Earth gravity field model.

**GRACE (Gravity Recovery and Climate Recovery)** is a cooperative US-German dual-mission with a launch March 17, 2002 — and the reason for the greatly improved

1611) http://164.214.2.59/GandG/wgs---84/egm96.html
1616) http://www.csr.utexas.edu/grace/gravity/ggm01/GGM01_Notes.pdf
1618) http://www.csr.utexas.edu/grace/gravity/
gravity models. The mission concept makes use of measurements of the inter-satellite range and its derivatives between two co-planar satellites (in low-altitude and polar orbits), using a K-band microwave tracking system (with ultrastable quartz oscillators) and a GPS receiver system (BlackJack) for precision orbit determination to enable accurate orbit determination. The tiny relative orbital changes of the two GRACE spacecraft permit to deduce the Earth’s minute gravity field changes from one month to the next mostly due to the mass changes of water on Earth’s surface. Since water in all its forms has mass, the ocean can actually be weighted as it moves around (changes in polar ice caps or local rainfall may also be determined). Hence, GRACE observes the hydrologic cycle of Earth, allowing the analyst to track water as it evaporates into the atmosphere, falls on land in the form of rainfall or snow, or runs off into the ocean. The biggest freshwater hydrologic events that GRACE detects are the rainfall runoff in the larger river basins, like the Amazon, and the monsoon cycle in India. In addition to gauging changes in water mass on Earth’s surface, GRACE can detect large-scale water (or moisture) changes underground.  

- Some background on differential gravity ("g") measurements: Instrumental capabilities for both relative and absolute gravity measurements have evolved over the last 40 years of the 20th century to the point, where today measurements can be made at the parts in $10^9$ level of precision (1 μgal ≡ $10^{-9}$ g). Conventional instruments which measure gravity differences are basically the pendulum and the gravimeter (which is in essence a spring balance). A gravimeter consists of a measured weight on a spring scale.

By the mid 19th century, measurement capabilities (pendulum method) for g had reached a precision of 1 in $10^6$ (1 μgal ≡ $10^{-6}$ g) and an accuracy of 1 in $10^5$. In the 20th century, two principle gravimeter methods have been employed (both can be used to measure the vertical gravity differences at the 10 μgal level of precision):

- The LaCoste & Romberg gravimeter that uses a “zero length” spring to create a stable mechanical configuration with the result that a small change in gravity results in a large position change of the supported mass.
- The Scintrex gravimeter that uses a simple (fused silica) spring with a (necessarily) high degree of temperature control (to avoid temperature induced changes in the length of the spring masquerading as gravity changes) and a sensitive sensor to detect the minute gravity-induced length changes of its spring.

The 2nd half of the 20th century saw also the development of free-fall and free-fall interferometric methods for absolute gravity measurement (1980). As a consequence, JILA, an interdisciplinary institute for research at the University of Colorado and NIST, developed the “JILAg” instrument in the 1990s, capable of measuring absolute gravity at the parts in $10^9$ level of accuracy. JILAg was commercialized in 1998 as the FG-5 (tradename) via a government-to-industry technology transfer. As of 2001, FG-5 is a transportable absolute gravimeter apparatus of Micro-g Solutions, Inc. of Erie, CO. The instrument measures the gravity gradient by tracking the differential free-fall of two simultaneously falling objects with a laser interferometer.

The technique of airborne gravimetry has advanced considerably over the last decade. Beginning with Greenland (1995) and extending to other regions of the world lacking in terrestrial gravity observations, airborne gravity surveys have proven to be accurate and cost effective. Airborne gravimetry has made a significant contribution to the Arctic Gravity Project, an initiative under IGGC (International Gravity and Geoid Commission) of IAG (In-

1621) Note: Gravity may be observed by an absolute technique (e.g. in a free fall experiment) or relatively (as a difference) by a spring gravimeter.
1623) http://www.microgsolutions.com/gradiometer.press.htm
ternational Association of Geodesy), where the gravity anomaly field of the entire Arctic region north of 64º N has been compiled on a 5' x 5' grid. The goal of airborne gravimetry is to achieve a 1 mgal precision with a spatial resolution of 1 km. Airborne gravimetry has contributed to the development of EGM96 and will play a significant role in future Earth Gravity Models (EGM200X). 1624)

Conventionally, the gravity field has been treated as a static field because it is dominated by the internal mass distribution of the solid Earth, which was created on time scales from millions to billions of years. With the new satellite gravity missions, complemented by airborne gravity, it is possible to observe variations caused by dynamic processes (mass redistribution) that vary on time scales from hours to thousands years.

See also 1.8.3.8 for further gravity models.

Current plans call for the development of a gravitational model complete to degree and order 720 by 2005/6 (suitable for CHAMP, GRACE and GOCE). 1625) From about 2008 onwards, it is expected that the computation of a 1 cm geoid accuracy with 100 km half wavelength will become possible.

• On the spaceborne side, the Earth’s gravity field is being measured with the use of three techniques:

1) Gravity measurements using GPS signals have been demonstrated in the 2nd half of the 1990s in combination with INS (Inertial Navigation System) devices. High-performance GPS/INS navigation systems, flown on aircraft, have proven to be suitable for vector gravimetry determination by a number of analyses and tests with actual data. In this configuration, the gravity vector can be determined with a precision of 3-6 mgal and a spatial resolution of about 10 km. This translates into a geoid profiling capability with a precision of better than 10 cm. 1626)

A variation of this technique is to track the orbit of a low-altitude satellite precisely with a system like GPS in combination with an accelerometer. The measurement by the accelerometer onboard the satellite, at its center of mass, is then used to determine the non-gravitational surface forces (solar radiation, aerodynamic drag, and so forth) to which the satellite is subjected, in order to find the trajectory deviations induced by the Earth’s gravitational anomalies alone. The US/German CHAMP mission (launch July 15, 2000) employs such a system. 1627)

2) Satellite-to-satellite tracking (SST) technique. This involves the measurement of relative speed variations of two low-altitude satellites induced by gravitational anomalies. This concept is being practiced in the US/German GRACE mission (launch Mar. 17, 2002). See also chapters 1.8.3.2 and 1.8.3.7 for more information.

3) Use of two accelerometers onboard a satellite and determination of the difference between the accelerations measured by each instrument. The difference is representative of the gravity gradient along the axis of the two accelerometers. This is a one-axis gradiometer. The GOCE mission of ESA (launch 2007) employs such a concept.
1.8.2 Attitude sensing and actuation instruments

Spacecraft attitude refers to the angular orientation of the spacecraft body vector with respect to an external reference frame. Generally, an AOCS (Attitude Orbit Control Subsystem) \(^\text{1628}\) or simply an ADCS (Attitude Determination and Control Subsystem) consists of a set of sensors (to measure attitude and position of the S/C), and a set of actuators to impart control functions (torques and forces) to the attitude and orbit of a S/C. An AOCS periodically acquires measurements (on the satellite attitude and orbital position) from a set of sensors and uses them to compute control signals that are sent to a set of actuators. A constraint imposed by all instrument design are physical characteristics involving size, mass, and power requirements of the device. The major performance characteristics are generally: accuracy, stability, FOV, modulation transfer function, resolution and reliability.

The most common types of attitude sensors are:

- Sun sensor: to measure the direction of the sun line in the sensor’s reference frame. The FOV of a sun sensor is nearly hemispherical.
- Earth horizon sensor: measures the Earth’s horizon direction in the sensor’s FOV (Field of View).
- Magnetometer (magnetic compass): measures the direction (and strength) of the Earth's magnetic field in the sensor’s FOV. Their accuracy is generally low and varies widely from system to system. The fluxgate magnetometer is the most common type utilized in space flight (heading device).
- Gyroscope: measures the inertial angular rate of the satellite. Gyroscopes can have one or two sensitive axes. They give the projection of the satellite angular rate on the sensitive axes. Gyroscopes are often combined in packages to give measurements along up to six axes.
- Star sensor: measures the positions of several stars in its field of view. It also performs pattern recognition on the stars it sees to identify the portion of sky at which it is looking.
- GPS receiver: primarily used for position determination; it can also provide an inertial measurement of the host satellite attitude.
- A very uncommon but rather effective attitude sensor is CESS (Coarse Earth-Sun Sensor) of CHAMP and GRACE heritage (a patented design of EADS Astrium GmbH). CESS will also be flown on CryoSat (launch Oct. 8, 2005 – but launch failure) and TerraSAR-X (launch June 15, 2007). CESS provides attitude measurements (<6°) with respect to the Earth and sun for initial acquisition and coarse pointing. The FOV of CESS is a full spherical one, i.e. no special search maneuvers are necessary to find the Earth or the sun. The concept is based on temperature differences measured by 6 omnidirectional arranged sensor heads (PT1000 thermistors) about the S/C surface. Three of these sensors are covered with a black paint coat, while the other three are covered with an OSR (Oil Stain Remover) coated sense area. Hence, each of the two equally sized sensor segments provide well known absorption properties in infrared (as same as possible) and visible spectral ranges (as different as possible). Subsequent computation in the software part yields the direction of the Earth and the sun vector (when visible). At spacecraft rates < 0.5°/s, the mean error (rms over one orbit) is < 6° for the Earth and sun vector at a 1σ noise of 1° (0.5°) for the Earth (sun) vector.

The most common types of actuators are:

- Reaction wheels (RW) and momentum wheels (MW): a set of rotating wheels that can be accelerated or braked. The action of accelerating or braking causes a torque to be applied to the satellite by reaction. The primary difference between RW and MW sys-

\(^\text{1628}\)http://control.ee.ethz.ch/~pasetti/AocsFramework/AocsBackground.html#AocsUnits
tems is in the nominal spin rate of the flywheels.\textsuperscript{1629}) Reaction wheels typically have zero nominal angular velocity, which slowly changes in response to small environmental torques. Once the maximum operating speed is reached, external torques must be applied to the spacecraft in a “momentum unloading” maneuver. These torques are typically applied using thrusters or magnetic torquer rods. Momentum wheels typically have a momentum bias, and spin at a large angular velocity, which slowly changes to absorb small environmental torques. Momentum unloading maneuvers are also required. Examples: All SPOT satellites of CNES use magnetically suspended momentum wheels, as does the AMSAT AO40 satellite, launched on November 15, 2000.

- Magnetorquers: devices that interact with the Earth’s magnetic field to generate a control torque. This function may be used for S/C attitude adjustment or for momentum unloading (see also 1.8.2.4 on magnetometry).
- Thrusters: generally, a gas jet is emitted which imparts a force to the spacecraft. If the direction of the gas jet does not go through the satellite center of gravity, then a torque on the satellite results. By combining jets from suitably located thrusters, it is possible to apply either pure forces or pure torques to the satellite. A thruster system or RCS (Reaction Control System) may also be used for reaction wheel unloading.

The gravity gradient stabilization is considered a passive technique. All early satellites were spin-stabilized to maintain inertial orientation.\textsuperscript{1630}) The spinning motion creates a stiff angular momentum vector which tends to resist external disturbance torques. However, spinners usually require a supplementary active control system to initiate and adjust the spacecraft’s spin rate and attitude and to counteract disturbances. Spin stabilization typically provides pointing accuracies between about 0.3 - 1°, depending on the spin rate.

Satellites with three-axis stabilization employ a multisensor attitude control assembly; however, this was not available technology in the early days of spaceflight. The three-axis concept is the most accurate method of stabilization, and the spacecraft may be pointed, in principle, into any direction, with accuracy limited only by the sophistication of the control system. At the turn of the 21st century, there is a tendency to replace conventional Earth horizon sensors and also sun sensors of the attitude control system by star trackers. Stars provide a much finer reference (point source) thus keeping the satellite pointing more accurately (in fact, stars provide an inertial reference).

The image formed of a star by focussing through a lens is actually not a point but a blurred spot. Thus point sources emit light which is processed by the optical system, because of diffraction (and the possible presence of aberration), this light is smeared out into some sort of blur spot over a finite area on the image plane rather than focus to a point. When this patch is scanned the distribution of intensities can be described by a mathematical function. This function is known as the point spread function (PSF) of the lens. It is the impulse response of the system whether it is optically perfect or not. In a well corrected system, the PSF is is the Airy irradiance distribution function centered in the Gaussian image point.\textsuperscript{1631})

IMU (Inertial Measurement Unit). For S/C that use onboard guidance and undergo multi-axis propulsion, IMUs are necessary to provide the information needed to update the spacecraft’s position and velocity. IMUs may also provide attitude updates for these S/C.

\textsuperscript{1630}) Note: The development of early satellite stabilization technology is closely related to the study of spinning objects. The so-called “major-axis-rule” states that a spacecraft can only be spin-stabilized about its major axis, due to the internal energy dissipation which is present in any physical system.
### Table 82: Common attitude sensing techniques/devices

- The first spaceborne horizon sensor was flown on TIROS-2 (launch Nov. 23, 1960). A further new feature on this S/C was the introduction of magnetic attitude control, i.e., adjustment of spin axis orientation along the orbital path. The attitude device consisted of 250 cores of wire wound around the outer surface of the spacecraft. The interaction between the induced magnetic field in the spacecraft and the Earth’s magnetic field provided the necessary torque for attitude control.

### Table 83: Common actuation techniques for attitude control

<table>
<thead>
<tr>
<th>Method/System</th>
<th>Accuracy</th>
<th>Axes</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin stabilization</td>
<td>0.1° - 1.0°</td>
<td>2</td>
<td>Passive, simple, cheap, inertially oriented; S/C is spun about an axis with high moment of inertia. Spin must be maintained by another system (thrusters, etc). A spin stabilized spacecraft may be a pure spinner, or it may be dual spun. In a dual-spin S/C the payload, e.g. the antenna, is despun while the other portion of the S/C spins to provide gyroscopic stability.</td>
</tr>
<tr>
<td>Gravity Gradient (GG)</td>
<td>1° - 5°</td>
<td>2</td>
<td>Passive, simple, cheap, central body oriented; to completely determine attitude, another sensor is needed. Often, a sun sensor or magnetometer is being used in combination. GG can provide a stable reference below an orbital altitude of 2000 km. Torque range: $10^{-6}$ - $10^{-3}$ Nm.</td>
</tr>
<tr>
<td>RCS (Reaction Control System)</td>
<td>0.01° - 1°</td>
<td>3</td>
<td>Expensive, quick response, consumables; active control using multiple thrusters; torque range: $10^{-2}$ - 10 Nm. IMUs or accelerometers are being needed to update both position and attitude.</td>
</tr>
<tr>
<td>Magnetorqueer</td>
<td>1° - 2°</td>
<td>2</td>
<td>Cheap, slow, lightweight, LEO only; magnetic torquer (coils or rods) use a current through wires that interacts with the Earth's magnetic field to produce a torque. Torque range: $10^{-2}$ - $10^{-3}$ Nm.</td>
</tr>
<tr>
<td>Momentum wheel (MW)</td>
<td>0.1° - 1°</td>
<td>2</td>
<td>Expensive, similar to dual spin; momentum wheels operate with a bias momentum, meaning that they run at a steady-state, nonzero speed. There are several MW types: A zero momentum wheel stabilizes one axis by changing the rotational rate to produce a torque. Momentum and reaction wheels do not exert external torques on a S/C. Instead, they exchange momentum with the vehicle, enabling it to rotate about an axis while the wheels themselves speed up or slow down accordingly.</td>
</tr>
<tr>
<td>Reaction wheel</td>
<td>0.001° - 1°</td>
<td>3</td>
<td>Expensive, precise faster slew; Usually at least three zero momentum wheels aligned with each axis. Reaction wheels usually operate at a nominal speed of zero. They provide control torque by changing their speed of rotation. In this way, angular momentum is exchanged between the wheel and the S/C. Torque range: $10^{-1}$ - 1 Nm</td>
</tr>
<tr>
<td>CMG (Control Moment Gyro)</td>
<td>0.001° - 1°</td>
<td>3</td>
<td>Expensive, used to be heavy, quick for fast slew, 3-axes; CMG: one or more wheels on gimbals that rotate; CMG, is a high-performance actuator that consists of wheels spinning at constant speed, mounted on one or more gimbals. Torque range: $10^{-2}$ - $10^{-3}$ Nm.</td>
</tr>
</tbody>
</table>
Passive Control | Semi-passive Control | Active Control
---|---|---
Gravity Gradient (GG) | Momentum bias with magnetics | Propellant
Spinner with nutation damping | Reaction wheels with magnetics for momentum dumping | Reaction wheels with propellant for momentum dumping
Dual spinner with nutation damper | CMGs with magnetics for momentum dumping | CMGs with propellant for momentum dumping

Table 84: Overview of various attitude control concepts

- The first microsatellite known to fly a modern momentum exchange device is TUBSAT-B (launch Jan. 25, 1994, mass of 40 kg) of the Technical University of Berlin. The reaction wheel is based on a modified COTS DC brushless motor. The technology of the reaction wheel was further enhanced on the TUBSAT-N nanosatellite (launch July 7, 1998, mass 8 kg). A single 659 g reaction wheel was used, along with a magnetic control system. A further improved ADCS (Attitude Determination and Control Subsystem) was used on DLR-TUBSAT (launch May 26, 1999, mass 45 kg). The microsatellite used 3 improved reaction wheels. The reaction wheels for all TUBSAT missions were provided by Teldix GmbH of Heidelberg. More recent Teldix wheels (Teldix RSI-01 and -02) are based on the TUBSAT wheel design and have been used on a number of small missions including KITSAT-3 (KAIST, launch May 26, 1999), Inspector (EADS Astrium, launch Oct. 5, 1997 to MIR Station), Orbcomm (microsatellite constellation of Orbcomm), and on PROBA-1 (DLR, launch Oct. 22, 2001). The first reaction wheel developed by SSTL was flown on FASat-Alfa (launch Aug. 31, 1995) and FASat-Bravo (launch July 10, 1998).

- Programmed yaw steering of the S/C. The ERS-1 S/C (launch July 17, 1991) of ESA introduced the concept of yaw steering (a form of dynamic attitude control) to compensate for Earth rotation (about 4° per orbit). The vertical axis of the S/C is pointed towards the geodetic nadir to optimize the observation performance of its payload instruments. This involves a carefully controlled rotation about the yaw axis over the course of each orbit. As a result, the natural coordinate system of the radar instrument (AMI) remains orthogonal to the ground track of the S/C. In addition, ERS-1 introduced a roll-tilt mode in which the entire S/C can be rotated about its horizontal axis. This permits radar imaging at different incidence angles over limited periods of time.

1.8.2.1 Sun sensors

Historically, the first sun sensors were employed in the early 1950s for the guidance of ground-based solar telescopes as well as in automatic sextants. They entered the space age on rocket flights in the late 1950s. The development of solar cells for spacecraft power generation provided indirect benefits to the sun sensor technology. Silicon solar cells suitably modified, photodiodes, and light-activated semiconductor controlled rectifiers were rapidly incorporated into solar sensor designs.

The sun was used as the first natural reference in space flight for attitude determination of the spacecraft and/or sensor orientation (attitude calculated from sun angle measurements), usually in combination with an Earth horizon sensor and/or other sensors (magnetometers, gyroscopes, etc.). A multitude of sun sensor designs have been developed throughout the space age for a great variety of applications and performance characteristics (coarse and fine pointing combinations, etc.).

Two categories of conventional sun sensors exist: digital and analog types. The digital sun sensor illuminates different geometric patterns on the detector plane. The presence or absence of light imaged on the plane defines a digital signal that can be translated into the...
sun angle. In comparison, an analog sun sensor outputs analog currents, from which the sun angles can be derived directly.

- **Digital Sun Attitude Detector (DSAD).** The apparent position of the sun is an important spacecraft attitude measurement that is used by virtually all attitude determination and control subsystems. This measurement is commonly made with a sensor called a digital solar attitude detector (DSAD). DSAD is a sensor assembly and technology that computes the 2-D position of a bright spot (sun) within its FOV. All DSAD detectors are comprised of an optical system, (often a pinhole, or an array of slits), a position-sensitive detector (sometimes constructed from an array of discrete photodetectors), and an electronic signal processing system to provide an interface to the spacecraft. JHU/APL is a principal developer of the DSAD technology sponsored by NASA’s ATP (Advanced Technology Program). A DSAD imaging system is planned to fly in NASA’s STEREO mission (launch Oct. 26, 2006) to demonstrate the feasibility of autonomous solar navigation.

The next step in the program was the development of a \( \mu \text{DSAD} \) (Micro DSAD), capable of incorporating the entire sensor and its interface on a single chip. Such a sensor is of great utility in microsatellites in support of formation flying as well as many other applications. The patented \( \mu \text{DSAD} \) design combines a centroiding position-sensitive active-pixel architecture (on CMOS basis, 0.5 \( \mu \)m process, 200 x 200 pixels) with standard imaging capability for providing optional “engineering channel” images (for use in monitoring solar panel, boom, and antenna deployments or for sighting stars or other items of interest). The chip includes all analog support circuitry. An external FPGA is used to implement digital control and an I\(^2\)C interface (4 wires including power and ground). The entire system (\( \mu \text{DSAD} \) chip and FPGA controller) dissipates less than 20 mW with nominal illumination conditions. \(^{1636} \, \text{1637}\) The first two prototype \( \mu \text{DSAD} \) sensors are being flown on NASA’s CONTOUR (Comet Nucleus Tour) mission with a launch on July 3, 2002.

- **Micro sun sensor.** As of 2002, NASA/JPL developed a micro sun sensor based on MEMS technology. The design employs a tiny gold and chrome-plated silicon wafer placed at a distance of 0.9 mm from an APS (Active Pixel Sensor) chip. The APS chip contains all camera functions on the chip. The mask consists of hundreds of pinholes. The sun angle can be determined based on the position of the aperture centroids, just like a sundial. The centroid of the apertures is calculated with algorithms similar to those utilized in star trackers. The packaged micro sun sensor has a mass of 11 grams, a volume of 4.2 cm\(^3\) and a power consumption of 30 mW. The accuracy of the micro sun sensor is better than 1 arcminute and the maximum field of view is 160\(^\circ\). The micro sun sensor is essentially a pinhole camera with an f/No of about 30 and multiple pinholes. It consists of two key components: 1) a MEMS based mask and 2) a “camera on a chip” APS image detector. The high-resolution multi aperture mask is placed close to the image detector. \(^{1638}\)

- **DSS (Digital Sun Sensor).** \(^{1639}\) In 2002, a low-cost DSS was developed within the framework of ESA’s ARTES-5 program (built by TNO-TPD, EADS-SODERN, and FillFactory). The sensor employs APS detector technology (512 x 512 pixels) with on-chip AD conversion. A FOV of 120\(^\circ\) x 120\(^\circ\) is provided with a target accuracy of 0.02\(^\circ\) and a resolution of 0.01\(^\circ\). The sensor incorporates a maximum of operational autonomy.

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Autonomy in attitude and orbit determination in an Earth-sun based system. An inherent disadvantage of conventional Earth-sun based attitude sensing functionality of an AOCS (Attitude and Orbit Control Subsystem) are occasional singularities (for instance: occasional or periodic collinear positions of Earth and sun references), during which a direct three-axis attitude determination is no longer possible. Instead of using ground-based measurements, onboard GPS attitude measurements in combination with various attitude sensors, e.g. star sensors, are used in a semi-autonomous AOCS. The nomenclature “semi-autonomous” is used since the solution relies on the presence of GPS satellites for orbit determination.

1.8.2.2 Sextant-type attitude and position determination in spaceborne missions

The idea of a sextant-type optical navigation capability in space is as old as spaceflight itself. Robert J. Magee of MIT (Massachusetts Institute of Technology) began his studies and experimentation of a space sextant concept in 1959. The design employed two telescopes, a reference (fixed) telescope, and an adjustable acquisition telescope, both mounted in the same plane of sight. The operation of the sextant required in addition a pair of sun finders, a general-purpose computer, and a reaction system to make corrections to the vehicle’s flight path. This was indeed a very bold and courageous undertaking in the very early space age, considering the non-existence of any space infrastructure with regard to instrumentation, algorithms, and processors to handle such a monumental task.

The traditional sextant is an observation instrument with double-reflecting mirrors, which combines the locations of dual objects into a single image for the determination of angles between reference surfaces and/or celestial bodies. In all Earth-based applications, use is made of “local vertical” or “local horizontal” references to obtain a location determination. However, the realization of a generalized sextant concept in space turned out to be rather demanding. Position and attitude determination by a single instrument in orbit around a central body requires multiple references to determine a) the instantaneous state vector to the center of the body, and b) angular references to celestial bodies. For an Earth-orbiting spacecraft, this implies the simultaneous and continuous knowledge of the Earth center vector, as well as angle references to celestial bodies for an unambiguous triangulation analysis (free of singularities). Obviously, the most accurate celestial references in this observation scheme are provided by the stars as inertial references and point sources.

A modern optical multi-target (or multi-object) sensor design approach, such as an Earth-Star based imaging system in an AOCS (Attitude and Orbit Control Subsystem) of a spacecraft, offers the means to mimic the sextant design concept and to provide sufficient processing power. It has the potential to provide a fully autonomous attitude and position determination service, including the function of a planning tool (navigation aid) in space flight. In fact, such a space sextant system is capable to provide a rather generalized solution, regardless of orbit type (LEO, GEO, etc.), including satellite observations in orbits around other planets.

Following are some examples of sextant-concept introduction/demonstration in spaceborne missions.

- The first spaceborne sextant experiments (with a hand-held device) were conducted aboard Gemini-4 (June 4-7, 1965) and in the follow-up Apollo missions. The instrument was designed to measure the angle between the edges of the Earth, or the angle between celestial bodies. The astronauts took angular readings on stars, the planets, the moon, and other visible objects to derive the spacecraft’s position along its trajectory.


Earth Observation History on Technology Introduction

SS-ANARS (Space Sextant-Autonomous Navigation and Attitude Reference System). SS-ANARS, a USAF instrument within STP (Space Test Program), built by Martin Marietta Aerospace, Denver, CO, was flown on Shuttle flight STS-4 (June 27–July 4, 1982), as part of a DoD payload (the SS-ANARS project definition started in 1973). Obviously, this new sextant design was strongly influenced by Magee’s earlier design. SS-ANARS was a gimbaled two-telescope system, consisting of a lunar- and a star telescope, azimuth prism, elevation collimation mirror, and a gyro package. The objective was to provide an onboard angle determination capability with the use of an onboard computer by measuring the angles between celestial bodies to an accuracy of 1 arcsec. Observations of stars and lunar limb angles from a nadir reference gyro were measured. The Earth horizon azimuth and elevation were separately referenced. The total mass of the SS-ANARS instrument was about 112 kg. - The major drawbacks of this sextant implementation were: a) the relative motion of the two telescope FOVs (Field of View) to each other, and b) only two lines of sight were used (in a single acquisition), resulting in an ambiguity/unobservability of the complete state (position and attitude), as is the case for a Sun–Earth-sensor combination. From hindsight, the SS-ANARS development was indeed a very complex and challenging design, a bold and daring attempt by all parties involved.

A more advanced scheme of an onboard sextant-mode implementation into a single instrument (Earth/star optical imaging system) of an AOCS was flown on MITA. The MITA (Microsatellite Italiano a Tecnologia Avanza) mission of ASI, Italy (launch July 15, 2000; end of mission Aug. 15, 2001, LEO orbit of 450 km altitude), carried a technology sensor package by the name of MTS-AOMS (Micro Tech Sensor-Attitude and Orbit Measurement System), developed and funded by EADS Astrium GmbH (see M.23) and consisting of three elements: an APS (Active Pixel Sensor) Camera with beamsplitter-optic, a Magnetic Field Sensor, and an Angular Rate Sensor (ESA provided the flight opportunity for this package in its Technology Flight Opportunity Program). A major objective was to obtain combined attitude and orbit measurements in the optical AOCS experiment by referencing Earth's horizon and star images. The camera with beamsplitter optics and APS detector (size of 386 x 290 pixels), was used in this experiment in a so-called 'sextant-mode' configuration. This arrangement permitted the simultaneous imaging of the star field and the Earth horizon onto the detector via the beamsplitter. The MTS-AOMS flight experiment was an experimental prototype with no onboard processing capability. Although this new dual-object camera observation concept was challenging from the standpoint of image processing (algorithms for Earth horizon and center determination) - it represented in effect a first-step result to a “true autonomous attitude and orbit determination capability” by means of a single optical AOCS instrument.

The next logical step in the space sextant development process is obviously the provision of real-time onboard algorithms (in form of an ASIC or a microprocessor implementation), supporting the sextant orbit and attitude determination; and of course a flight opportunity for a full demonstration of the autonomous sextant capability.

1644) Considerable information and background to this chapter was kindly provided by Christopher Kühlof of EADS Astrium GmbH, Munich, Germany
1.8.2.3 Gyroscopes

Some gyroscope history: The mechanical gyroscope (gyros = rotation in Greek) has been around since the early 1800s. The first known modern prototype gyroscope apparatus was built in 1810 by Johann G. F. von Bohnenberger (1765-1831) of Tübingen, Germany. It was made using a heavy ball instead of a wheel, but since it had no scientific application, it faded into history.

In 1851, the French physicist J. B. Leon Foucault (1819-1868) first conceived of the gyro as an inertial reference (he also named the instrument “gyroscope” consisting of a rotor wheel mounted in gimbal rings to permit free turning in any direction—Foucault detected the Earth’s rotation in his pendulum experiment). Foucault subsequently showed that a gyroscope could detect the rotation of the Earth (a gyroscope employs the principle of conservation of angular momentum). The better-known demonstration of the Foucault pendulum (a purely mechanical system) showed that the plane of rotation of a freely-swinging pendulum rotated with a period that depends on the latitude of its location. In 1852, on the basis this experiment, Foucault invented the first spinning gyroscope in which the inertia of the rotor’s axis of rotation is substituted for that of the plane of vibration.

The availability of electricity set the stage of the first electrically driven gyroscope by G. M. Hopkins in 1890. In 1908, the German inventor H. Anschütz-Kaempfe patented the first gyroscopic compass that aimed in the north direction. In the same year, the American entrepreneur Elmer A. Sperry (1860-1930) patented his version of a gyroscopic compass (the first automatic pilot) into a usable technology which found immediate applications in early aircraft and later in maritime navigation. The first automatic pilot for ships was produced by the Anschütz Company in Kiel, Germany, and installed in a Danish passenger ship in 1916. Also in 1916, a three-frame gyro was used in the design of the first artificial horizon for aircraft. This instrument indicates roll (side to side) and pitch (fore and aft) attitude to the pilot and is especially useful in the absence of a visible horizon.

![Figure 38: Typical two-axis mechanical gyroscope configuration](image)

- Gyroscopes, accelerometers and star trackers are inertial sensors to obtain information on orientation (attitude) and accelerations relative to an inertial reference frame. Atti-
Titude measurements of a gyroscope provide angular information, while acceleration measurements (which are corrected for gravity and, integrated twice for distance) provide linear information.

The classical gyroscope is a mechanical device with a rapidly spinning mass (solid body or rotor of substantial moment of inertia), supported on a mount (e.g. a gimbal structure) that allows freedom of tilt of the spin axis relative to the base on which it is mounted. The momentum of such a rotor causes the gyro to retain its attitude when the mount is tilted. The ability of the gyro to maintain its orientation (due to the stored energy, namely the angular momentum) is employed in a number of applications (compass, direction finder, steering mechanisms, inertial guidance systems, etc.). A practical gyroscope suffers from a phenomenon known as drift due to undesired torques resulting from imperfections in machining, bearing and lubrication frictional torques, material impurities, etc.

Since the early 1960s, new generations of gyroscopes were developed (in particular through research funded by the military), working on different principles than the conventional mechanical gyroscope. The Ring Laser Gyro (RLG) and the Fiber-Optic Gyro (FOG) are such new developments based on optical (interferometric) principles.

- **RLG** (Ring Laser Gyro). RLG is a Sagnac effect optical gyro which uses an active HeNe lasing medium in a mirror-defined ring cavity. Two contra-rotating beams of coherent (laser) light circulate within the quartz ring cavity. The RLG technique was first demonstrated in 1960 at Bell Labs, it took another 20 years of testing for operational use of the system in commercial aircraft (RLGs of the Sperry Corporation were introduced in the early 1980s in such aircraft as the Boeing 757 and 767). The RLG objective is the measurement of angular rate. The concept is based on the principles of general relativity, which predict that the distance around a closed optical path in a rotating frame of reference depends on the direction the path is traversed. A beam of light traveling around the path in the direction of rotation has to travel farther than one traveling in the opposite direction of rotation. The pathlength difference (and frequency change) is used as a measure of angular rotation.

Some characteristics of an RLG are: 1) it offers long-term stability and it is insensitive to the environment; 2) it can operate continuously and has no start-up time; 3) it can withstand large angular rates (800°/s); 4) it has a digital output; 5) it has no moving parts as the conventional gyro (however, in practice it is kept in motion to minimize some error sources); 6) it requires very little power for operation.

- **FOG** (Fiber-Optic Gyro). A solid-state device with no moving parts for the measurement of angular rate (first demonstrated in 1976). In a FOG, the two light beams rotate in a spool of optical fiber. The measurement concept is based on the Sagnac effect, which defines an optical phase shift between counter-propagating beams in a rotating coil of fiber. This phase shift is proportional to the rotation rate about the axis of the coil, with a scale factor related to the coil geometry and the optical wavelength. Examples of implementations: NASA’s TR1-A rocket (a microgravity mission, Japan), launched in 1991, marked the first spaceborne experimental application of a FOG instrument. The Japanese MUSES-B (Mu Space Engineering Satellite - VLBI measurements in astronomy) mission of ISAS, launch Feb. 12, 1997, uses a hybrid FOG/radio-wave guidance system as well as an open-loop FOG for rate control (providing a drift rate of 0.05°/h). - In the late 1990s, performance range sensitivities (drift rates) of FOG devices vary from 0.001°/hr

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1651) E. Boussarie, “Pleiades high-resolution system - innovative technologies,” CNES Magazine No 17, Nov. 2000, pp.20-21
1652) Note: After launch the MUSES-B satellite (the initial name of MUSES-B was VSOP) was renamed to HALCA (Highly Advanced Laboratory for Communications and Astronomy). The SVLBI measurements provide baseline lengths of up to 3 Earth diameters.
to 100°/hr with dynamic ranges (usable measuring range) of $10^4$ to $10^5$. The CNES Pleiades spacecraft series (first launch in 2008) employs FOG technology to deliver the required pointing performance in terms of image geolocation and geometric quality.

- **LTP (LISA Technology Package)** of ESA flown on the LISA Pathfinder mission (there are two minisatellites flying to L1). The key technology to be demonstrated by the LISA Pathfinder mission (launch in 2009) is 'inertial sensor performance' - the inertial sensor makes sure that the proof mass is really flying 'disturbance-free', and also measures the position of the satellite with respect to the proof mass, and 'disturbance-free flight control' - which uses mN (micro-Newton) thrusters to control the spacecraft position with an accuracy at the level of microns ($\mu$m).\textsuperscript{1653} The inertial sensor works by detecting changes in the electrical field created by the proof mass itself, with electrodes mounted on the housing around the proof mass. The LTP core instrument includes two inertial sensors. Each inertial sensor is located in a cube of 10 cm side length that surrounds the proof mass (the proof mass floats inside this cube without touching its walls). Note: The LISA Pathfinder mission does not aim to make measurements of separation between proof masses in distant satellites, as LISA will do, but at testing the performance of the inertial sensor (and two proof masses in the same satellite are enough for that). See M.18.

- **Piezoelectric microgyroscope**. Piezoelectric vibrating gyroscopes use Coriolis forces to measure rate of rotation. Starting in 1997, a new generation of microgyroscopes, based on MEMS principles, was developed out of a technology cooperation agreement between NASA/JPL, UCLA, and HSC (Hughes Space and Communications Company). The instrument (1999), an all-silicon chip, has a size of 4 mm x 4 mm and a mass of less than one gram (the mass of the entire 3-axis microgyroscope is < 30 gram, power of about 1 W, size of 1.5 cm x 1.5 cm x 3 cm, rate of > 360°/s, etc.). The new microgyroscope is lighter, cheaper, higher-performing and less complex than its conventional counterparts, while uniquely designed for continuous and long-term space operation. The instrument concept is based on a cloverleaf design that is tied down and vibrates at a very high speed. The gyroscope senses the Coriolis acceleration, which results from the vibratory motion in a rotating reference frame, to detect rotation. The design represents a qualitative step forward in gyroscope development.

The applications of angular rate gyroscopes include navigation of manned and unmanned platforms, location of fleet vehicles, and attitude heading measurements. Fiber-optic gyroscopes can also provide antenna pointing and tracking. Following are some typical classes of gyro applications:

- General low-precision navigation (such as for automobiles) is done with gyroscopes providing drift rates of 10°/hr - 100°/hr
- Attitude and heading references for airplanes use gyro with drift rates of 1°/hr
- Precision inertial navigation as used in commercial airplanes and on some space platforms use gyro with drift rates of 0.01°/hr - 0.001°/hr.
- High-precision inertial navigation with a drift rate of <0.001°/hr is used for satellite pointing and tracking applications.

Three parameters define the performance of optical gyroscopes:

- Bias drift (a shift in the instrument zero point in the absence of rotation)
- Optical scale factor (a proportionality constant between applied rate and instrument output)
- Output noise (due to signal processing electronics, noise in the optical detection process, and thermal fluctuations in the optical fiber).

- **HRG (Hemispherical Resonant Gyroscope)**. Among the vibration gyroscopes, the HRG is the only one of the inertial class. The HRG technology was first developed in the United States (research work started in the mid-1960s — and first patented in 1979) by the
The HRG technique is based on a high-performance vibratory gyro whose inertially sensitive element is a fused silica hemispherical shell covered with a thin film of metallization. Electrostatic forceps surrounding the shell establish a standing resonant wave on the rim of the shell. As the gyro is rotated about its axis, the standing wave pattern does not rotate with the peripheral rotation of the shell, but counter-rotates by a constant fraction (0.3) of the input angle. Thus, the change in position of the standing wave, detected by capacitive pick-offs, is directly proportional to the angular movement of the resonator. In this mode of operation, termed whole angle mode, the HRG is an integrating sensor. The HRG can also be caged in a force rebalance mode to restrain the standing wave to a particular location, and acts as a rate sensor. The whole angle mode is useful when an excellent scale factor stability and linearity are required over a wide dynamic range. The force rebalance mode offers excellent angle resolution for pointing operations.

The advantages of the HRG concept is that it is lightweight, very compact, operates in a vacuum, and has no moving parts, so that life expectancy limited only by the electronics, which are provided redundantly for expected lifetimes of more than 15 years. Since its debut in space in the mid-1990s, the HRG technique has been used on many spacecraft, including the NEAR/Shoemaker (Near Earth Asteroid Rendezvous) spacecraft (launch Feb. 17, 1996) and the Cassini mission (both missions of NASA). \(^{1654}\)

1.8.2.4 Magnetometry and magnetometers

Magnetic fields are omnipresent in nature; just about every body in the solar system has magnetic fields associated with it, either of interior origin, induced, or remanent. The IMF (Interplanetary Magnetic Field) is the extension into space of the sun’s magnetic field carried outwards by the supersonic flow of the solar wind. Space magnetometry can be traced back to measurements of the Earth’s magnetic field with instruments flown on balloons and rockets in the early 1950s. The early space probes made significant discoveries: the Earth’s magnetosphere, the comet-tail-like geometry of the anti-sunward Earth magnetic field, the IMF, and the many boundaries associated with the interaction of the Earth’s magnetic field with the solar wind. \(^{1655}\)

Magnetic field measurements are essential to organize and understand energetic charged particle and plasma flows and to derive fundamental information about the environment surrounding different bodies in the solar system. Magnetic field measurements represent also one of the few remote-sensing tools used by spacecraft (gravity being the other) that provide information about the deep interior of of a planet rather than just its surface and/or atmosphere (dynamic processes in the core and mantle). Planetary magnetic fields like those of the Earth, Jupiter, and Saturn are generated by currents circulating their liquid metallic cores or perhaps the core-mantle interface. - Magnetic field measurements are being used in many Earth-orbiting spacecraft for engineering applications; these include attitude determination and control, spacecraft momentum management, and scientific instrument pointing. Earth’s magnetic frame provides a convenient “natural” frame of reference, which can be modeled with good accuracy and be used by onboard instruments to establish their orientation and by active control systems.

At the start of the 21st century, geomagnetic mapping missions are the most demanding in terms of absolute accuracy and resolution, approaching < 1 part in 100,000 in magnitude and a few arcsec in direction. - Magnetic instruments provide significant cost, simplicity, and reliability advantages over inertial-based sensor systems, whenever absolute angular measurement accuracies of 1-2° are acceptable. A common application of magnetometers


in LEO spacecraft is the control of electromagnets which, when energized, apply a torque to the spacecraft by interacting with the geomagnetic field. This technique is utilized either to desaturate momentum wheels or to re-orient the S/C along a desired direction. A more recent application of magnetometer data is in the field of “space weather” prediction and the quantitative assessment of solar-terrestrial events.

The Earth’s magnetic field at the surface near the equator has an approximate strength of 31,000 nT (nano-tesla) or 0.31 G (Gauss). In SI units, the magnetic induction is measured in tesla which corresponds to $10^4$ G (1 T = $10^4$ G = $10^9$ gamma, the latter two are alternate units to the SI unit of Tesla). The following examples illustrate the large dynamic ranges of magnetic field intensities encountered in the solar system: Solar magnetic fields associated with coronal loops and prominences can reach values as high as several thousand Gauss. The IMF at Earth’s orbit (at 1 AU) is typically in the order of 5-10 nT. At the orbit of Uranus and Neptune, the IMF is as low as 0.05 nT.

The design and implementation of magnetically “clean” spacecraft is a demanding task. Since it is practically impossible to reduce the stray S/C magnetic field for sensitive measurements, magnetometers are commonly boom-mounted. This technique exploits the fact that the magnetic fields produced by finite sources decrease rapidly with distance (proportional to $r^{-3}$ where $r$ is the distance to the source). Many missions use long, deployable booms which must be rigid (typically a truss-like boom) to preserve the alignment of the measurements. However, the high cost of deployable booms and their potential effects on spacecraft dynamics limit the affordable boom length. Hence, a so-called “dual magnetometer” technique was proposed and later introduced by Norman F. Ness et al. at NASA in 1971 to ease the problem of making sensitive magnetic field measurements in the presence of a significant S/C field. The method is based on the experimental observation that beyond a certain distance most spacecraft-generated magnetic fields decrease proportional to $r^{-3}$. Hence, when two magnetometers are used in parallel, mounted along a radial boom at distances $r_1$ and $r_2$ (of a moderately long boom), respectively, it is possible to separate the spacecraft-generated magnetic field from the external ambient magnetic field. A particular advantage of the dual magnetometer method is that it allows unambiguous real-time identification and monitoring of the time variation of the spacecraft-generated field. In addition, the use of two magnetometers provides full measurement redundancy. The Pioneer-10 and -11 spacecraft, launched in 1973 to explore Jupiter and Saturn, were able to achieve a residual static field of <0.01 nT with the principal magnetometer located at the end of a 3 m boom.

- Magnetometers measure the strength and direction of the magnetic field. There are two generic classes of instruments:
  - Scalar magnetometers capable of measuring the magnitude of the magnetic field
  - Vector magnetometers which measure the strength and direction of the magnetic field.

Both classes of instruments are being used in space. However, vector magnetometers are far more common due to their capability of providing directional information. This “heading” information is a very significant navigation parameter.

- A simple scalar magnetometer was devised by C. F. Gauss in 1832, consisting of a permanent bar magnet suspended horizontally by a gold fiber. Measuring the period of oscillation of the magnet in the Earth’s magnetic field gives a measure of the field’s strength.

- The fluxgate magnetometer, a vector-type device, is the most common type of magnetic instrument used in spacecraft. The technique was invented in the late 1920s and pub-

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lished in 1936 in Germany by H. Aschenbrenner and G. Goubau. 1657) 1658) This was followed by rapid developments during and after World War II when fluxgate systems were installed in aircraft to search for submarines, to aid in making navigation charts and for geophysical exploration. The fluxgate sensor, as the name implies, is a device used to “gate” the ambient magnetic flux threading a coil, converting it from a time stationary field into a time varying field. The latter gives rise to induced voltage in a sensing coil proportional to the strength and direction of the field. A variation of the same principle introduced by Aschenbrenner and Goubau uses a continuous ring core in place of the two inductors.

- Magnetometers are flown to measure the attitude of the S/C relative to the Earth’s magnetic field. 1659) As such, they are normally part of the onboard attitude system. Magnetometers, in particular triaxial fluxgate instruments, are also flown as a science instrument to measure the geomagnetic field. The first ring core fluxgate magnetometers used in space were in the Lunar Surface Magnetometer package left on the surface of the moon by the Aug. 10, 1992) of NASA astronauts of Apollo 16 in April 1972. Table 85 represents a chronology of fluxgate magnetometers flown as science instruments on various missions.

- Magnetic damping. In a satellite, magnetic damping can be realized with hysteresis rods (nickel-iron rods which are easily magnetized, even by the Earth’s weak magnetic field. Such rods, rotated in a magnetic field, dissipate a fixed amount of energy for every revolution). The concept was invented by R. E. Fischell of JHU/APL and first flown on Transit-5A-3 in 1963. Such a rod produces a constant retarding torque which opposes any rotation. Since this opposing torque remains constant, even for a small rotation, hysteresis damping is effective even at low angular velocities.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch</th>
<th>Instrument</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DODGE (DoD)</td>
<td>July 1, 1967</td>
<td>Triaxial magnetometer</td>
<td>S/C was operational for over 3 years</td>
</tr>
<tr>
<td>GEOS-2 (NASA))</td>
<td>Jan. 11, 1968</td>
<td>Uniaxial fluxgate</td>
<td></td>
</tr>
<tr>
<td>TRIAD-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIAD-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEO-2 (ESA)</td>
<td>Oct. 30, 1979</td>
<td>Scalar and vector magnetometers</td>
<td>MAGSAT employed a scissor boom of 6 m length</td>
</tr>
<tr>
<td>IRM (Germany)</td>
<td>Aug. 16, 1984 Aug. 16, 1984 Aug. 16, 1984</td>
<td>Triaxial magnetometer Triaxial magnetometer Triaxial magnetometer</td>
<td>AMPTE mission with 3 subsatellites</td>
</tr>
<tr>
<td>EXOS-D (ISAS)</td>
<td>Feb. 22, 1989</td>
<td>MFG (triaxial)</td>
<td>Akebono mission (Japan)</td>
</tr>
<tr>
<td>Magion-2 (Czech)</td>
<td>Sept. 28, 1989</td>
<td>SGR-7 (triaxial)</td>
<td>Magion is subsatellite of ACTIVE</td>
</tr>
<tr>
<td>Ulysses (ESA/NASA)</td>
<td>Oct. 6, 1990</td>
<td>FGM/VHM</td>
<td>Boom-mounted magnetometers</td>
</tr>
<tr>
<td>UARS (NASA)</td>
<td>Sept. 13, 1991</td>
<td>VMAG part of PEM</td>
<td></td>
</tr>
<tr>
<td>APEX (USSR)</td>
<td>Dec. 18, 1991</td>
<td>SGR-5 (triaxial) SGR-7 (triaxial)</td>
<td>Magion-3 is subsatellite of APEX</td>
</tr>
<tr>
<td>APEX (Czech)</td>
<td>Dec. 18, 1991</td>
<td>SGR-5 (triaxial) SGR-7 (triaxial)</td>
<td></td>
</tr>
<tr>
<td>FREJA (Sweden)</td>
<td>Oct. 6, 1992</td>
<td>F2 (triaxial)</td>
<td>Boom-mounted</td>
</tr>
<tr>
<td>WIND (NASA)</td>
<td>Nov. 1, 1994</td>
<td>MFI</td>
<td>Astro-mast boom of 12 m length</td>
</tr>
<tr>
<td>POLAR (NASA)</td>
<td>Feb. 24, 1996</td>
<td>MFE (triaxial)</td>
<td>Two instruments, 6 m boom</td>
</tr>
<tr>
<td>FAST (NASA)</td>
<td>Aug. 21, 1996</td>
<td>MFE (triaxial)</td>
<td></td>
</tr>
</tbody>
</table>

1659) http://wwwssc.igpp.ucla.edu/personnel/russell/ESS265/History.html
Table 85: Chronology of some fluxgate magnetometers flown on geomagnetic field missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch</th>
<th>Instrument</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE (NASA)</td>
<td>Aug. 25, 1997</td>
<td>Magnetic Field Monitor</td>
<td>Triaxial fluxgate</td>
</tr>
<tr>
<td>DMSP/F7 (DoD)</td>
<td>Dec. 18, 1983</td>
<td>SS (triaxial)</td>
<td>NASA instrument</td>
</tr>
<tr>
<td>DMSP/F12 (DoD)</td>
<td>Aug. 29, 1994</td>
<td>SS (triaxial)</td>
<td></td>
</tr>
<tr>
<td>DMSP/F13 (DoD)</td>
<td>Mar. 24, 1995</td>
<td>SS (triaxial)</td>
<td></td>
</tr>
<tr>
<td>DMSP/F15 (DoD)</td>
<td>Dec. 12, 1999</td>
<td>SS (triaxial)</td>
<td></td>
</tr>
<tr>
<td>Equator-S (MPI)</td>
<td>Dec. 2, 1997</td>
<td>MAM (triaxial)</td>
<td>Boom-mounted</td>
</tr>
<tr>
<td>ASTRID-2 (Sweden)</td>
<td>Dec. 10, 1998</td>
<td>EMMA</td>
<td></td>
</tr>
<tr>
<td>Ørsted (Denmark)</td>
<td>Feb. 23, 1999</td>
<td>Vector+ scalar magnetometer</td>
<td>Both instruments are boom-mounted. Precise mapping of the geomagnetic field.</td>
</tr>
<tr>
<td>SACI-1 (INPE)</td>
<td>Oct. 14, 1999</td>
<td>MAGNEX (triaxial)</td>
<td>Boom-mounted</td>
</tr>
<tr>
<td>OPAL (Stanford)</td>
<td>Jan. 27, 2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHAMP (GFZ)</td>
<td>July 15, 2000</td>
<td>MIAS (scalar+triaxial)</td>
<td>Boom-mounted package of OVM and FGM</td>
</tr>
<tr>
<td>Cluster-2 (ESA)</td>
<td>July 16, 2000</td>
<td>FGM</td>
<td>Boom-mounted (2) on all S/C. FGM measures the 3-D ambient magnetic field.</td>
</tr>
<tr>
<td>SAC-C (CONAE)</td>
<td>Nov. 21, 2000</td>
<td>Ørsted-2</td>
<td>Boom-mounted</td>
</tr>
<tr>
<td>FedSat (CSIRO)</td>
<td>Dec. 14, 2002</td>
<td>NewMag</td>
<td>Boom-mounted</td>
</tr>
</tbody>
</table>

- Magnetometers traditionally have been used on spacecraft for sensing of coarse attitudes (in the order of 1°) and for input to the momentum control logic (magnetic torquers). However, in combination with accurate calibration and the availability of accurate gyroscopic data, attitude accuracies of better than 0.1° can be obtained using only magnetometer data and rate data. This was done at GSFC with UARS data (launch of UARS, Sept. 13, 1991).

- A new magnetometer technology, referred to as SQUID (Superconducting Quantum Interference Device), offers significantly increased sensitivity over conventional magnetometers. A first spaceborne implementation of this technology is flown on the DoD ARGOS satellite (launch Feb. 23, 1999). The SQUID instrument is called HTSSE-II (High Temperature Superconducting Space Experiment II), designed and developed at NRL to demonstrate the performance of superconducting (semiconductors and RF) components at cryogenic temperatures of 70-80 K (see M.3).

- A SQUID magnetometer is also flown on Gravity Probe-B (launch April 20, 2004).

- While fluxgate magnetometers are expected to remain the mainstay of magnetometry, there have been considerable improvements in the field of magnetoresistance technology. New miniature magnetoresistive devices may eventually replace conventional fluxgate magnetometers. The advantages of magnetoresistive sensors include high sensitivity, wide bandwidth, large dynamic range and easy incorporation into payloads of many small networked spacecraft.

1.8.2.5 Star sensors

The stars in the sky have been used as guideposts throughout the long history of human navigation. By their very nature, all stars represent an inertial reference as well as an excellent point source (in comparison, the apparent sun disk angle as seen from Earth is on average about 32 arcmin). Hence, space navigation by stars is a very attractive solution for high-accuracy pointing applications. The determination of attitude of a spacecraft by triangulation of stars in an image is therefore a rather desirable input for an AOCS (Attitude and Orbit Control Subsystem). However, the very faint energy level of starlight in the presence of extraneous light sources and noise has provided considerable design challenges in the detection and tracking process of these minute references (stars) throughout the history of spaceflight.
Background: The first attempt to operate a star tracker\(^{1660}\) in the upper atmosphere was made in 1959 by JHU/APL in connection with a balloon-borne Venus experiment by the name of Stratolab High (demonstration of a planet-oriented fine pointing system). Later,\(^{1661}\) star trackers for extended operation periods in space were developed for such programs as Mariner, Surveyor (launches 1966-68 to the moon), Lunar Orbiter (launch of Lunar Orbiter-1 Aug. 10, 1966), OAO (Orbiting Astronomical Observatory) with OAO-1 launch April 8, 1966, Voyager (Voyager-1 launch Sept. 5, 1977), etc.

All these star tracker implementations employed the following basic principle: a) optics for energy collection of a target star, b) a scanning or mechanical modulation mechanism to focus the star light, c) a photodetector to detect the signal and to convert it into an electrical signal (information on star brightness and the angle of the star direction relative to the optical axis).\(^{1662}\) In the tracking systems on Mariner and Lunar Orbiter, electronic deflection served to null the track signal anywhere in the field of view (FOV). Surveyor, with its photomultiplier system, achieved null tracking by roll motion of the spacecraft. In the OAO star tracker, nulling was done with a photomultiplier by means of torque-driven gimbals. - The unique location of the bright star Canopus near the southern pole of the ecliptic plane (14º) has been used by many of these missions as the reference star.

Early attitude sensors in EO missions as well as in commercial communication missions (LEO, GEO) didn’t use the stars as reference due to a lack of sensitivity of early CCDs and APS detectors (first CCD detectors for imagery were only available starting with the 1970s and they were initially used in spaceflight for solar radiation applications, with an energy source several orders of magnitude larger than a star; first APS detectors showed up in the 1990s). Also, the period of early space flight didn’t enjoy today’s infrastructure of affordable microelectronics, storage capacity for star catalogs and extensive algorithms, to develop star sensors in the first place. While the early star sensors were only able to track a single star (mostly in an on-off support mode), modern star sensors (21st century) are capable to identify and track multiple stars of various brightness levels and to provide continuous highly-accurate pointing data to the AOCS of a spacecraft.

Star sensors/trackers are onboard cameras that scan areas in space and digitally record the position and brightness of stars. Using a sensed image of a portion of the sky, stars are located and identified. An onboard computer compares the images with star maps in memory to determine the spacecraft’s exact 3-D attitude. The second step (after identification) is to “track” (follow) the star(s) and to control the orientation of the platform (input information to onboard control subsystems to more precisely orient the satellite for maximum pointing accuracy). The term “star sensor” is used to refer generically to any sensor using star measurements to derive its output.

The first star sensors with CCD detector technology for improved attitude control were developed in the 1980s. Some early instruments are:

- The Giotto S/C of ESA (launch Mar. 14, 1986) carried “Star Mapper,” a solid-state star sensor of TNO/TPD (Delft), which relayed stellar coordinates to ESA/ESOC to enable the reconstitution of the S/C attitude during its interplanetary journey.
- All spacecraft in the IRS imaging satellites series of ISRO employ a star sensor as part of the attitude sensing devices in AOCS, starting with IRS-1A (launch March 17, 1988).
- ASTRO-1, developed by Jena-Optronik GmbH between 1984-1987 (as VEB Carl Zeiss Jena). The ASTRO-1 has been operating successfully aboard the Russian MIR station since 1989. ASTRO-1 consists of three optical heads each including a CCD-chip (520 x

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1660) A star tracker is basically a camera and pattern matching system that uses constellations and stars to determine the direction in which a satellite is pointing.

1661) Note: The Mariner-1 and -2 missions to Venus had launches July 22 and August 27, 1962; Mariner-3 and -4 missions to Mars with launches Nov. 5 and 28, 1964; there were a total of 10 Mariner mission, the last one was launched Nov. 3, 1973 to Venus and Mercury.

ASTRA (Advanced Star Tracker), developed in 1990 by Hughes Danbury Optical Systems, Inc., Danbury, CT (later Raytheon Optical Systems; now Goodrich Electro-Optical Systems), was flown on TOPEX/Poseidon (launch Aug. 10, 1992) of NASA and CNES. ASTRA uses a CCD detector with the processing capability of a 16-bit microprocessor, FOV = 8.8° x 9.6°. The T/P mission employs two units, ASTRA-1A and -1B, each has a mass of 2.6 kg. Tracking of a single star. ASTRA was furnished with a TEC (Thermoelectric Cooler) to maintain the CCD at -2°C. ASTRA has a pointing accuracy of 17 arcsec (1σ) @ 10 Hz. An ASTRA-1A failure occurred in April 1998 when the backup ASTRA-1B took over. 1663)

Some background on resolution history: As imagers, star sensors depend of course on the resolving power of their optical system. The unaided human eye is capable to see detail as fine as approximately 100 arcseconds. When Galileo turned his optical telescope toward the sky in 1609/1610, he was able to resolve features of about 10 arcseconds. This mere 10-fold increase in optical resolution allowed Galileo to see moons around Jupiter and craters on our own moon. The reflecting telescope of HST (Hubble Space Telescope), launched April 24, 1990, has a resolving power of about 0.1 arcseconds, representing a 100-fold improvement over Galileo’s telescope. The MUSES-B satellite of ISAS (Japan), launched Feb. 12, 1997 and renamed to HALCA (Highly Advanced Laboratory for Communications and Astronomy), employs SVLBI (Space Very Long Baseline Interferometry) techniques in combination with Japanese ground telescopes and other telescopes around the world (international project cooperation), achieving a maximum resolving power of about 90 microarcseconds with observations at microwave wavelengths. This is about 100 times better than that of the HST. The HALCA mission was retired in 2005. – At the start of the 21st century, NASA is in the process of defining a future mission called MAXIM (Micro-Arcsecond X-ray Imaging Mission). The goal is to achieve a resolving power of 1 microarcsecond – to be able to investigate eventually black holes! Again, interferometry (i.e., SVLBI technique) is the answer to achieve such extreme resolutions.

In the 1990s, more demanding pointing requirements resulted in the development of new star sensors for many missions. The minimum capabilities for an autonomous star tracker are: a) autonomous attitude determination (lost-in-space solution) and autonomously recognizes the inertial orientation of its boresight axis, and b) autonomous attitude tracking, all to a prescribed reference system. Today, star trackers are a key attitude-measuring component in most new attitude control systems. Some examples of advanced star sensor systems are:

- ASC (Advanced Stellar Compass), a pioneering star tracker developed by DTU (Technical University of Denmark) at Lyngby, and flown on the Danish satellite Ørsted (launch Feb. 23, 1999, see E.18) with an attitude precision of a few arcseconds. Redundant ASCs are also flown on the SAC-C mission of CONAE (launch Nov. 21, 2000). In addition, the CHAMP mission of GFZ/DLR is flying ASC (launch July 15, 2000, see E.1) as well as GRACE (launch Mar. 17, 2002), CONTOUR (launch July 3, 2002), ADEOS-2 (launch Dec. 14, 2002), SMART-1 (launch Sept. 27, 2003), and GOCE (launch 2007). ASC (Advanced Stellar Compass) of DTU and PASS (Payload Autonomous Star Sensor), the latter developed and built in collaboration by Sira Electro-Optics Ltd and MMS (UK), are both flown on ESA's PROBA (launch Oct. 22, 2001, see M.30) mission. PASS has a wide FOV (19.3° x 14.4°) and about 3 arcseconds of pointing accuracy in pitch and yaw. First flights of the ASC series instruments were on TEAMSAT (launch Oct. 30, 1997) and on ASTRID-2 (launch Dec. 10, 1998). ASC is flying on all these missions in slightly varying configurations; the full

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autonomy support of the ASC includes, among other things such functions as: fast solving of the lost-in-space problem, outlier rejection, performance tuning, SEL/SEU (Single Event Latch-up/Single Event Upset) detection, and recovery.  

As of 2002/3, a μASC (Micro Advanced Stellar Compass) is under development at DTU whose performance parameters are given in Table 86 alongside with those of ASC. There are additional features of μASC such as:

- The μASC consists of a fully hot/cold redundant μDPU (micro Data Processing Unit) that drives up to four CHU (Camera Head Units).  
- Improved radiation tolerance [in particular to radiation environment increases such as SAA (South Atlantic Anomaly)] for longer life times  
- The μASC has a considerable amount of computing power that can be used to support other applications or devices that can be triggered or implemented depending on the mission (external devices may be sun sensors, magnetometers, etc.)  
- DSN (Deep Space Navigation) module. Enabled by telecommand, this function computes the instantaneous heliocentric inertial position of the S/C relying solely on the knowledge of the Julian date and the observed right ascension and declination of at least one planet. The accuracy of this attitude determination is sufficient to autonomously point the high gain antenna toward Earth from anywhere in the solar system, should the ground link be lost for any reason.  
- IVM (Inertial Velocity Measurement). The μASC is also the first and only instrument capable of determining autonomously and instantaneously the inertial velocity of the S/C (measurements available for earthbound and Deep Space missions)  
- TDI (Time Delay Integration) at user control. The main advantages of this application are: 1) to increase the accuracy of the attitude determination at high speed; 2) to improve the maximum rate at which the attitude can reliably be measured; and 3) to have a better accuracy in the tracking of faint objects.  

- AST (Autonomous Star Tracker) of the DoD/NRO STEX (Space Technology Experiment, P59) satellite (launch Oct. 3, 1998), developed by LMMS (Lockheed Martin Missile & Space Company). AST provides attitude information to an accuracy of 0.005º. AST is also flown on the following missions: DS1 of NASA (launch Jul. 29, 1999); SRTM (Shuttle Radar Topography Mission of NASA, launch Feb. 11-22, 2000); IMAGE of NASA (launch Mar. 25, 2000), EO-1 of NASA (launch Nov. 21, 2000); TIMED of NASA (launch Dec. 7, 2001), and WMAP (Wilkinson Microwave Anisotropy Probe of NASA/GSFC with a launch June 30, 2001). AST identifies up to 50 stars in the field-of-view and then computes and outputs the satellite attitude. - Following attitude acquisition, AST returns to its track mode, where it provides three-axis attitude and rate at a customer-selectable frequency up to 5 Hz. The AST comprises athermalized, radiation-hardened refractive optics, a frame-transfer CCD, camera electronics, a compact single board computer with a 32-bit RISC processor, and an all-sky guide star database.  

- The attitude control and navigation system of DLR’s BIRD mission 1666) (launch Oct. 22, 2001) employs redundant ASTRO-5 star sensors (plus a three-axis gyro + sun sensors, etc.). Each ASTRO-5 has a mass of 1.5 kg. The two star sensors have different lines of sight for measurement of the attitude with a high precision in all axes. The BIRD mission is the first spaceborne realization of the ASTRO-5 star sensor of Jena-Optronik.

- ASTRO-15 is a new-generation autonomous CCD star sensor of Jena-Optronik GmbH (Jena, Germany) with a FOV of 13.8º x 13.8º, up to 8 stars per frame can be recog-

nized. It is providing a LOS pointing accuracy of \( \leq 1 \) arcsec in pitch/yaw and \( \leq 10 \) arcsec in roll (1 \( \sigma \)). The ASTRO-15 system may be used a) as autonomous star sensor (with its own processor for attitude determination), or b) as a star tracker (only sensor head, no processor). A first application of ASTRO-15 is realized on a classified communications mission of the USAF, namely DSCS-III-A3 (Defense Satellite Communications System), a LM (Lockheed Martin) built satellite series with a launch March 11, 2003. As of 2004, ASTRO-15 became the standard star sensor flown on the BSS 702 platform. 1667)

- **PASS** (Payload Autonomous Star Tracker), developed by Sira Electro-Optics and EADS Astrium Ltd., UK, is being flown on ESA's PROBA mission (launch Oct. 22, 2001). PASS is of AST (Autonomous Star Tracker) heritage flown on XMM-Newton (launch Dec. 10, 1999) of ESA. PASS has a mass of 2.4 kg and a FOV of 19º x 14º with pointing accuracies of a few arcseconds at 5 Hz update rate. Other features: a) PASS uses a miniature optical head with a radiation-hardened lens and a CCD qualified for space missions, radiatively cooled; b) radiation tolerant DSP-based processor system; c) patented EADS Astrium/Quine algorithms with an efficient star pattern matching against the onboard star catalogue leading to a low processor load. The commercial name of PASS is AST20 (Autonomous Star Tracker).

<table>
<thead>
<tr>
<th>Star Tracker Class</th>
<th>Requirement</th>
<th>ASC</th>
<th>( \mu )ASC (dual redundant, *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial acquisition (solve lost-in-space problem)</td>
<td>&lt; 1 minute</td>
<td>300 ms</td>
<td>80 ms</td>
</tr>
<tr>
<td>Pointing accuracy (EOL)</td>
<td>30 arcsec (3 ( \sigma ))</td>
<td>3 arcsec (3 ( \sigma ))</td>
<td>2 arcsec (3 ( \sigma ))</td>
</tr>
<tr>
<td>Attitude rate</td>
<td>Up to 1º/s</td>
<td>Up to 7º/s</td>
<td>Up to 20º/s</td>
</tr>
<tr>
<td>Update rate</td>
<td>Up to 4 Hz</td>
<td>Up to 4 Hz</td>
<td>Up to 32 Hz</td>
</tr>
<tr>
<td>Operational availability</td>
<td>99.9%</td>
<td>99.995%</td>
<td>99.995%</td>
</tr>
<tr>
<td>Instrument mass, power</td>
<td>&lt; 2 kg, &lt;10 W</td>
<td>1 kg, 7.8 W</td>
<td>0.425 kg (*), 1.9 W</td>
</tr>
<tr>
<td>Instrument size</td>
<td>10x10x10 cm, proc. unit 5x5x5 cm, camera head</td>
<td>DPU:10x10x10 cm CHU: 5x5x5 cm</td>
<td>( \mu )DPU: 10x10x4.5 cm (*) ( \mu )CHU: 5x5x5 cm (up to 4)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>3-5 years</td>
<td>11 years</td>
<td>30+ years</td>
</tr>
<tr>
<td>Reliability</td>
<td>99.995%</td>
<td>99.95%</td>
<td>99.999%</td>
</tr>
</tbody>
</table>

Table 86: Typical performance requirements for autonomous star trackers

- **CALTRACR** is a wide-angle star tracker system developed by EMS Technologies Inc. Ottawa, Canada. The sensor employs CCD imaging technology (tracking of up to 8 optical samples/s of the portion of the sky in view and calculation of the quaternion) for autonomous attitude determination; a pointing accuracy of \( < \pm 0.005^\circ \) in pitch & yaw and \( < \pm 0.01^\circ \) in roll is provided. The engineering model was space-qualified on STS-101 (May 19-29, 2000) and on STS-106 (Sept. 8-20, 2000). CALTRAC is being also being flown on NASA's Genesis mission (launch Aug. 8, 2001) and on Jason-1 of NASA/CNES (launch Dec. 7, 2001), as well as on other missions.

- **MAST** (Micro APS-based Star Tracker) of NASA/JPL. 1668) The MAST concept uses advanced CMOS/APS imaging technology with a low-mass and low-power instrument design, consisting of only two chips, one is used to image the stars and an ASIC chip. MAST has an attitude accuracy of 7.5 arcseconds, an APS of 1024 x 1024 pixels, the instrument mass is 42 gram, and the total radiation dose is 30 krad. The first fabrication of the APS chip at the end of 2002. The following features are provided:
  - Wide FOV (Field of View) of 20º x 20º
  - The imaging detector is a single chip device that incorporates the imaging array, timing and control, programming registers, 10 bit A/D converter and operates

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from a single power supply. The instrument power consumption is 69 mW in tracking mode.

- The APS tracks multiple windows simultaneously (up to 8 with programmable window size). This capability greatly simplifies the interface, enabling system miniaturization.
- A single ASIC chip includes all star tracker functions. The ASIC contains an I²C interface, fast logic for initial centroid acquisition, 8051 microcontroller, memory
- MAST outputs only the raw pixel data in predefined small windows. The spacecraft computer includes the star catalog, does the initial attitude acquisition and calculates the attitude quaternion.

Generally, star sensors in the time-frame 1997-2000 are designed to image only a portion of the sky and report the location of any stars that are tracked. Among other factors, the accuracy of these devices is historically limited by three design parameters: 1) A small FOV in the order of 8° x 8°, 2) The capability to track 5 stars simultaneously, and 3) A CCD detector array with a 512 pixel square imaging area. These choices have led to a limiting measurement accuracy of about 5 arcseconds per star and per frame.

UniNav (Universal Navigator). UniNav is a complete, integrated attitude sensing package developed by EADS Astrium Ltd. and partners, UK (the UniNav design is of PASS heritage flown on PROBA). It comprises a miniaturized autonomous star sensor based on APS (Active Pixel Sensor) technology and three MEMS rate gyro. The software, situated in its own optional miniaturized processor or in the spacecraft avionics system, uses the patented Quine star recognition algorithm and Kalman filter data fusion of star and rate measurements to produce a nine element state vector that is highly reliable across a wide dynamic range. 1669) 1670) - The overall objective is to provide generalized AOCS (Attitude Orbit Control System) functions, ranging from launch vehicle separation through coarse or fine pointing to anomaly (lost-in-space) recovery, as a single-sensor solution. UniNav can be used as the primary attitude sensing system for mini- and microsatellites or as a highly capable, but cost-effective, fault detection and correction system for large spacecraft. The demonstration model is based on a commercial lens, providing a FOV of 20° x 20° with a STAT-250 APS. UniNav was completed and tested in 2003. The instrument has a mass of 0.5 kg, power consumption of 3 W average and 9 W max, size = 140mm x 70mm x 70mm, interface = SpaceWire (IEEE 1355), accurate 3-axis measurement of rate range: up to ±25°/s. The UK mission EarthSHINE (Earth Sun-Heliosphere INteractions Experiment – a launch expected in 2009 to L1) uses the UniNav package.

### 1.8.2.6 Advanced actuators -CMG (Control Moment Gyroscope)

A CMG represents a new actuator class for an agile attitude control system — consisting of a spinning rotor and one or more motorized gimbals that tilt the rotor’s angular momentum. As the rotor tilts, the changing angular momentum causes a gyroscopic torque that rotates the spacecraft. CMGs are inertial actuators capable of generating a very high torque, in particular with respect to conventional reaction wheel or momentum wheel performance characteristics (which provide typical torques in the range 0.01 Nm to a few Nm). CMGs convert electrical power into angular momentum (a gimbal motor controls the spin, while a wheel motor controls the rate of wheel rotation). 1671)

1669) UniNav is part of the UK AMSTAP (Aerospace Microsystems Technology Applications Partnership) initiative (started in 2000), a team comprising EADS Astrium Ltd., University of Cranfield and Sira Electro-Optics, with the support of BNSC (British National Space Center), are developing the concept of an attitude sensor that exploits MST (Micro System Technology) gyro and the rapidly evolving star tracking technology.
1670) Information provided by David J. Purll of Sira Electro-Optics, Chislehurst, UK
Since electric power is a renewable energy source on a spacecraft, this makes CMGs an attractive alternative to propulsive control on long-duration missions. CMGs are momentum exchange/storage devices (a recoverable energy source), offering gyroscopic stability inherent in flywheels to control attitude; hence, they represent an attractive actuator solution for an AOCS (Attitude Orbit Control System) of a spacecraft. CMG devices provide generally an actuator/sensor function, i.e. a control/measurement combination. A CMG is an actuator consisting of a wheel spinning at constant speed (flywheel), mounted on one, two or a four-gimbal assembly, providing one-degree, two-degree, or three-degree of freedom attitude control, respectively. Note: The use of a flywheel is to store energy. Conceptually, a flywheel is a “mechanical battery” providing the potential to combine the energy-storage and the attitude-control functions into a single device.

**Principle of operation:** A CMG attitude control systems use flywheels mounted in gimbal frames that can be rotated about the gimbal axis. The spin rate is held constant relative to the gimbal frame, and the gimbal axis is perpendicular to the spin axis. The attitude control is effected by changing the gimbal angles to absorb external torques or to produce a large-angle rotational maneuver. Two types of CMGs have been used: single-gimbal CMGs and double-gimbal CMGs. The double-gimbal variety may experience gimbal lock.

When a torque is applied about the input axis of a CMG, the angular momentum vector of the wheel precesses in order to align itself with the input torque. This causes a change in the CMG’s momentum vector. Since the total angular momentum vector of the spacecraft is conserved, the entire spacecraft then rotates in such a way as to maintain the total angular momentum at a constant value. – A CMG or gyrotorquer is used in the opposite sense of a rate gyro. A commanded displacement of the gimbal output axis, with a resultant change in the angular momentum vector, causes a control torque to be applied to the spacecraft at the gyro input axis.

CMGs can generate large torques up to 5000 Nm normal to the rotor axis and to the gimbal rotation axis. The efficiency of the CMG system is greatly improved over the reaction wheel system since the rotor operates at a constant speed for which the efficiency can be optimized. A Single Gimbal CMG (SGCMG) is an actuator (flywheel and motor) with a constant speed momentum wheel, gimbaled in one axis only. For full three-axis control of a spacecraft, a cluster of four CMGs is normally used. Conventional designs including four or more CMGs do not suppress singularities, but there is then an infinity of paths of the precession angles (i.e. tilting angles) which generate the required kinetic or dynamic moment, and this redundancy is used to avoid singular configurations.

**CMG history in space:** Fairly large CMG designs have already some history in spaceflight, the first application of CMGs was mainly momentum management onboard large space structures, all of them space stations (Skylab, MIR, ISS).

- Three CMGs (each with a rotor diameter of 53 cm, and a mass of 65.5 kg) were installed on NASA’s Skylab to provide attitude control for the ATM (Apollo Telescope Mount) Solar Observatory of the US Skylab (launch May 14, 1973) during solar observations. The instrument had to be pointed within 2.5 arcseconds of the desired direction and held there with-

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out drifting more than 2.5 arcseconds in 15 minutes’ time. Each CMG was a double-gimbal-
mounted unit, electrically driven with a nominal spin of 9,100 rpm, and capable of providing
an angular momentum of 315 Nm·s. This CMG system maintained the Skylab orientation to
within 3 arcmin. An order of magnitude more stable pointing was needed for the Solar Ob-
servatory. This was accomplished with a solar pointing control system (PCS). Since me-
chanical constraints limited the travel of the CMG gimbals, saturation was experienced.
This required desaturation (momentum dumping) of the gyroscopes using the thrusters of
the attitude control system. 1678) 1679) 1680)

- The CMG concept of gyro-stabilization has also been employed on the Russian MIR
station, referred to as ROS (Gyrodyne Flywheel Orientation System). The Kvant 1/2 mod-
ules each carried six gyrodyne CMGs (launch of Kvant-1 module on March 30, 1987; launch
of Kant-2 module on Nov. 26, 1989). They were being used to provide attitude stabilization
for MIR (provision of 10 arcsec orientation during astronomical observations). A gyrodyne
replacement was installed on the MIR complex on Shuttle flight STS-76 (Atlantis, March
22–31, 1996) to MIR.

- Four CMGs were installed on ISS (International Space Station) as the primary attitude
control system, along with an RCS (Reaction Control System) for CMG desaturation with
RCS [STS-92 flight of Discovery (Oct. 11–24, 2000, ISS-05-3A flight) provided: ITS (In-
tegrated Truss Structure) Z1 and the CMGs which were attached to the Z1 truss]. Their objec-
tive is to keep the ISS (International Space Station) complex oriented. The four CMGs op-
erate as momentum storage devices that exchange momentum with the ISS through in-
duced gyroscopic torques created by a motor-driven constant-speed momentum wheel
mounted in two orthogonal gimbals. Both gimbals have torque motors and position resolv-
ers mounted on the rotational axis and move by use of a gear train system. The momentum
wheel is mounted inside the inner gimbal and is supported by bearings on both sides of the
spin axis. Each CMG has a diameter of 1.22 m, a mass of 227 kg, a nominal spin rate of 6,600
rpm, and is capable of producing a torque of up to 257 Nm. Each CMG consists of a large
flat wheel that develops an angular momentum of 485 Nm·s (newton meter second) about its
spin axis. 1681) The total momentum storage capacity of the CMG cluster is about 1,900
Nm·s. The gimbal rotational velocity is 0.2°/s (average) and 3.1°/s (max). Each rotating
wheel is mounted in a two-degree-of-freedom gimbal system that can point the spin axis
(momentum vector) of the wheel in any direction. Only the operation of two CMGs is need-
ed to keep the ISS stabilized. The CMGs are also needed for momentum desaturation, in
particular during robotic payload operations. One of the stabilizing CMGs (CMG-1) suf-
f ered a failure on June 8, 2002 (a replacement of CMG-1 occurred on flight STS-114, July
26–Aug. 9, 2005).

Note: Initial attitude control of ISS was provided by the Zarya (or FGB) module of Rosko-
mos, until the CMGs of NASA were attached with the Z1 truss assembly, and activated
during the 5A flight (STS-98 flight of Atlantis, Feb. 7–20, 2001).

Operation of the ISS CMG system: 1682)
- The flywheels spin at constant speed of 6,600 rpm
- The onboard control software uses the actual angular position and momentum data to
calculate the torque needed to rotate the station in the desired direction
- Electric motors apply a torque to the gimbals, speeding up or slowing down their rota-

1678) http://wwwsolar.nrl.navy.mil/skylab_atm.html
1680) http://history.nasa.gov/SP-4208/ch9.htm#170
1681) R. R. Burt, “International Space Station Control Moment Gyro Failure,” Proceedings of the 26th AAS Confer-
ence on Guidance and Control, Breckenridge, CO, Feb. 5–9, 2003, Vol. 113 Advances in the Astronautical Sciences,
Edited by I. J. Gravseth and R. D. Culp, AAS 03-072, pp. 543–556
1682) http://www.eng.auburn.edu/users/voss/aero4740/Do%20not%20remove%20---%20lecture%20%20imbed-
ed%20info/267,11,Operation
- If the flywheel axis aligns with the axis about which the station rotates, it is unable to apply a useful torque. This is referred to as gimbal lock.
- If the torque required to rotate the station to a desired position is more than the CMGs can supply, then the system is said to be saturated and the station thrusters must be used to rotate the station. In general, a CMG saturation may occur during orbiter rendezvous and docking periods.

**New-generation small-scale CMG technology development.** Agility considerably increases the operational envelope and efficiency of spacecraft and substantially increases the return potential of observational data. In the time frame 1996-97, an ESA-funded study at EADS Astrium SAS (formerly MMS, France) provided a first proof that a small CMG with a few Nms (newton meter second) of angular momentum could fulfill the pointing needs of a number of future EO missions based on small platforms (simple and cost-effective CMG designs based on conventional components). A design breakthrough was achieved in 1998 when a singularity-free steering method was defined. This ensured singularity-free maneuvers within the complete capacity envelope of the CMG cluster.

The algorithms developed make it possible to operate with only three CMGs in case of a reduced cluster (failure case or nominal case for some missions), making the concept particularly attractive for reliability aspects. Once the feasibility of an agile normal mode was demonstrated in 1999, the operations during the other phases were analyzed. Then the fine-pointing performance during imaging sequences was assessed, in coordination with micro-vibration analyses. The other ACMS (Attitude Control and Measurement Subsystem) modes were redefined for CMG-based attitude control; in particular, the orbit control and safe-hold modes of new LEO platforms was adapted to CMGs. In the time frame 2001-02, the new CMG technology was considered a mature enough solution to be chosen as the baseline for the new-generation Pleiades imaging satellite series of CNES. The new CMG design is patented by EADS Astrium SAS.

At the start of the 21st century, the new small CMG technology (small mass, small volume, and small power requirements as well as new control algorithms and advances in bearings and lubricants) is just beginning to be used for demanding attitude control applications in small spacecraft (the angular momentum range of 5-20 Nms is of particular interest). These CMGs rely on the gyroscopic effect to produce large output torques. In particular, the potential of spacecraft agility considerably increases the operational envelope and efficiency of the observation process (larger field of regard) and substantially increases the return of Earth and science data. Agile scenarios in Earth observation include multi-strip mosaics or dense successions of images, with combined roll (cross-track coverage), pitch (along-track motion) and yaw (image strips orientation) maneuvers.

Some examples of **small-scale CMG implementations** with spacecraft body-pointing capabilities are:

- **GyroWheel™** is a CMG development of Bristol Aerospace Ltd of Winnipeg, Manitoba, Canada (a subsidiary of Magellan Aerospace Corporation). GyroWheel is being flown on SciSat-1/ACE mission of CSA (launch Aug. 13, 2003) as an actuator/sensor demonstration experiment. The design is based on a spinning flex-gimbal system as opposed to the

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1686) Note: In a body-pointing configuration the imaging instrument has a coaligned orientation with regard to the S/C. Hence, the entire system is tilted into a particular line-of-sight to image a target region.
conventional non-spinning motor-driven gimbals. This innovation allows for maintaining the same three-axis momentum steering capability as a CMG. 1687) 1688)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument mass</td>
<td>5.5 kg @ 4 Nms torque 6.75 kg @ 16 Nms</td>
<td>Instrument power</td>
<td>15.5 W @ 1500 rpm 101 W @ 6000 rpm</td>
</tr>
<tr>
<td>Min reaction torque</td>
<td>76 mN (at 1200 rpm) 122 mN (at 0º tilt)</td>
<td>Command &amp; data I/F</td>
<td>Serial RS-422, or MIL-STD-155B &gt; 10 years</td>
</tr>
<tr>
<td>Gyro bias stability</td>
<td>&lt; 1º/hr</td>
<td>Speed range</td>
<td>1200-6000 rpm</td>
</tr>
<tr>
<td>Max rotor tilt angle</td>
<td>±7º</td>
<td>Onboard processing</td>
<td>16 MIPS total</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>100 krad (Si) total dose</td>
<td>Input voltage</td>
<td>28±6 V</td>
</tr>
<tr>
<td>Instrument size</td>
<td>23.5 cm dia x 13.5 cm</td>
<td>Static balance</td>
<td>&lt; 1 gm-cm</td>
</tr>
</tbody>
</table>

Table 87: Characteristics of the GyroWheel

- The BilSat-1 microsatellite of TUBITAK-BILTEN, Turkey, part of SSTL’s (Surrey, UK) DMC (Disaster Monitoring Constellation) mission, features an experimental CMG system with a total mass of 1.17 kg including all electronics (power = 1.7-6.5 W, output torque = 52.5 mNm, average slew rate of 3º/s). The three-axis control mode provides the satellite the ability to slew about any defined axis of nominally up to ±40º permitting observation capabilities within a wide FOR (Field of Regard), even wider slews are possible. The body-pointing feature and slewing capability enables also stereoscopic imaging as well as target tracking within the operational scenario of BilSat-1. The CMGs are placed in a 2-CMG parallel arrangement where the gimbal axes are perpendicular to the x-y plane and are parallel to each other. A launch of BilSat-1, along with NigeriaSat-1 and UK-DMC, took place Sept. 27, 2003. 1689) 1690) 1691) 1692) 1693) 1694)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument mass</td>
<td>2.2 kg</td>
<td>Instrument size</td>
<td>135 mm x 155 x 190</td>
</tr>
<tr>
<td>Power (max)</td>
<td>12 W</td>
<td>Torque</td>
<td>95 mNm</td>
</tr>
<tr>
<td>Angular momentum</td>
<td>0.28 Nms</td>
<td>Gilbal rate</td>
<td>9º/s</td>
</tr>
</tbody>
</table>

Table 88: General performance characteristics of SSTL CMG system design

- The Pleiades satellite series of CNES (first launch in 2009, S/C mass of 940 kg) 1695) features a CMG cluster design system, developed by EADS Astrium SAS (with CNES support), on a LEOSTAR platform in support of spacecraft pointing agility (slew rate support),

and the use of FOGs (Fiber Optic Gyroscope) for high-accuracy attitude measurements.

The CMG system is being used in support of very demanding maneuvering requirements: rapid slewing (i.e. body pointing of the S/C within ±60°). A cluster of four CMG actuators is being used, positioned in a pyramid configuration. The system is referred to as CMG 15-45S (15 Nms, 45 Nm, standard); it delivers a torque up to 45 Nm with a wheel of 15 Nms (angular momentum), sufficient to point a satellite in the 1000 kg class at more than 3°/s of slew rate within < 2 s; the compact architecture can be used for satellites from 1000 kg down to mini- and microsatellites. For Pleiades program applications, the requirements call for CMG fatigue failure modes in excess of 1.8 x 10^6 cycles under an average output torque of 19 Nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output torque</td>
<td>45 Nm</td>
<td>CMG mass; volume</td>
<td>15 kg; diameter = 270 mm, height = 350 mm</td>
</tr>
<tr>
<td>Angular momentum</td>
<td>15 Nms</td>
<td>Stiffness</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Data bus interface</td>
<td>MIL-STD-1553 (or RS-422)</td>
<td>Electronics mass (1 box for 4 CMGs)</td>
<td>1.7 kg per channel</td>
</tr>
<tr>
<td>Power use per CMG</td>
<td>23 W at max speed</td>
<td>Electronics volume (1 box for 4 CMGs)</td>
<td>270 mm x 200 mm x 160 mm</td>
</tr>
</tbody>
</table>

Table 89: Characteristics of the CMG 15-45S (for S/C in the 1000 kg class)

- DigitalGlobe of Longmont, CO is planning to fly its next-generation commercial high-resolution imaging satellite, WorldView-1 (launch in 2007), with CMG actuator technology (of Honeywell Defense & Space Electronic Systems, Phoenix, AZ) for precise and highly responsive pointing control and considerably increased spacecraft agility (slew maneuver support). WorldView-1 will be the successor to QuickBird-2. The Honeywell M–50 CMG capitalizes on the wide range and experience of Honeywell on large CMGs that have flown on a number of military related missions. The M50 CMG has an angular momentum range of 25-75 Nms, an output torque of 0.075-75 Nm, power of 11-95 W, rotor speeds of 4500-6500 rpm, and a mass of 28 kg.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>µCMG (SSTL)</th>
<th>15–45S (Astrium)</th>
<th>M–50 (Honeywell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (Nms)</td>
<td>0.28</td>
<td>15</td>
<td>75</td>
</tr>
<tr>
<td>Torque, peak (Nm)</td>
<td>0.074</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>2.2</td>
<td>16.7</td>
<td>28</td>
</tr>
<tr>
<td>Power (Q/P, W)</td>
<td>8.5, 12</td>
<td>25, 92 (4)</td>
<td>35, 95</td>
</tr>
<tr>
<td>Rotor speed (rpm)</td>
<td>20,000</td>
<td>&lt; 6,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Design life (year)</td>
<td>–</td>
<td>–</td>
<td>&gt; 7</td>
</tr>
<tr>
<td>Rotation (degrees)</td>
<td>180</td>
<td>360</td>
<td>360</td>
</tr>
</tbody>
</table>

Table 90: Comparison of some small CMG systems

- Coupled energy storage and attitude control capability in flywheels. NASA/GRC is developing the IPACS (Integrated Power and Attitude Control System) concept (and a long-term program), combining existing reaction wheel technology with flywheel energy storage con-
cepts (CMGs) to combine attitude control and electrical power components (i.e. the function of onboard storage batteries).

The use of flywheels instead of batteries to store energy on spacecraft was suggested as early as 1961 in a paper by J. B. Roes. Power tracking for charging and discharging the wheels is added to complete the IPACS functional framework. An IPACS must perform two functions - attitude control and power tracking - simultaneously. It must provide commanded torques for attitude control and generate power, accumulate energy, and store energy. A flywheel produces or absorbs power by changing its wheel speed. Attitude control torques are produced by changes in the net angular momentum vector. - The torques applied by the energy/momentum wheels (CMGs) are decomposed into two spaces that are orthogonal to each other, with the attitude-control torques and power-tracking torques in each space. - Future NASA missions like GEC (Geospace Electrodynamic Connections) and many others (NPOESS series) are planning on this technology. Some examples of IPACS demonstrations are: (1702) (1703) (1704) (1705) (1706) (1707) (1708) (1709)

- An IPACS laboratory demonstration unit, called COMET (Coordinated Momentum and Energy Transfer), is being developed at Lockheed Martin with NASA/GRC funding.
- The objective of the NASA FESS (Flywheel Energy Storage System) project is to develop a prototype flywheel battery system for possible use as replacements for the ISS electro-chemical batteries.
- The FACETS (Flywheel Attitude Control Energy Transmission and Storage) program of AFRL was initiated with Honeywell Engines, Systems & Services Division, Tempe, AZ.

1.8.2.7 Spacecraft/platform and instrument pointing

- Spacecraft/platform and instrument pointing is an important aspect of navigation (see also same heading in Appendix A). The ability to locate a sensor measurement with the required accuracy on the Earth’s surface (or to point at a faint celestial body from an orbiting platform) has made great strides in four decades of spaceflight. (1710) (1711)

Precision pointing is also a function of platform stability through suitable attitude sensing and control mechanisms. Early spacecraft had pointing accuracies of about ±1° which is in the same order of magnitude as spacecraft with gravity-gradient boom stabilization in the 1990s. Three-axis stabilized spacecraft, such as the NOAA/POES series (starting with TIROS-N) and the early SPOT series (SPOT-1, -2, -3) offer pointing accuracies of 0.1°. IPS (Instrument Pointing System) of ESA (built by Dornier, Friedrichshafen), first flown on

1703) http://space-power.grc.nasa.gov/pp/projects/flywheel/techdet.html
1710) http://www.esrin.esa.int/htdocs/esa/progs/mg.html
1711) http://liftoff.msfc.nasa.gov/Shuttle/Astro2/description/ips/ips.html
Shuttle flight STS-51-F as Spacelab-2 in July/Aug. 1985, then on STS-35 as Astro-1 (Dec. 2-10, 1990), and again on STS-67 as Astro-2 (March 2-18, 1995), is providing a pointing stability within ±1.2 arcseconds for all sensors on the platform (see J.7).

- The imaging sensor OSA (Optical Sensor Assembly) on Ikonos-2 (launch Sept. 24, 1999) is providing an absolute ground location accuracy of 12 m (without the use of ground control points), the relative accuracy is 2 m. The imagery of such a sensor may certainly be used for cartographic applications (see Table 813).

- The HST (Hubble Space Telescope) is the most precisely pointed instrument in space-borne astronomy. The pointing requirements call for a continuous 24 hour target lock maintenance of 0.007 arcseconds (2 millionth degree).

- High-accuracy pointing for intersatellite links is needed for a number of acquisition applications, in particular for the support optical free-space communication (optical terminals at end points). The technology involves: a) the acquisition of signals, b) the tracking of the signal sources, and c) the pointing of transmitters and receivers; all functions require high speed and high-accuracy pointing support (without the ability to return a beam along the line-of-sight towards the companion terminal, communications cannot take place). Conventional ATP (Acquisition, Tracking & Pointing) systems generally employ large angle tracking and scan capability with fine-tracking mode and acquisition step stability. The SILEX (Semiconductor Intersatellite Link Experiment) design of ESA, with a LEO terminal on SPOT-4 and a GEO terminal on ARTEMIS, required pointing errors of < 10 μrad (or < 0.0005º). This pointing accuracy is several orders of magnitude smaller (better) than open-loop pointing of a typical platform. 1712)

- A separate class of pointing accuracy, namely < 1 milliarcsecond (arcsec), is required of Gravity Probe-B (Relativity Mission, launch April 20, 2004), a spin-stabilized spacecraft. This is four orders of magnitude higher than IPS or close to six orders of magnitude higher than normal three-axis stabilized spacecraft. The GP-B spacecraft contains two star trackers to perform the “spotting function” for the telescope - one wide FOV (Field of View) and one narrow FOV (called the star sensor). The wide FOV star tracker is used to locate the general region of the heavens containing the guide star, and then the narrow FOV star tracker helps align the space vehicle with the guide star (< 20 marsec). – The onboard telescope basically performs the same function as the star trackers, but it uses a different technique, and it is orders of magnitude more precise and more accurate. The narrow FOV star tracker has a field of view on the order of 1º (60 arcminutes), and it can focus to a position within perhaps one arcminute - about the same as the entire FOV of the onboard telescope, which can pinpoint the guide star’s position to within a milliarcsecond (in fact 0.1 marsec).

- The ARGOS mission of DoD (launch Feb. 23, 1999) is flying an instrument by the name of USA (Unconventional Stellar Aspect) also referred to as NRL-801 experiment. USA conducts feasibility tests of X-ray satellite navigation and new computational approaches to autonomous parameter estimation that includes GPS inputs and a variety of redundant truth measures. There are reasons why X-ray navigation might prove to be attractive in the future. The advantages are associated mainly with drawbacks of optical methods or with potential advantages of X-ray characteristics that have no exact analogs in the optical wavelengths (M.3).

- Hexapod and CPD (Coarse Pointing Device) systems of ISS (International Space Station), developed and provided by ESA. - One of the many ISS services is the accommodation of scientific/technological payloads and observing instruments on a standard carrier, the ExPS (Express Pallet System), located on the Integrated Truss Assembly. Up to six pay-

loadsites can be grouped on one Pallet by means of ExPA (Express Pallet Adapter). Depending on the location of the ExPA (nadir and zenith facing), both Earth and universe observations are possible. However, accurate instrument pointing requires a pointing system if mounted on the Pallet directly. This is due to several disturbance effects such as orbital motion, orbital plane precession, seasonal sun apparent motion, and ISS deviation from nominal attitude resulting from gravity and drag forces. 1713)

1) Hexapod is a Steward platform for small range accurate pointing based on a six-degree-of-freedom concept. The objective is to support such instruments as SAGE-III of NASA/LaRC (see L.2.13). Hexapod pointing requirements call for a pointing accuracy of ±90 arcseconds, a pointing stability of 0.0025º/s, a pointing range of ±8º, and a pointing rate of 1.2º/s.

2) The CPD is a two-axes cardinae platform for coarse pointing and larger rotational capabilities; it is devoted to accommodate sun pointing instruments and radiation and biology experiments requiring sun pointing. CPD is a tracking system, the objective is to compensate the ISS attitude variation. CPD supports the payloads: a) Expose Payload a multi-user facility accommodating photo-processing, photo-biology and exo-biology experiments. b) SIA (Sun Instrument Assembly) for the study of solar irradiance. CPD pointing requirements call for a pointing accuracy of ±1.0º, a pointing stability of 0.3º, a pointing range of ±40º, and a pointing rate of 4º/min.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Instrument</th>
<th>Mission</th>
<th>Pointing accuracy (angular resolution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star tracker (based on CCD detectors)</td>
<td>ASC (Advanced Stellar Compass)</td>
<td>Ørsted (launch Feb 23, 1999)</td>
<td>3-4 arcsec</td>
</tr>
<tr>
<td></td>
<td>ASC + PASS (Payload Autonomous Star Sensor)</td>
<td>PROBA (launch Oct. 22, 2001)</td>
<td>3-4 arcsec (ASC) 3-4 arcsec (PASS)</td>
</tr>
<tr>
<td></td>
<td>AST (Autonomous Star Tracker), built at LMMS</td>
<td>EO-1, (launch Nov. 21, 2000) TIMED (launch Dec. 7, 2001) WMAP (launch Jun. 30, 2001)</td>
<td>0.005º</td>
</tr>
<tr>
<td></td>
<td>CALTRAC (of EMS Technologies)</td>
<td>Genesis (launch Aug. 8, 2001) Jason-1 (launch Dec. 7, 2001)</td>
<td>&lt;±0.005º in pitch &amp; yaw, &lt;±0.01º in roll</td>
</tr>
<tr>
<td>Star tracker (APS detectors)</td>
<td>ISC (Inertial Stellar Compass), Draper Lab</td>
<td>TacSat-2 of DoD (launch Dec. 16, 2006)</td>
<td>0.1º (1 σ) in each axis</td>
</tr>
<tr>
<td></td>
<td>MAST (Micro APS-based Star Tracker), JPL</td>
<td></td>
<td>7.5 arcsec</td>
</tr>
<tr>
<td>VLBI</td>
<td>VLBI system (Earth-based system)</td>
<td>HALCA (Highly Advanced Laboratory for Communications and Astronomy), launch Feb. 12, 1997</td>
<td>0.1-0.2 arcsec (milli-arcsecond level)</td>
</tr>
<tr>
<td>SVLBI (Space-Very Long Baseline Interferometry)</td>
<td>SVLBI system (first mission of its kind)</td>
<td>ARISE (Advanced Radio Interferometry between Space and Earth), launch in 2005</td>
<td>10-20 µarcsec</td>
</tr>
<tr>
<td></td>
<td>SVLBI system</td>
<td>JWST (James Webb Space Telescope) launch 2013 to L2</td>
<td>(milli-arcsecond level)</td>
</tr>
</tbody>
</table>

Table 91: Comparison of some instrument/system pointing accuracies

- DMC (Dynamic Motion Compensation). The GOES-N spacecraft of NOAA (launch May 24, 2006) carries a newly developed AOCS instrument, SIAD (Stellar Inertial Attitude Determination), designed by BSS (see F.4.4). SIAD provides a real-time dynamic compensation environment of S/C jitters to an accuracy of 10 μrad, 3 σ. This technology is referred to as DMC (Dynamic Motion Compensation), permitting a high precision “virtual platform” for scanning observations of imaging instruments flown in GEO.

• Very high pointing requirements and platform stability constraints are in particular needed for the GOES-R next-generation satellites series of NOAA with an initial launch planned for 2014. The current plan of GOES-R calls for the support of three Earth-scanning instruments, namely ABI (Advanced Baseline Imager) and two HES (Hyperspectral Environmental Suite) imagers. The HES instruments will perform full Disk Soundings (DS) and Coastal Water (CW) imaging. The spacecraft disturbance sources include reaction wheels, solar array tracking, and the Earth-scanning instruments themselves. The optical performance requirements of these Earth-scanning instruments drive their instrument line of sight (LOS) stability requirements.\(^{1714}\)

• “SmartScan” is an intelligent imaging correction technique under development at ESA solving the problem of image correction for satellite pushbroom cameras which are disturbed by satellite attitude instability effects [satellite cameras with linear sensors are particularly sensitive to attitude errors, which cause considerable image distortions].\(^{1715}\) The SmartScan concept uses in-situ measurements of the image motion with additional CCD sensors in the focal plane and real-time image processing of these measurements by an on-board Joint Transform Optical Correlator. The system has been successfully demonstrated by laboratory tests and by an airborne flight demonstration in July 2002 (Do-228 aircraft of DLR). The errors of the image motion record (corresponding to the residual image distortions after correction) were generally within \(\leq 0.25\) pixels (1 sigma). The application of the SmartScan system allows high quality imaging with a pushbroom image sensor from satellites with only moderate attitude stability, including satellites, which are not specially designed for imaging missions.\(^{1716}\)\(^{1717}\)


1.8.3 Tracking Techniques

The term “tracking” has many meanings and connotations in the context of navigation. In general, it refers to:

- The process of measuring position (range, angles, round-trip signal time) by following a moving object.
- Orbit determination: using the measured data determining and predicting its position and velocity over time (real-time by a GPS receiver). Unlike conventional land-based tracking techniques, onboard GPS tracking methods are not limited by the time that a spacecraft is in the line-of-sight of a tracking station. GPS tracking also has the advantage that it provides measurements throughout any orbital arc and requires additional reference data from only relatively inexpensive terrestrial GPS receivers. Finally, the three dimensional nature of GPS measurements allows for superior 3-D positioning. An onboard GPS receiver can thus provide a real-time orbit solution.
- The ability of measuring/determining relative position between several objects in orbit (this may for instance be used for rendezvous monitoring using a range finder in form of a laser range finder and a vision sensor)\(^{1718}\)
- The function or ability of “pointing” an instrument, an antenna (following a ground station while transmitting data), an array of instruments (possibly in various orbits), a spacecraft, a beam -- in the prescribed direction with varying degrees of required pointing accuracy and speed.
- The parameter of acceleration (range rate) plays also an important role next to position and velocity of an object, in particular in geodetic applications (gravity) involving drag-free orbits.
- Onboard attitude sensing is also a tracking function (of horizon sensors, sun sensors, star trackers, magnetometers, etc.), finding attitude by triangulation against known references.
- Event monitoring, either by an onboard instrument (searching its imagery for particular events), or of an onboard DCS (Data Collection System) searching the ground segment for possible data-transmission contacts, represents also a tracking function in a wider sense. This applies also to S&RSAT (Search and Rescue Satellite Aided Tracking) by tracking emergency beacons like PLB (Personal Locator Beam).
- ATP (Acquisition, Tracking & Pointing) system in support of optical intersatellite communications.
- etc.

Over the years, a multitude of tracking techniques and concepts have been developed; often several techniques are being used in parallel (onboard, on-ground, from other sources, continuously, intermittently, in real-time, offline, in combination with attitude, absolute or relative positioning, etc.), depending on the requirements of orbital accuracy. The time (epoch) is the fundamental parameter to all measurements.\(^{1719}\)

Tracking measurements (data) may originate from such measurement sources/devices as: Doppler, onboard GPS receiver (at the start of the 21st century, onboard GPS receivers have advanced to such a state, where they are considered the primary tracking source for orbit determination of many LEO missions), ground-based SLR (Satellite Laser Ranging); SST (Satellite-to-Satellite) microwave tracking; altimetry, radio tracking systems such as: PRARE (Precise Range And Range-rate Equipment), and DORIS (Determination Orbitte Radiopositionnement Integres Satellite); radio tracking by interferometry such as VLBI (Very Long Baseline Interferometry), and SVLBI (Space VLBI); etc. - Modern satellites

\(^{1718}\)Note: A laser range finder is a device that measures the distance to a target, but the beam orientation is fixed. This is different from a laser radar, where the orientation of the beam can be changed (navigation and guidance device). Laser range finders have been demonstrated on a number of missions. The Apollo-15 mission in 1971 was probably the first to use a range finder.

\(^{1719}\)Note: By convention, the epoch in use today is called J2000.0, which refers to the mean equator and equinox of year 2000, nominally January 1st 12:00 hours Universal Time (UT). The “J” means Julian year, which is 365.25 days long.
that require precise positioning are equipped with several independent tracking devices. Starting from the 1970s, most satellite tracking techniques improved by several orders of magnitude, both in terms of quality (measurement precision and accuracy) and quantity (number and rapid availability of data, and spatial and temporal coverage). 1720)

Note: The field of “tracking” is so large that its theme is spread over virtually all chapters of navigation and not just dealt with under “tracking techniques.”

The two-way support of the communication function requires the satellite to carry a simple transceiver (i.e., a dedicated transmitter and receiver). In order to also accomplish the tracking function, the satellite must carry a transponder which, in addition to providing two-way communications, also returns the tracking antenna’s transmitted ranging signal, thus, permitting the quick determination of the distance between the ground antenna and the spacecraft.

Ground-based navigation is with us from the very beginning of the space age. The conventional tracking methods are “ranging,” “Doppler velocity,” and “angle-only” (when no transponder is onboard) determination along the line of sight. 1721) Ranging (radial distance) is derived form transit time, namely the round-trip light time of ranging signals from the spacecraft transponder, while the ground antenna pointing direction provides angular information. More precise angle measuring methods are those of “differenced Doppler” and VLBI. The Doppler shift is a measure of object velocity. A two-way coherent transmission mode permits the measurement of the induced Doppler shift to within 1 Hz, since the uplink frequency is known with great precision. The Doppler shift is directly proportional to the radial component of the spacecraft’s velocity. - The measurement accuracy is dependent on the frequency band selected. Conventional ranging and Doppler measurement capabilities are in the microwave region, such as S-band with typical accuracies in the order of about 0.5 m. Satellite laser ranging (SLR) techniques between a ground-based laser station and a satellite use the much shorter wavelengths of visible light, resulting in a single-shot precision of <2 cm.

1.8.3.1 Doppler tracking techniques

The Doppler shift is the phenomenon of how an object’s relative motion changes the apparent frequency of its radiation source. The Austrian physicist Christian Doppler (1803-1853) first described it in 1842, in relation to stars. By definition, the Doppler shift denotes the difference between the frequency of the radiation received at a point and the frequency of the radiation at its source, when observer and source are moving with respect to each other. The concept of Doppler tracking (one-way or two-way) employs the Doppler shift (Doppler ranging) to determine the orbit (angular information is provided by the antenna direction). Doppler tracking is a well established tracking technique.

- Background: The concept of Doppler tracking is to determine a satellite’s orbit and the inverse problem of locating transmitters on Earth using satellites. 1722) 1723) Soon after the launch of Sputnik-1 (Oct. 4, 1957), JHU/APL (Johns Hopkins University/Applied Physics Laboratory) researchers W. H. Guier and G. C. Weiffenbach discovered that they could determine a satellite’s orbit solely from RF Doppler shift measurements made on a single pass over their laboratory. Their technique was based on the following premises: if one knew the geodetic position from which the signal was recorded, and made certain assump-

1721) Note: In the very early period of space flight, the technique of optical tracking was employed by the use of the Baker-Nunn camera.
1723) Note: The very concept of being able to compute a location on Earth by observing the change in frequency of a spaceborne transmitter during a single pass was initially ridiculed by a number of reputable scientists.
tions about the Earth’s mass, the Doppler shift could be used to derive the characteristics of the satellite’s orbit — and permitting to calculate the satellite’s Keplerian elements.

The Doppler technique is to observe the effect of a transmitter and a receiver in motion. This is a relative velocity measurement. In satellite geodesy, the Doppler effect is only observed with radio techniques (taking into account the dry and wet tropospheric signal delay). The DORIS system of CNES is based on Doppler measurements. The DORIS configuration consists of about 40 Doppler beacons in the ground segment and a receiver on a LEO satellite (space segment).

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launch Date</th>
<th>Innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sputnik-1</td>
<td>Oct. 4, 1957</td>
<td>Satellite Doppler tracking</td>
</tr>
<tr>
<td>Transit-1A</td>
<td>Sept. 17, 1959</td>
<td>Yo-Yo spin/despin mechanism</td>
</tr>
<tr>
<td>Transit-1B</td>
<td>Apr. 13, 1960</td>
<td>Dual-frequency Doppler tracking for correcting ionospheric error First attitude-controlled S/C using permanent magnets First solar attitude detectors</td>
</tr>
<tr>
<td>Transit-2A</td>
<td>June 22, 1960</td>
<td>First dual-payload launch (Transit-2A and Solrad-1 of NRL) and first piggyback separation, demonstrated before on Transit-1B</td>
</tr>
<tr>
<td>Transit-3B</td>
<td>Feb. 21, 1961</td>
<td>First satellite electronic memory in space (384 bit of magnetic core register - required to store its own orbit ephemeris)</td>
</tr>
<tr>
<td>Transit-4A</td>
<td>June 29, 1961</td>
<td>First nuclear power generator tested in a spacecraft (RTG)</td>
</tr>
<tr>
<td>TRAAC</td>
<td>Nov. 15, 1961</td>
<td>Damping of satellite vibration by lossy spring-and-mass technique. (TRAAC = Transit Research And Attitude Control) satellite</td>
</tr>
<tr>
<td>ANNA-1B</td>
<td>Oct. 31, 1962</td>
<td>First geodetic satellite (ANNA = Army Navy, NASA, Air Force) which also flew the first gallium arsenide cell in space.</td>
</tr>
<tr>
<td>Transit-5A-1</td>
<td>Dec. 19, 1962</td>
<td>First uplink authentication system</td>
</tr>
<tr>
<td>Transit-5A-3</td>
<td>June 16, 1963</td>
<td>First successful gravity-gradient stabilization (plus spring-and-mass damping) to maintain Earth pointing for one side of the S/C - Automatic temperature S/C control</td>
</tr>
<tr>
<td>Transit-5C-1</td>
<td>June 4, 1964</td>
<td>Demonstration that hysteresis rods, used previously for damping magnetic stabilization, were also effective for gravity-gradient stabilization</td>
</tr>
<tr>
<td>DME-A</td>
<td>Nov. 29, 1965</td>
<td>Magnetic spin/despin system (DME = Direct Measurement Explorer)</td>
</tr>
<tr>
<td>SAS-1</td>
<td>Dec. 12, 1970</td>
<td>Dual-spin control of satellite pointing (Small Astronomy Explorer-1)</td>
</tr>
<tr>
<td>Triad</td>
<td>Sept. 2, 1972</td>
<td>First satellite compensated for drag and radiation pressure. The drag-free concept was realized with DISCOS (Disturbance Compensation Device). First demonstration of single-frequency refraction-free satellite navigation using pseudonoise modulation.</td>
</tr>
<tr>
<td>DODGE</td>
<td>July 1, 1967</td>
<td>First yaw stabilization of a satellite using a ‘pitch axis wheel’ [constant-speed ‘momentum wheel’] DODGE = DoD Gravity Experiment, M.8</td>
</tr>
<tr>
<td>GEOS-3</td>
<td>April 9, 1975</td>
<td>Demonstration of first satellite-to-satellite tracking. By closed-loop tracking with a S-band transponder, the position of GEOS-3 was measured relative to that of ATS-6 of known position.</td>
</tr>
<tr>
<td>TIP-II</td>
<td>Oct. 12, 1975</td>
<td>Crystal oscillator as onboard timing system with all drift removed by a programmable synthesizer. TIP = Transit Improvement Program</td>
</tr>
<tr>
<td>SeaSat SAR downlink</td>
<td>Jun. 27, 1978</td>
<td>Quadrifilar helix antenna with beam shaping to compensate for slant range</td>
</tr>
<tr>
<td>Magsat</td>
<td>Oct 30, 1979</td>
<td>First attitude and command systems using microprocessors</td>
</tr>
<tr>
<td>Landsat-4</td>
<td>Jul. 16, 1982</td>
<td>GPSPAC (see 1.12.5) the first spaceborne GPS receiver in history</td>
</tr>
<tr>
<td>GEOSAT-A</td>
<td>Mar. 12, 1985</td>
<td>Bifilar helix antenna</td>
</tr>
<tr>
<td>MSX</td>
<td>April 24, 1996</td>
<td>First spaceborne hyperspectral imager, UVISI (Ultraviolet/Visible Imaging and Spectrographic Imaging)</td>
</tr>
</tbody>
</table>

Table 92: Some technology innovations introduced by JHU/APL

In early 1958, F. T. McClure of JHU/APL inverted the problem: if the position of the satellite were accurately known, then Doppler data could tell an observer on the ground his unknown position. (Note: the inverse problem became later known as the “navigation prob-

lem”). The implications of this discovery were enormous. It opened the world, particularly the world’s oceans, to electronic positioning. This realization led eventually to the conceptual design of the first satellite Doppler navigation system, namely “Transit” for the US Navy (H.6, and I.1.12.2). Other names of Transit were NAVSAT and NNSS (Navy Navigation Satellite System). The accuracy of the positioning was critically dependent on the accuracy of the determination of the satellites’ positions. 1726)

All satellites that transmit continuously on stable frequencies can be used for Doppler measurements. When the Doppler principle is to be used for orbit analysis, i.e. for the establishment of a precise global navigation system with real-time capability, the satellite system must meet at least the following requirements:

- Global distribution of satellite orbits, and
- Real-time transfer of information about satellite position and time to users.

- S/C tracking techniques, tracking system behavior and geodetic studies were the objective of three dedicated NASA missions, namely GEOS-1 (launch Nov. 6, 1965, E.6.1), GEOS-2 (launch Jan. 11, 1968) and GEOS-3 (launch April 9, 1975). Doppler instruments onboard and on-ground were employed for systematic range and range-rate measurements. Doppler shift measurements of a spaceborne Doppler instrument were also used to establish the structure of the Earth’s gravity field to a fairly good accuracy.

Note: In the early space age, the SECOR (Sequential Collation of Ranges) technique was developed particularly for geodetic applications (two-way ranging). One of the first SECOR transponders was flown on the US satellite ANNA-1B (launch Oct. 31, 1962). A total of 16 satellites with SECOR transponders were launched in the period 1964-1979, among them GEOS-1 and GEOS-2. The basic idea of SECOR tracking is forming a group of 4 ground stations and one satellite. Three of the four ground stations were considered to be at known positions while the fourth one had to be “located” using the method of triangulation.

- Noncoherent Doppler in-flight tracking. Noncoherent Doppler tracking has been devised as a means to achieve highly accurate, two-way Doppler measurements with a simple, transceiver-based communications system. This technique has been flown as an experiment on NASA’s TIMED spacecraft (launch Dec. 7, 2001, see A.31), as the operational technique for Doppler tracking on CONTOUR, and is baselined on several future deep space missions at JHU/APL. The JHU/APL-developed technique obviates the need for coherency between the uplink’s carrier tracking oscillator and the downlink carrier. In this technique, the uplink carrier signal is received and compared with the receiver’s onboard reference oscillator. This operation results in a set of phase comparison counts, placed in the telemetry and transmitted to the ground. The challenge to making Doppler velocity measurements with a transceiver is that the downlink carrier frequency is determined solely by the onboard frequency reference. The bias and drift of the reference oscillator frequency will obscure the Doppler velocity if no provision is made to remove their effects. 1727)

- Australia’s FedSat (launch Dec. 14, 2002) Ka-band Earth station for the downlink of the onboard DCS (Data Collection System) data (see M.13), is regarded the world’s first implementation of the Doppler principle as a Ka-band tracking technique with a single dish, located at the UTS (University of Technology Sydney), Kuringai Campus. The tracking technique is called FAST (Frequency Assisted Spatial Tracking). 1728) 1729) The FAST concept states that assuming the orbit is known, then the Doppler and Doppler rate are sufficient to specify the satellite position. The derived position can then be fused with other

spatial data and used to track the satellite. Fairly stable microsatellite pointing accuracies are required for this type of tracking technique. The Ka-band system is mainly used as a demonstration and research tool (properties of low-power Ka-band signals on small satellites, etc.). In the meantime, a second Ka-band station was set up at the University of South Australia in Adelaide for FedSat tracking/research.

1.8.3.2 Satellite-to-satellite tracking technique (SST)

SST is an indirect gravity field mapping technique, using satellites as test masses to measure the effect of gravity through the precise monitoring of the motion of the satellites. The concept is based on tracking the “relative motion” between two satellites (high-low measurement concept based on the GPS constellation and a spacecraft in LEO). SST is employed in particular in geodetic applications (gravity missions) to obtain highly accurate orbits for LEO satellites, and from these, by applying orbit perturbation analysis, the structure of the Earth’s gravity field. The lack of sufficient coverage in ground station tracking capability requires such measures. SST was demonstrated for the first time ever in 1968, mapping the near side gravity field of the moon (with Earth being considered a satellite of the moon). With regard to the Earth’s gravity field, SST was first demonstrated between GEOS-3 (in LEO) and ATS-6 (Applied Technology Satellite), a geostationary S/C of NASA in April 1975 (closed-loop tracking with a S-band transponder, the position of GEOS-3 was measured relative to that of ATS-6 of known position). However, few results were obtained due to the relatively high altitude of the lower satellite (E.7.3, GEOS-3 perigee of 818 km, apogee of 858 km). \[1730\] \[1731\] \[1732\] \[1733\]

Later in 1975, there were SST measurements between the Apollo-18 S/C (launch of Apollo-18 ASTP on July 15, 1975) in LEO and ATS-6. A further SST demonstration was conducted between the GPS constellation (in MEO) and the TOPEX/Poseidon altimeter satellite in LEO (the GPS receiver (6 channels, two frequencies, code and phase) aboard TOPEX/Poseidon is providing GPS-SST data since Dec. 1992; there exits an almost continuous data set for 1993. In addition to the GPS receiver, TOPEX/Poseidon was tracked with TDRS (Tracking Data Relay Satellite), DORIS (onboard the S/C) and SLR (Satellite Laser Ranging). Comparison of the tracking information from the four sources has demonstrated a satellite position determination capability in the <5 cm range. This level of accuracy is achieved through post-pass processing of the GPS data obtained from the satellite’s GPS receiver. Unfortunately, the artificial anti-spoofing GPS signal degradation switched on again in 1994/5, permitted only occasional GPS observations, not advantageous for routine precise orbit determination]. The contribution of TOPEX/Poseidon GPS-SST data to existing gravity-field models were not very significant, due to the relative high altitude of the TOPEX/Poseidon (1334 km) orbit. But whenever anti-spoofing-off periods were available, then GPS observations provided an orbit restitution with centimeter-level accuracy, an essential requirement for the quality of an altimeter mission.

Note: \[1734\] SST methods for applications in gravity field recovery favor low-altitude orbits (referred to as low-low SST or SST-LI), in which two orbiters flying close-proximity circular trajectories, perform relative velocity or range measurements of high accuracy, at the lowest possible altitude (in the co-orbiting satellite approach, the basic observed quantity can be a distance or a Doppler frequency shift, or both). - The other viable approach (at the end of the 1990s) is continuous onboard GPS position measurements with high-quality receiv-

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1733) Information provided by P. Schwintzer of GFZ Potsdam
1734) http://www.estec.esa.nl/vrwww/explorer/GRAVITY.html#introduction
ers, providing a second and independent satellite-to-satellite tracking method, in combination with low-low SST-hl. The global long-wave gravity field recovery by GPS is based primarily on the combined carrier-phase measurement onboard the LEO S/C, and a network of ground receivers which allow the recovery of the GPS trajectories. High-low GPS SST-hl is also applied for onboard navigation purposes.


- The SST technique is extensively being employed on the dual-minisatellite GRACE mission (launch March 17, 2002, see E.13) separated about 200 km in a near-polar, near-coplanar orbits. This involves continuous ranging measurements between the two spacecraft. Variations in the gravity field cause the range between the two satellites to vary. The objective is to obtain long-term data with unprecedented accuracy for global (high-resolution) models of the mean and the time-variable components of the Earth’s gravity field. In fact, GRACE software products provide monthly estimates of the time-varying gravity field, which are largely due to the redistribution of water mass in the Earth system, with a spatial resolution of ~ 500 km and an accuracy of 1 cm equivalent water.

- The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission of ESA (launch 2007, see E.11) is a combined SGG (Satellite Gravity Gradiometry) and SST (Satellite-to-Satellite Tracking) mission using SSTI (Satellite-to-Satellite Tracking Instrument). The objective is to provide the SST-hl (Satellite-to-Satellite Tracking - high/low) contribution to the gravity field recovery, by the simultaneous tracking of up to 12 GNSS signals. In addition, SSTI provides data for precise orbit determination; it is also used for real-time on-board navigation and attitude-reference-frame determination.

1.8.3.3 VLBI (Very Long Baseline Interferometry) and SVLBI (Space VLBI)

VLBI is an Earth-based geometric observation technique, originally pioneered and introduced in the field of radio astronomy, measuring simultaneously the time difference between the arrival of radio signals, emitted from a distant source (such as quasars), at two or more widely-separated antennas (up to an Earth diameter) of the global radio-astronomy network. The electronic linkage of a network of radio telescopes creates in effect a virtual interferometer array geometry, permitting the simultaneous view of the same target from widely-separated locations on Earth, where all antennas in the network form an effective synthetic aperture (a sparse synthetic aperture of enormous size, as large as the largest separation of the individual antennas, all of known positions). Obviously, such a powerful measurement technique is capable to observe astrophysical objects in better detail (sensitivity) and with a much greater angular resolution than any other astronomical technique. However, Earth-based VLBI is limited by the physical dimensions of Earth. 1735) 1736) 1737)

While VLBI was originally conceived to produce ultra-high resolution images of those distant radio objects, the technique was extended in the late 1960s to make also ultra-high precision geodetic (triangulation) and geodynamic measurements. VLBI is unique in its ability to define an inertial reference frame and to measure the Earth’s orientation in this frame. Since the antennas of the global radio astronomy network are fixed to the Earth, their locations track the instantaneous orientation of the Earth in the inertial reference frame. Relative changes in the antenna locations (the measurement precision at the centimeter level) from a series of measurements indicate tectonic plate motion, regional deformation, and local uplift or subsidence. Hence, VLBI has also become an effective tool for geodetic observations.

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1735) Note: Radio astronomy refers to the spectral range of microwaves, generally considered to be in the wavelength range from 1 mm to 1 m (<300 GHz frequencies < 300 MHz)
1737) http://lupus.gsfc.nasa.gov/brochure/bintro.html
VLBI applications are based on international cooperation. The current average accuracy of quasar positions observed by VLBI radiosystems is about 0.1-0.2 milliarcseconds (1 milliarcsecond = 0.00000028º or 2.8º x 10^-7). In comparison, a single large optical telescope achieves average star position accuracies of about 10 milliarcseconds.

Deep space tracking of S/C with VLBI: The VLBI technique, also referred to as the ∆DOR (delta-Differential One-way Ranging) or ∆VLBI, is also available for space navigation (location of an interplanetary or deep space probe) thanks to pioneering work by NASA/JPL. In these applications, the ground antennas at two different locations on Earth record sequentially the signal from a spacecraft and a nearby extragalactic radio source of known celestial coordinates (generally a quasar) to produce two different time delays. The time delay of the quasar signal is used for clock synchronization at the two ground tracking stations. What matters for orbit determination is the difference between the spacecraft and quasar delays, hence the name ∆VLBI or ∆DOR for this type of observables. The ∆DOR techniques provides very accurate plane-of-sky measurements of spacecraft position which complement existing line-of-sight ranging and Doppler measurements. 1738)

Until the early 1990s interplanetary navigation relied almost exclusively upon range and range rate measurements exploiting two-way, coherent radio links at S-band or X-band. These radiometric observables were routinely generated at ground stations equipped with suitable electronics and highly stable frequency standards (such as hydrogen masers). Single dish observations are operationally simple, but unfortunately do not provide an immediate determination of the angular position of interplanetary probes (the angle observables obtained from conical scanning are so poor to be useless for the navigational needs of current interplanetary missions). 1739)

Following is some historic background on VLBI introduction:

- In 1957, two large steerable dishes at Owens Valley Radio Observatory (OVRO is a Caltech facility) near Big Pine, CA, were linked together to form a microwave interferometer. 1740)
- In 1964, Cambridge University (Cambridge, UK) demonstrated the operation of the “One Mile Array.” 1741) This system introduced a new technique called “aperture synthesis” which processed data from each element in the system and constructed an image as if it had been made by a single telescope.
- In the late 1970s, the Very Large Array (VLA), an aperture synthesis array, was built by the National Radio Astronomy Observatory (NRAO) near Socorro, New Mexico (USA) in a Y-shape consisting of 27 antennas. The data collected from all antennas combined in VLA was comparable to the resolving power of a single antenna of 36 km in diameter. The US VLBI Consortium was formed in 1981.
- In 1980, EVN (European VLBI Network) was formed by five European institutions: MPIfR (Max Planck Institut für Radioastronomie), Bonn, Germany; IRA (Istituto di Radio Astronomia), Bologna, Italy; ASTRON, Dwingeloo, The Netherlands; OSO (Onsala Space Observatory), Onsala, Sweden; and the Merlin/VLBI National Facility at the University of Manchester, UK. EVN is administered by the European Consortium for VLBI. As of 2000, it includes a total of 14 major institutes, including JIVE (Joint Institute for VLBI in Europe). The EVN is a collaboration of the major Radio Astronomical Institutes in Eu-

1741) Note: The technique of “mosaicking”, or aperture-synthesis interferometry, combines images of different parts of the sky (generated by each telescope of an array) to produce a large field of view, in effect, simulating one large telescope from an array.
rope, Asia and South Africa and performs high angular resolution observations of cosmic radio sources.

- In 1985, the VLBA (Very Long Baseline Array) initiative\(^{1742}\) was started by NRAO and the Haystack Observatory of MIT, Cambridge, MA. VLBA consists of a system of 10 radio telescopes from Hawaii to the Virgin Islands, controlled from Socorro, New Mexico (VLBA was dedicated in 1993). In May 1997, VLBA and VLA made combined observations with the HALCA spacecraft of ISAS in an SVLBI configuration.

- Geodetic VLBI observations provided the first direct confirmation of tectonic plate motion at the end of the 1980's [CDP (Crustal Dynamics Project) of NASA/GSFC which lasted until 1991]. At the start of the 21st century, VLBI observations measure the motions with an accuracy less than 1 mm/year jointly with other space geodetic techniques such as GPS and SLR [international cooperation within a SGP (Space Geodesy Program)].

- In Sept. 2004, European and US astronomers linked up their radio telescopes for the first time in real-time, through the Internet, thereby creating the world's biggest virtual radio telescope by merging observations from instruments in the UK, Sweden, the Netherlands, Poland, and Puerto Rico.\(^{1743}\) The virtual instrument had a maximum separation of the antennas of 8200 km, giving a resolution of at least 20 milliarcseconds (mas); this is about 5 times better than the Hubble Space Telescope (HST). Note: HST provides resolutions of about 0.1 arcsec. – In the past, the VLBI technique was severely hampered because the data had to be recorded onto tape and then shipped to a central processing facility for analysis. The solution, to link the telescopes electronically in real-time, enables astronomers to analyze the data as it happens. The technique, referred to e-VLBI, is only possible now that high-bandwidth network connectivity is a reality. The emerging technology of e-VLBI is set to revolutionize radio astronomy. As network bandwidths increase, so too will the sensitivity of e-VLBI arrays, allowing clearer views of the furthest and faintest regions of space.

- In the spring of 2006, ESA completed the implementation of its ΔDOR (delta-Differential One-way Ranging) deep space ground station network in New Norcia (Australia) and Cebreros (Spain). The new capability provides tracking services for such deep space missions as Rosetta, Mars Express, Venus Express and SMART--1.

- **SVLBI (Space Very Long Baseline Interferometry)** is an extension of the VLBI concept by linking a spaceborne radio telescope with an array of Earth-based telescopes. Such configurations increase the effective synthetic aperture generally by an order of magnitude as compared to purely VLBI observations. A number of scenarios are possible such as: a) spaceborne telescope in LEO or GEO with a corresponding Earth VLBI segment; b) a purely spaceborne configuration of two or more satellites, each equipped with a telescope, in widely-spaced orbits; c) a spaceborne configuration with one satellite at L1 or L2, another one in GEO, as well as a corresponding Earth VLBI segment; d) etc. The following items give a short overview of initial SVLBI activities.

- The first ever SVLBI (Space Very Long Baseline Interferometry) technical feasibility experiments were carried out on Aug. 2, 1986 by Levy et al. Use of the TDRSE (TDRS-1) 4.9 m antenna as a spaceborne radio telescope (in GEO) operating at 2.3 GHz for the observation of three quasars.\(^{1744}\) 1745) In the setup, the received signals were transmitted over an analog data link to a Mark 3 terminal at White Sands, NM. Baselines from TDRSE to Earth-based 64 m telescopes at Tidbinbilla (a NASA DSN station, built in 1964), Australia, and at Usuda (25 m telescope of ISAS), Japan, ranged up to 17,800 km, about 1.4 earth

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1743) http://www.universetoday.com/am/publish/radio_telescopes_around_world_realtime.html?8102004


diameters. A total of four successful 800 second scans were obtained in that session. After the event, the data from all three antennas were successfully cross-correlated.

- ISAS (Institute for Space and Astronomical Science) of the University of Tokyo, Japan, launched the MUSES-B satellite on Feb. 12, 1997 which was renamed to HALCA (Highly Advanced Laboratory for Communications and Astronomy) after launch. The HALCA spacecraft carries a telescope for SVLBI observations. Elliptical orbit: apogee of 21,400 km, perigee of 560 km, 31º inclination and a period of about 6.3 hours. HALCA is considered a 1st generation SVLBI mission (deployable parabolic mesh antenna of 8 m aperture diameter, total antenna mass of 200 kg). Observations are made at the following frequencies: 1.6 GHz (18 cm), 5 GHz (6 cm), and 22 GHz (1.3 cm). The SVLBI measurements provide baseline lengths of up to about 3 Earth diameters (32,000 km) in combination with Japanese ground telescopes and other telescopes around the world (international project cooperation), achieving a maximum resolving power of about 90 microarcseconds at microwave wavelengths (about 100 times better than that of the Hubble Space Telescope).

- VSOP-2 (VLBI Space Observatory Project-2) is a further SVLBI project of JAXA (formerly ISAS), a follow-up mission to HALCA considered for launch in 2012. After launch the VSOP-2 mission will be referred to as ASTRO-G.

- ARISE (Advanced Radio Interferometry between Space and Earth). A NASA/JPL SVLBI astronomy satellite mission in planning consisting of a 25 m diameter radio telescope (an inflatable structure with a very thin reflecting surface that does all the work in collecting light from the cosmos) in a highly elliptical Earth orbit (HEO). The nominal orbit has a perigee height of 5,000 km and an apogee of 40,000-50,000 km. ARISE provides SVLBI observations in combination with a network of ground telescopes (resolutions up to 10-20 microarcseconds. A launch is now considered for 2015.

### 1.8.3.4 Nulling interferometry

- Nulling interferometry refers to a new multi-aperture (large baseline) technique at the start of the 21st century for optical imaging of planets circling nearby stars (used by astronomers). Nulling interferometry works by creating at least two subapertures, both looking at the same target (a bright star), but positioned so starlight from each subaperture travels in slightly different paths before being sensed by the detector. When properly aligned, crests of lightwaves from one subaperture will line up with the troughs of the lightwaves from the other, thereby cancelling the light of the bright star (the star signal is roughly 10^6 times stronger than the planet signal orbiting the star). - Nulling interferometry is a promising technique for reducing the apparent brightness of a star relative to its surroundings. As such, nulling interferometry has the potential to enable direct detection of extrasolar planets (also referred to as exoplanets) and zodiacal light (see O.9.3).

The idea of nulling interferometry was first proposed in 1978 by Ronald N. Bracewell of Stanford University. The first exoplanet was detected indirectly in 1995 (around the star 51 Pegasi — discovered by Michael Mayor and Didier Queloz of the Observatoire de Genève, Switzerland) by the so-called “transit survey” using the method of photometric observations, i.e. periodic dimming of starlight (tiny Doppler shifts) as a planet moves across a star. As of 2007, evidence of over 200 exoplanets have been found by various groups of researchers.

Examples of proposed/planned nulling interferometry satellite missions are: SIM (Space Interferometer Mission, launch 2009) and TPF (Terrestrial Planet Finder, launch 2014.

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1746) Note: Japan started in 1979 with a five year plan of VLBI development which included VSOP (VLBI Space Observatory Program). An official proposal was made by ISAS 1987. Later, VSOP was renamed to MUSES-B, which was again renamed to HALCA, after launch.

1747) http://www.vsop.isas.ac.jp/index.html


1749) http://arise.jpl.nasa.gov/

TPF is in pre-phase A as of spring 2003), both of NASA; from ESA there is DARWIN (Detection and Analysis of Remote Worlds by Interferometric Nulling) with a planned launch for 2015. Prior to TPF, NASA is planning a technology demonstration mission (launch 2007), called CINDIS (Cold Interferometric Nulling Demonstration In Space). The CINDIS spacecraft (Ball Aerospace bus RS-300) will perform the first nulling interferometry in space, employing two 40 cm diameter apertures (telescopes), 2 m apart (baseline length), forming a simple Bracwell nulling interferometer (wavelength band of 6-12 μm) with a null depth around 10^-5.

Recent studies on a two-aperture nulling interferometry instrument design at NASA/GSFC suggest that instrument angular resolution can be better than conventionally assumed, namely by an order of magnitude. The reasons: a) the interferometer response decreases quadratically inside the null while the number of signal photons increases exponentially as the planet gets closer to the star; and b) use of the new “ratio-of-two-wavelength” technique. Simulations were conducted with FSKI (Fourier-Kelvin Stellar Interferometer), consisting of two 0.5 m apertures on a 12.5 m baseline. The results indicate that a significant number of known extrasolar planets will be detectable when using the FSKI technique. This research will have implications in the design of the TPF mission and others as well.

1.8.3.5 Satellite Laser Ranging (SLR)

SLR provides a direct and unambiguous observation of the distance between a laser station on the surface of the Earth and a spacecraft equipped with a passive laser retroreflector (LRR). The concept of SLR is based on measuring the round-trip signal time of a laser beam between a ground station and retroreflectors onboard a spacecraft (see Glossary). The “range” or distance between the satellite and the observing site, is approximately equal to one half of the two-way travel time multiplied by the speed of light. SLR is a highly accurate measuring technique providing, among others, the mm-level terrestrial reference frame and the product of the universal gravitational constant G (SLR data, collected from a variety of satellites, is the dominant contributor to modern gravity field models). SLR is also sensitive to the location of the Earth’s center of mass; the time history of its motion with respect to the origin of the terrestrial reference frame has been obtained since 1987 with an accuracy of a few millimeters. In particular, SLR is often used to calibrate other measurement techniques such as radar altimeters. SLR techniques are also a strong contributor to advances in precision orbit determination. The SLR measurement precision has improved from a few meters in the mid-1960s to the cm level (even several mm) at the start of the 21st century. The statistical treatment of a large number of measurements helps to improve the precision. The main drawbacks of SLR are its reliance on weather conditions (atmospheric refraction models), the treatment of systematic errors in the measurement apparatus, and the need of trained personnel on the ground.

The passive SLR technique was first successfully demonstrated with a ‘laser tracking reflector experiment’ flown on the following spacecraft: BE – B (Beacon Explorer-B/ or Explor-
er-22) of NASA, launch Oct. 10, 1964; GEOS-1 of NASA (launch Nov. 6, 1965); Diademe-1 and -2 (Feb. 1967) of CNES, GEOS-2 of NASA (launch Jan. 11, 1968) also referred to as Explorer-36, GEOS-3 (launch Apr. 9, 1975) and SEASAT of NASA/JPL (launch June 27, 1978). International cooperation and participation of many agencies has successively led to a global network of SLR ground stations (see H.4.3.6). - SLR measurements are applied to such fields as: global tectonic plate motion, regional crustal deformation near plate boundaries, Earth’s gravity field and the orientation of its polar axis and its rate of spin. - A passive satellite laser-ranging measurement capability (entire S/C consists of laser corner reflectors) from ground to space was first provided with the CNES Starlette satellite (launch, Feb. 6, 1975).

In the early 1980s, the SLR and Lunar Laser Ranging (LLR) communities participated in MERIT (Monitoring Earth Rotation and Intercomparison of Techniques) to demonstrate the utility of modern space geodesy techniques in determining Earth rotation parameters. Earth rotation solutions, based on laser ranging to LAGEOS, have been delivered weekly since 1981, and represent the longest, continuous Earth rotation series obtained using modern space techniques.

<table>
<thead>
<tr>
<th>S/C or Mission (instrument)</th>
<th>Launch</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE-22 (Beacon Explorer-B/ or Explorer-22)</td>
<td>Oct. 10, 1964</td>
<td>First corner cube experiment on a S/C</td>
</tr>
<tr>
<td>GEOS-1 (Laser Tracking Reflector), NASA</td>
<td>Nov. 6, 1965</td>
<td>322 cubes were mounted on fiberglass panels on the bottom rim of the S/C</td>
</tr>
<tr>
<td>Diademe-1 of CNES, Diademe-2 of CNES</td>
<td>Feb. 8, 1967</td>
<td>Payload: USO (Ultra Stable Oscillator) to test one-way Doppler, and laser reflectors (SLR pilot experiment with 3 ground stations)</td>
</tr>
<tr>
<td>GEOS-2 (Laser Tracking Reflector), NASA</td>
<td>Jan. 11, 1968</td>
<td>Identical system as flown on GEOS-1</td>
</tr>
<tr>
<td>GEOS-3 (Laser Tracking Reflector), NASA and JHU/APL</td>
<td>Apr. 9, 1975</td>
<td>264 quartz cube corner reflectors mounted on a 45° conic frustum</td>
</tr>
<tr>
<td>Starlette, CNES</td>
<td>Feb. 6, 1976</td>
<td>First mission where the entire S/C consists of laser corner reflectors</td>
</tr>
<tr>
<td>LAGEOS-I, NASA, MEO orbit</td>
<td>May 4, 1976</td>
<td></td>
</tr>
<tr>
<td>SEASAT (Laser Tracking Reflector), NASA/JPL</td>
<td>June 27, 1978</td>
<td>96 fused silica 3.75 cm hexagonal corner cube retroreflectors</td>
</tr>
<tr>
<td>EGS (Ajisai), NASDA, Japan</td>
<td>Aug. 12, 1986</td>
<td>318 mirrors and 120 laser reflector assemblies (1436 corner cube reflectors)</td>
</tr>
<tr>
<td>GEO-1K, NPO PM, Krasnojarsk, USSR</td>
<td>May 30, 1988</td>
<td>Orbit: 1500 km altitude, inclin. = 73.6°</td>
</tr>
<tr>
<td>The series of GEO-1K S/C is incomplete due to lacking information</td>
<td>Aug. 28, 1989</td>
<td>Orbit: 1500 km altitude, inclin. = 73.6°</td>
</tr>
<tr>
<td></td>
<td>Nov. 24, 1994</td>
<td></td>
</tr>
<tr>
<td>ETALON-1, (RRA), USSR, MEO orbit</td>
<td>Jan. 10, 1989</td>
<td>2140 laser reflectors on RRA</td>
</tr>
<tr>
<td>ETALON-2, (RRA), USSR, MEO orbit</td>
<td>May 31, 1989</td>
<td></td>
</tr>
<tr>
<td>ERS-1 (LRR), ESA</td>
<td>July 17, 1991</td>
<td></td>
</tr>
<tr>
<td>TOPEX/Poseidon (LRA), NASA/CNES</td>
<td>Aug. 10, 1992</td>
<td></td>
</tr>
<tr>
<td>LAGEOS-II of ASI and NASA, MEO orbit</td>
<td>Oct. 22, 1992</td>
<td></td>
</tr>
<tr>
<td>Stella, CNES</td>
<td>Sept. 26, 1993</td>
<td>Stella is an exact twin of Starlette</td>
</tr>
<tr>
<td>MSTI-2 (RRA), BMDO/SMC</td>
<td>May 8, 1994</td>
<td></td>
</tr>
<tr>
<td>GFZ-1 of GFZ, Potsdam, Germany</td>
<td>April 9, 1995</td>
<td>Low-altitude and slowly decaying orbit</td>
</tr>
<tr>
<td>ERS-2 (LRR), ESA</td>
<td>April 21, 1995</td>
<td></td>
</tr>
<tr>
<td>Meteor-22, Russia</td>
<td>Aug. 31, 1993</td>
<td>Fizeau retroreflector array</td>
</tr>
<tr>
<td>RESURS-01-3 (RRA), Russia</td>
<td>Nov. 4, 1994</td>
<td>Fizeau retroreflector array</td>
</tr>
<tr>
<td>TiPS (Tether Physics and Survivability), DoD/NRL, see M.46</td>
<td>June 20, 1996</td>
<td>Retroreflectors are mounted on the exterior surfaces Ralph and Norton</td>
</tr>
<tr>
<td>ADEOS (RIS), NASDA, JEA</td>
<td>Aug. 17, 1996</td>
<td>Design of a hollow and flat cube-corner retroreflector</td>
</tr>
<tr>
<td>WESTPAC, EOS Australia (RESURS-O1-4)</td>
<td>July 10, 1998</td>
<td>Fizeau retroreflector array</td>
</tr>
<tr>
<td>Techsat/Gurwin-II (SLRRE), Technion Israel Institute of Technology, launched with RESURS-O1-4 satellite, see M.29</td>
<td>July 10, 1998</td>
<td>Array of laser retroreflectors, corner-cube mounted on the Earth-viewing panel</td>
</tr>
<tr>
<td>STEX/ATEx, DoD/NRL</td>
<td>Oct. 3, 1998</td>
<td></td>
</tr>
</tbody>
</table>
An extension of the SLR (ground to satellite) technique inverts the traditional SLR system with the ranging hardware being placed onboard a satellite to range to the ground. This technique is being introduced with the GLAS (Geoscience Laser Altimeter System) instrument of the EOS program on ICESat (launch Jan. 13, 2003) for high-resolution ice and land topography mapping (realized already in the Mars Explorer Mission). 1756)

- Modulation of retroreflectors. The state of the art of modulating retroreflectors has progressed considerably in the 1990s. The advent of ferro-electric liquid crystals (FLCs) and the technology to produce MEMS (Micro-Electro-Mechanical Systems) make new optoelectronic systems available. The most significant development has been the increase in the switching speeds that now allow data to be sent at tens of kilohertz up to multi-megahertz with very low power consumption. The technologies used for these devices are:
  - Ferro-electric liquid crystal (FLC) - Switches the polarization by reversing the polarity of the bias voltage
  - Multiple Quantum Well Device (MQW) 1757 - Switches resonance to pass or reject optical beam by electro-absorption. Solid-state MQW retroreflectors may be utilized to provide spacecraft-to-spacecraft laser communication (interrogation) and navigation (relative position and orientation). MQW modulators have very high switching speeds.
  - Atomic Absorption Cell (AAC) - Quantum electronic filter
  - MEMS Spoiled Corner Cube - Diffuse or specular surface reflection on one surface of the retroreflector
  - Switchable Gratings (PLZT) - Uses piezo-electric transducers to momentarily create diffracting surface on one surface of the retroreflector.

**1.8.3.6 Active laser tracking systems**

At the start of the 21st century, there is great interest and considerable demand for space surveillance applications, in particular in risk mitigation and debris avoidance for satellites. There is also a need to provide accurate flight information from a single observation point on a moving platform or on a cluster of spacecraft (maintenance and control of these cluster configurations require accurate position sensing and actuation). Hence, the requirements (goal) call for automated tracking capabilities of spaceborne objects (in LEO, MEO, GEO) from the ground, including high-resolution information on the spatial features of such space objects for identification purposes. The desired parameters are object orientation, precision orbit track (position and velocity), and size and shape of the object. In addition,
temporal variations of these spatial parameters are needed to characterize and assess the nature and intent of a specific space object being tracked. Generally, none of these objects have laser retroreflectors (as in conventional SLR applications) that could be used for tracking. Passive SLR systems measure the position (range) of a spacecraft, but do not provide velocity and other needed parameters of the object to be tracked.

A possible solution may be found in active laser tracking systems. In such a concept, a laser is being used to illuminate distant objects; light reflected by the object(s) is then detected and analyzed by a surveillance system to identify and track them. The laser beam is locked onto the target surface in an active tracking configuration. This permits for retrieving complete information on the target’s spatial/angular position and the velocity component that is normal to the measuring platform. A promising technique to realize such laser tracking concepts is to use the non-linear Optical Phase Conjugation (OPC) scheme; it allows for compensation of spatial intra-cavity non-uniformities, as well as atmospheric turbulence on the laser pass. In this detection scheme, a PCM (Phase Conjugate Mirror) in a laser coupled-cavity uses OPC to eliminate the imperfections and aberrations of the lasing media and the intra-cavity optical elements, and to generate a diffraction-limited laser.

The technology introduced so far has only been on a demonstration level. Obviously, the military is very interested in such tracking systems for its surveillance needs, but there are also demands for civil tracking applications to analyze potential debris problems and more. An example of an early experimental system is ATLAS (Active Tracker Laser) of the US AFRL (Air Force Research Laboratory) which was developed by Northrop Grumman in 1996. ATLAS employs a solid-state, diode-array-pumped laser with an average output power of 500 W in the infrared region and a pulse repetition rate of 2.5 kHz.

- MRR (Modulating Retroreflector), a communication device using a corner cube reflector (CCR) array at one node of the link. An optical modulating retroreflector is a device that couples an optical retroreflector with a modulator, which provides the ability to turn the retro-reflected beam on or off as a method of encoding data. Using an MRR device allows a node to send data without having its own active laser, provided that the recipient of the data supplies the optical energy. An MRR-based optical link consists of two nodes: an interrogator node, equipped with an active laser, and an MRR node, equipped with an MRR device. Typically an MRR-based link operates in half-duplex mode. MRR components can be very small and operate at extremely low power level, which significantly extends the operational lifetime. A distinct advantage of using MRR technology is the much relaxed pointing requirement. The typical field of view (FOV) of an MRR device can be as large as several ten’s degrees. Using an array of MRR, a very large field of regard (FOR) can be achieved. Using a space-division receiver, an MRR-based optical system can be channelized to receive multiple modulated beams simultaneously.

1.8.3.7 Gradiometry, accelerometry, drag-free satellites

Gradiometry is the measurement and study of the gradient of the gravitational field of the Earth (or some other body). Gradiometric techniques are used in remote sensing applications because a gravitational sensor cannot discriminate between the local gravity vector and instrumental accelerations (the Equivalence Principle). To distinguish gravity from platform accelerations (vibrations, drag, etc.), the Equivalence Principle requires a differ-


1760) http://www.eos-aus.com/corporatedetails.htm

ential measurement. A gravity gradiometer detects the spatial derivative of the gravitational field and ideally is immune to the vibrations of the platform. However, the gradient technique measures only the effects of gravity and does not respond (at least not in principle) to instrumental accelerations. Gravity gradiometry is strongly sensitive to the gravity field induced by the topographic and isostatic masses of the Earth. 1762)

Gradiometry and accelerometer are important measurement techniques in the field of geodetic and geodynamic applications (i.e., tracking). The measurement principle of gravity gradiometry is based on differential accelerometry (gravity gradients are the second order derivatives of the gravitational potential). The overall objective is the determination of Earth’s gravity field to a sufficient degree of accuracy and resolution (grid size) to permit such functions as gravity field modeling, high-resolution geoid modeling (the geoid is defined purely by the Earth’s gravity field), and a number of other evaluations including inputs for plate tectonics and crustal dynamics. A better knowledge of the Earth’s gravity field and its temporal changes may improve our understanding of the physics of the interior of the Earth; it may also explain a number of mechanisms leading to the building of the Earth’s crust, the evolution of the greenhouse effect, the ocean dynamics and its currents, and of the interaction of continents. 1763) 1764)

The Earth’s gravity field is the response to the mass density distribution of the Earth and its rotation. While the rotational contribution to gravity is represented by a mathematically very simple model, the gravitational part is extremely difficult to model and not known with sufficient accuracy and resolution on a global scale. 1765) The gravitational field is harmonic outside the Earth’s surface and can be conveniently represented by a series of solid spherical harmonics. The modeling all of its irregularities (which are due to the irregularities of the Earth’s mass density distribution), requires, strictly speaking, an infinite number of parameters (e.g., harmonic coefficients). The estimation of these parameters requires data which are sensitive with respect to these parameters. Naturally, a finite data set can only provide an approximation to reality.

- Gradiometry measurement of the Earth’s gravity field from space. Two basic and complementary approaches are in use:
  - SST (Satellite-to-Satellite Tracking Technique), see 1.8.3.2
  - SGG (Satellite Gravity Gradiometry)

SGG measures second derivatives of the gravity vector, called gravity gradients, onboard a S/C in various directions with the use of a gradiometer, consisting of several accelerometers operated in differential mode. Gravity gradients are highly sensitive to the local features of the gravity field in the proximity of the measurement location. SST is best at providing the long and medium wavelength of the geopotential, while SGG performs best at the shorter wavelengths as a result of the measurement bandwidth characteristics of the accelerometers. Both approaches favor low-altitude orbits (providing a greater sensitivity to gravity variations) in which air drag modeling is critical, because the non-gravitational orbit perturbations have to be separated from the purely gravitational ones. 1766)

- Synergies of gravity missions. The three satellite missions designed for gravity field recovery, CHAMP (launch July 15, 2000), GRACE (launch March 17, 2002) and GOCE

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1762) Note: The gravity vector is, by definition, normal to a surface of gravitational equipotential.
1763) Note: The conventional gravimeter measures a single component (the vertical component) of the gravity field vector. In contrast, a gravity gradiometer can measure up to five of the nine terms in the gravity field’s gradient tensor which completely describes the anomalous gravity field gradient. A very appealing advantage of the gradiometer method is its greater immunity to the large translational accelerations which adversely affect conventional gravimeters in dynamic environments (e.g., ships and aircraft).
http://www.asaspace.at/topics/download/Austrian%20COSPAR%20Report%202002.pdf
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(launch 2007) are complementary in observation technique, sequence, coverage, spatial and time resolution. While CHAMP and specifically GRACE have global coverage (with orbit inclinations of 87.28° for CHAMP and 89° for GRACE), GOCE will have to fly in a sun-synchronous orbit (inclination 96.5°) due to solar power constraints. This means on one hand that CHAMP and GRACE will help to fill the polar gap for GOCE, and on the other hand that GRACE and GOCE will complement each other with their expected error characteristics in their measurement bandwidths. 1767) 1768) 1769)

One of the main goals of the GRACE mission is to provide monthly global gravity field solutions to determine the time-variable gravity field. The data of the three missions offer indeed a great potential for global geoid model improvements. The GRACE twin mission by itself is expected to improve knowledge of the Earth’s geoid height from the current meter level to the centimeter level. If the mission meets all of its goals, the knowledge of the gravitational field will be improved by a factor 100, and the changes in the field will be determined on a monthly basis.

- **Drag-free satellite.** A drag-free satellite, free falling along a space-time geodetic, is the ideal test bench for some of the most advanced gravitation theories, from the general relativity validation to the search for experimental evidence of the existence of gravitational waves. The objective of all drag-free systems is to compensate all non-gravitational disturbances acting on an orbiting satellite. In addition to the primary scientific data, the analysis of the thrust history and the orbit-tracking data yields highly valuable information about the residual atmosphere density and the higher harmonics of the gravity field of the Earth.

Note: 1770) For S/C operated in LEO, gravitational forces due to the non-uniform mass distribution of the Earth are dominating the orbit and attitude perturbation spectra. Non-gravitational forces are mainly caused by momentum exchange with the spacecraft surface, they are mostly of second order. The most prominent of these forces originate from the interaction of the S/C surface with molecules and ions of the thermosphere, and from the solar photon pressure (photons are reflected as albedo from the illuminated Earth hemisphere, or which are reemitted by the whole Earth as delayed IR reradiation). In contrast with gravitational perturbations, the aerodynamic and radiation pressure effects are difficult to model since they require a good knowledge of the S/C geometry and surface properties, and they also require reliable estimates of the molecule and photon particle flux.

In general, the elements of a drag-free system consist of high-precision accelerometers (using free-floating proof masses), micro-Newton (µN) thrusters (using technologies like FEEP, cold gas, etc.), and a corresponding control system, referred to as DFC (Drag-Free Control) system. When combined with the attitude control system of the S/C, the system is mostly referred to as DFACS (Drag-Free and Attitude Control System), to compensate for the non-gravitational influences.

The original drag-free concept involves centering a free-floating test mass located inside a satellite. 1771) As the test mass is free of external disturbances, it follows a purely gravitational orbit. Since the satellite is forced to follow the test mass, it too follows the same gravitational orbit. The schematic is illustrated in Figure 39. The external disturbance forces \( F_{\text{dist}} \) will move the satellite (housing) relative to the test mass (TM). The change in the relative position is measured and then used to derive the appropriate control force \( F_{\text{control}} \) which has to be applied.
in order to drive the displacement to zero. As the relative displacement of the test mass has to be measured (electrostatically, magnetically or otherwise) there will be a coupling between the test mass and the satellite/sensor housing. This coupling is depicted as springs in Figure 39.

Operational modes in drag-free sensors: In general one can distinguish between two different operating modes, the so called Accelerometer Mode (AM), and the Displacement Mode (DM).

- The DM concept uses a “free-floating” test mass. The displacement of this test mass relative to the housing is measured by the sensor. This sensor signal is used to control the satellite to follow the test mass in order to drive the relative displacement to zero. In doing so the external disturbances on the test mass are minimized and the test mass — and thereby the satellite — will follow a free-fall orbit. The advantage of the DM concept is that the sensor accuracy is very high since no or very little force is needed to suspend the test mass which means there is very little sensor actuation noise. A disadvantage of DM is that the sensor is not inherently stable.

- In the AM concept, the test mass is forced to follow the satellite. The relative distance between test mass and satellite is driven to zero by the internal control system. The force needed to control the test mass is a measure for the acceleration acting on the satellite. The advantage of the AM concept is that the sensor is inherently stable. The disadvantages of AM is that the internal control loop limits the bandwidth of the drag-free control loop. Also, the sensor accuracy is lower due to the higher sensor actuation noise.

- The selection of an operational mode concept depends strongly on the scientific goal of the satellite. If the only purpose of the drag-free sensor is the measurement of the accelerations acting on a specific point inside the satellite (to minimize these accelerations by a drag-free control system), AM preferable. If, on the other hand, the relative displacement is needed for scientific issues, or if a very high accuracy demand forbids the use of AM, then DM should be chosen.

Examples of drag-free satellites are: Triad-1 of the US Navy and built by JHU/APL (launched Sept. 2, 1972) is considered the first satellite to fly a completely gravitational orbit (free-floating proof mass), free from all surface forces such as drag and radiation pressure. The orbit could in fact be predicted for up to 60 days (see also Table 92 and H.6).
Triad-2 (launch Oct. 11, 1975) and Triad-3 (launch Sept. 1, 1976) were follow-up drag-free missions to Triad-1. The GP-B (Gravity Probe-B) mission of NASA (launch April 20, 2004), and the ESA GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) mission with a launch in 2007, are further satellites employing the drag-free concept. - For illustration, the stringent DFC requirements for the LISA mission are shown in Table 95. 1772)

- Accelerometer mode (AM) concept. The measurement of spacecraft surface forces requires ingenious designs due to various forces (drag, solar and Earth radiation pressure) and orientation knowledge needed for proper results. An accelerometer at the S/C center of mass can measure these forces that cause non-gravitational orbit perturbations. A large accelerometer class employs the concept of force balance: a frame contains a moving proof-mass, the servo control detects its position and exerts a force to maintain the proof-mass motionless with respect to this frame. The combination of position sensing and force actuating results in accelerometer designs based on the following principles: piezoelectric, piezoresistive, acoustic, capacitive (electrostatic), and magnetic. The most commonly used measurement principles are a) electrostatic, and b) magnetic. 1773) 1774)

- Electrostatic measurement principle (Ref. 1771): In this concept, electrodes are distributed around the test mass. An electrode and the opposing test mass area forming a condenser. These condensers act as capacitive detectors. Two different principles can be applied in order to measure the relative displacement and attitude of the test mass relative to the housing: “gap sensing” or “slide sensing.”

<table>
<thead>
<tr>
<th>Mission</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAD series of US Navy (Triad-1 launch Sept. 2, 1972); Triad-2 launch Oct. 11, 1975</td>
<td>DISCOS obtained a residual acceleration of $5 \times 10^{-11}$ m/s$^2$. Triad-2 was equipped with a redundant pulsed-plasma thruster (PPT)</td>
</tr>
<tr>
<td>CHAMP of Germany, launch July 15, 2000</td>
<td>STAR of ONERA</td>
</tr>
<tr>
<td>GRACE, a dual minisatellite mission, launch March 17, 2002</td>
<td>SuperSTAR of ONERA to measure non-gravitational accelerations. Note, GRACE measures drag forces, but does not compensate for them.</td>
</tr>
<tr>
<td>GP-B (Gravity Probe-B) of of NASA/Stanford, launch April 20, 2004</td>
<td>Drag-free control with proportional helium thrusters and a drag-free proof mass ($&lt;10^{-12}$ g).</td>
</tr>
<tr>
<td>GOCE of ESA, launch 2007</td>
<td>DFACS (Drag-Free and Attitude Control System) compensates drag with thrusters</td>
</tr>
<tr>
<td>LISA Pathfinder of ESA (2009); Note: ST7 (Space Technology-7) NMP mission of NASA, originally a separate mission, is planned to fly on SMART-2 with its DRS (Disturbance Reduction System)</td>
<td>A technology demonstrator for LISA. LISA Pathfinder will carry two drag-free sensors operated in displacement mode (in addition, an accelerometer mode is foreseen)</td>
</tr>
<tr>
<td>Microscope of CNES (launch in 2008)</td>
<td>Drag-free S/C (DFACS) for a test of EP (Equivalence Principle) with an accuracy of one in $10^{15}$</td>
</tr>
<tr>
<td>HYPER (High-Precision Cold Atom Interferometry in Space), proposed ESA mission (2008-10)</td>
<td>DFACS is used to keep the measurement devices ASU (Atomic Sagnac Unit) and PST (Precise Star Tracker) within their operational envelope</td>
</tr>
<tr>
<td>LISA (Laser Interferometry Space Antenna) a joint mission of ESA and NASA with a launch in 2013</td>
<td>The LISA formation of 3 S/C represents a giant interferometer to be used to detect gravitational waves. Each S/C contains a proof mass and a DFACS (Drag-Free Attitude Control System)</td>
</tr>
</tbody>
</table>

Table 94: Overview of some drag-free missions

- Magnetic measurement principle: A relatively new concept to measure the relative displacement and attitude of a test mass is the use of the SQUID (Superconducting Quantum Interference Device) technique. This method provides measurement sensitivities in the or-


der of a femto meter ($10^{-15}$ m) with high stability made possible in a cryogenic environment at about 2 K. In their simplest form, the SQUIDs comprise a superconducting ring broken by two very narrow insulating gaps. The resistance of a SQUID to the passage of a supercurrent depends on quantum interference.

At the beginning of the 21st century, sensitivity requirements of accelerometers for space applications generally call for acceleration measurements below the pico-g ($10^{-12}$ g) level. The following instruments are examples of linear micro-accelerometers on various missions (past and future):

- **CACTUS.** A first version of an electrostatic accelerometer (measuring differential accelerations between the external surface and a small ball placed at the center of mass), referred to as CACTUS (Capteur Accélérométrique Capacitif Triaxial Ultra Sensible), developed and built by ONERA (Office National d’Études et de Recherches Aérospatiales) of Chatillon, France, was flown on the CASTOR D-5B S/C (of CNES, launch May 17, 1975, with nominal S/C operations until 1979) for atmospheric density studies. The measured precision was $10^{-10}$ m/s$^2$ (or $10^{-11}$ g). Note: The CACTUS accelerometer used a spherical proof mass inside a spherical cavity and capacitive position sensing. However, electrical forces were applied to the proof mass to keep it centered in the cavity, rather than servo-controlling the spacecraft to follow the proof mass. The strength of the electrical forces required on the proof mass determined the acceleration of the spacecraft due to non-gravitational forces.  

- **SAMS (Space Acceleration Measurement System).** SAMS is an operational space flight experiment developed by NASA/GRC (see also 1.4.2.2). The objective is to measure and record acceleration (vibrations and quasi-constant accelerations) in low-gravity settings, including facilities on Earth, the space shuttle, and the International Space Station. SAMS has already been used on more than 20 shuttle missions and the Mir Space Station. SAMS was also used on STS-107. Initial flight of SAMS on STS-43 /Aug. 2-11, 1991).

- The inertial sensor GRADIO was developed by ONERA in the early 1990s for use in a proposed joint ESA-NASA mission called ARISTOTELES. The differences in acceleration between four GRADIO accelerometers on the spacecraft were to be used to measure the gradients in the Earth’s gravitational field, and thus determine the field. However, the mission ARISTOTELES was cancelled in 1994/5 due to budget reasons. The GRADIO accelerometer used a rectangular proof mass 4 cm x 4 cm x 1 cm in size, rather than a sphere.

- Another ONERA accelerometer by the name of ASTRE (Accéléromètre Spatial Triaxial Electrostatique), was part of the ESA Microgravity Measurement Assembly (MMA), and flown on STS-55 (Apr. 26 - May 6, 1993), STS-83 (Apr. 4-8, 1997) and on STS-94 (Jul. 1-17, 1997). The objective was the characterization of the Shuttle’s microvibratory environment. The resolution achieved by ASTRE was $10^{-9}$ g in the measurement bandwidth DC to 1 Hz (monitoring of the low-frequency acceleration environment). The ASTRE working principle is based on keeping a proof mass motionless in its nominal position and attitude by means of electrostatic suspension, such that the required electrostatic forces are a direct measure of the three acceleration components.  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment or function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision thrust range</td>
<td>0.1 - 25 μN</td>
<td>Oppose solar radiation pressure</td>
</tr>
<tr>
<td>Precision thrust control</td>
<td>±0.1 μN</td>
<td>Spacecraft control to 10 nm</td>
</tr>
</tbody>
</table>

1777) http://microgravity.grc.nasa.gov/MSD/MSD_htmls/sams.html  
1778) http://esapub.esrin.esa.it/microgra/micrv8n2/nat8n2.htm  
1779) M. Nati, A. Bernard, B. Foulon, P. Touboul, “ASTRE, a highly performant accelerometer for the low frequency range of the microgravity environment,” Proceedings of the 24th Symposium on space environmental control systems, Friedrichshafen Germany, pp.9, 1994
### Table 95: DFC system requirements for the LISA mission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment or function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse thrust range</td>
<td>25 - 100 μN</td>
<td>Spacecraft tip-off recovery</td>
</tr>
<tr>
<td>Coarse thrust control</td>
<td>±1 μN</td>
<td>Spacecraft tip-off recovery</td>
</tr>
<tr>
<td>Thrust noise</td>
<td>&lt;0.1 μN (Hz)(^{1/2})</td>
<td></td>
</tr>
<tr>
<td>Specific impulse</td>
<td>&gt;500 s</td>
<td>Keep fuel within mass margin</td>
</tr>
<tr>
<td>Design life @ 25 μN</td>
<td>&gt; 3 years</td>
<td>10 year goal</td>
</tr>
<tr>
<td>Mass of instrument</td>
<td>&lt;10 kg</td>
<td>4 thrusters + electronics</td>
</tr>
<tr>
<td>Steady-state power</td>
<td>&lt;5 W</td>
<td>1 thruster @ 25 μN</td>
</tr>
<tr>
<td>Volume of instrument</td>
<td>&lt;1000 cm(^2)</td>
<td>4 thrusters + electronics</td>
</tr>
</tbody>
</table>

- STAR (Space Three-axis Accelerometer for Research mission) is a CNES-provided accelerometer system developed by ONERA and flown on the CHAMP mission (launch July 15, 2000). The objective is to measure all non-gravitational accelerations of the satellite (drag, solar and Earth radiation pressure) in order to determine the Earth's gravity field from purely gravitational orbit perturbations. The accelerometer measurement principle is based on electrostatic suspension of a proof-mass in a cage. Instantaneous position of the proof-mass is measured by three capacitive sensors which permit a determination of the acceleration vector. The instrument has a dynamic range of ±10\(^{-4}\) ms\(^{-2}\), a resolution of better than ±3 x 10\(^{-9}\) ms\(^{-2}\), and a frequency range of 10\(^{-1}\) to 10\(^{-4}\) Hz.\(^{1780}\)

- In 1996, a Czech micro-accelerometer by the name of MACEK (Mikroakcelerometr), designed and developed at the Institute of Astronomy of the Academy of Sciences of the Czech Republic at Ondrejov, was flown as a technology experiment on Shuttle flight STS-79 (Sept. 16 - 26, 1996). MACEK was placed inside of Spacehab, about 2 m away from the center of gravity of the Shuttle (measurement of Shuttle vibrations during the orbital flight phase, performance tests of MACEK). MACEK employs the concept of an electrostatically compensated proof-mass with a measurement accuracy of 10\(^{-9}\) m/s\(^2\). The first version of MACEK has been flown on the Russian satellite Resurs-F1 in 1992 (launch June 23, 1992, proof of concept flight for MACEK). - An upgraded version of the MACEK (10\(^{-10}\) m/s\(^2\)) instrument is flying on the Czech MIMOSA (Microaccelerometric Measurements of Satellite Accelerations) satellite mission (launch June 30, 2003, see E.17).\(^{1781}\)

- The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission of ESA with a planned launch date in 2007, flies EGG (Electrostatic Gravity Gradiometer), developed by ONERA, in an SGG (Satellite Gravity Gradiometer) configuration, combined with an SSTI (Satellite-to-Satellite Tracking Instrument) configuration. See E.11. The EGG will provide the medium- and short-wavelength terms of the Earth’s gravity field. The GOCE objective is to provide accurate models of the Earth’s gravity field (1-2 mgal) and its geoid (1-2 cm) at fairly high spatial resolutions of 100 km. This is in particular required for research in solid Earth physics, geodesy, oceanography and of the ice sheets.

Note: GOCE and GRACE (Gravity Recovery and Climate Recovery) are complementary missions with GRACE focusing in particular on the temporal variations of the gravity field and GOCE on attaining maximum spatial resolution of the gravity field. These various complementary satellite gravity field concepts as well as those from other satellite mission and airborne observations are summarized in Table 96. - It turns out that a global gravity field map, created from just two weeks of data in the early mission of GRACE, is proving to be substantially more accurate than the combined results of more than three decades of satellite and surface measurements collected before GRACE (GRACE is providing a global gravity field once every thirty days).


Gravity field/Field of application | Complementary data
--- | ---
Proof-of-concept of SST-hl combined with 3-D accelerometry | CHAMP
Temporal variations of Earth gravity field | Available models (tides, atmospheric pressure, ocean variability) and results from GRACE
Gravity field at polar caps and small-scale gravity information in some regions | Available and planned airborne and terrestrial gravimetry data
Solid-Earth physics | Topographic models (DTMs) and seismic tomography as primary data sets, lithospheric magnetic field from ØRSTED and CHAMP and planned magnetometry satellite missions
Oceanography | Data sets from past, current and future ocean altimetry (GEOSAT, T/P, ERS–1 & 2, Envisat, Jason etc.)
Ice research | Ice altimetry (ICESat, CryoSat) and INSAR
Geodesy | Current and future global satellite positioning and navigation systems (SLR, VLBI, DORIS, GPS, GLONASS, GNSS-2)
Sea-level | GLOSS (Global tide-gauge network), GPS/DORIS, satellite ocean and ice altimetry and GPS

Table 96: Overview of complementary data in combination with GOCE data

- For LISA (Laser Interferometry Space Antenna) a joint mission of ESA and NASA with a launch in 2013, the optical measurements are made between the proof masses in different spacecraft rather than between the spacecraft themselves. Thus the acceleration of the proof mass with respect to its cavity does not have to be measured (nevertheless, the displacement between proof mass and cavity has to be measured). The main objective of the LISA inertial sensor is to provide a reference mass that moves inertially to a high accuracy, except for the effects of slowly varying bias forces outside the gravitational wave frequency band.

Gravity/Mag.-field missions | Description
--- | ---
Cosmos-26 (Soviet Union) | Launch March 18, 1964. The USSR Cosmos-26 satellite provided the first global magnetic mapping of the Earth’s surface.
Prognoz-6 (Soviet Union) Magnetic field measurements | Prognoz-6 (launch Sept. 26, 1977), IZMIRAN (data provider)
Prognoz-7 (launch Nov. 11, 1978), IZMIRAN
Prognoz-9 (launch July 1, 1983), IZMIRAN
ISEE-1/2 (NASA/ESA) | ISEE-1/2 (launch Oct. 2, 1977). The RUM/RUD magnetometer experiment of UCLA studied the dynamic plasma field of the Earth
GEOS-2 (ESA) | GEOS-2 (launch July 24, 1978, E.6.2) into a near GEO. Objective: Measurement of fluctuations in the Earth’s magnetic field and waves and particles. Two years of data.
MAGSAT (APL, NASA, USGS) | MAGSAT (launch Oct. 30, 1979, operated to June 1980) was the first mission to systematically measure the Earth’s magnetic field. It provided the first IGRF (International Geomagnetic Reference Field) model based on global scalar and vector data of high accuracy, determining the core radius and mapping fluid motions at the core mantle boundary.
Interball (IKI, Russia) | Interball (launch Aug. 3, 1995) constellation of 4 S/C carries the FM-3L fluxgate magnetometers (solar wind interaction with the magnetosphere).
POLAR (NASA) | POLAR (launch Feb. 24, 1996) flies MFE (Magnetic Fields Experiment of UCLA to study the coupling of the solar wind and the magnetosphere
FAST (NASA) | FAST (launch Aug. 21, 1996) flies MFI (Magnetic Fields Instrument) of UCLA to measure the vector DC and AC magnetic fields.
ASTRID-2 (SSC, IRF-K, Sweden) | ASTRID-2 (launch Dec. 10, 1998) with the objective to perform high-resolution E-field and B-field measurements in the auroral region
Ørsted (TUD, Denmark) | Ørsted (launch Feb. 23, 1999) with the objective to perform highly accurate and sensitive measurements of the geomagnetic field
SACI-1 (INPE, Brazil) | SACI-1 (launch Oct. 14, 1999). The MAGNEX instrument investigates the phenomena related to current alignment with the trans-equatorial field and the plasma electrodynamics involving the Earth, specifically in the region of the South Atlantic Anomaly.
SAC-C (CONAE, NASA, DSRM, etc.) | SAC-C launch Nov. 21, 2000. The objective of Ørsted-2 (Magnetic Mapping Payload) instrument suite is to map the Earth’s magnetic field.

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Gravity/Mag.-field missions | Description
---|---
IMAGE (NASA, SwRI) | IMAGE launch on Mar. 25, 2000. The objective is to study the global response of the Earth’s magnetosphere to changes in the solar wind. NASA’s first S/C for making ENA measurements of the terrestrial magnetosphere.


GRACE (NASA/DLR) | A dual minisatellite mission (launch March 17, 2002) with accelerometers and GPS receivers for SST (+laser), like CHAMP plus ultra-precise low-low SST. The measured gravity field is about 10 times more accurate for large-scale features than any pre-GRACE gravity model of Earth.

FEDSAT (CSIRO) Australia | FEDSAT (launch Dec. 14, 2002). The objectives of the NewMag instrument are to measure electrical currents and perturbations in the Earth’s magnetic field.

GOCE (ESA) | A gravity field mission (2007) with three-axis satellite gravity gradiometry (SGG) provided by EGG (Electrostatic Gravity Gradiometer) and SSTI (Satellite to Satellite Tracking Instrument) for SST. The GOCE version gradiometry is considered to be two orders of magnitude more sensitive (and also more challenging) than that of CHAMP and GRACE.

Microscope (CNES, ONE-RA) | A microsatellite mission (2008) with the objective to measure EP (Equivalence Principle) to an accuracy of one part in 10^{15}.

Planned but not flown missions

Gravity/Mag.-field missions | Description (the listing of the following missions is kept for historical reasons). All the gravity objectives, concepts and goals which were elaborated for them are still valid.

GRAVSAT (NASA) | A mission defined in the 1980s and cancelled in 1987 due to technical difficulties and budget constraints.

GGM (Gravity Gradiometer Mission), NASA also known as SGGM | Objective: to map the Earth’s gravity and magnetic fields using two drag-free S/C orbiting in polar orbit at a very low altitude. The project was cancelled in 1987.

GRADIO (CNES) (a gradiometer instrument - not a mission) | Under study by CNES and terminated in the 1980s. GRADIO was a satellite gravity gradiometer experiment aimed at measuring the full set of gravity gradients (and separating it from the spacecraft attitude disturbances) by means of eight three-axis micro-accelerometers of a new generation.

ARISTOTELES (ESA/NASA) | Mission studies started in 1989 with the objective to fly a high-low SST mission using GPS and satellite gravity gradient measurements (GRA-DIO). ARISTOTELES was terminated in 1994/5 due to budget constraints.

GAMES (NASA/CNES) | A two (co-orbiting) S/C mission was designed with laser measurements between S/C. A GPS receiver on one S/C was planned for LEO orbit determination. Also measurement of the magnetic field. GAMES was cancelled in the 1990s due to budget constraints.

Table 97: Overview of gravity/magnetic field missions flown (and not flown)

1.8.3.8 Precise Orbit Determination (POD)

POD principle: 1783) 1784) Position and velocity of a satellite for given instants of time can precisely and continuously be determined by numerical integration of the orbit dynamics within a differential improvement process. Starting from an initial orbital motion model a set of parameters for the adjustment of the initial conditions and the perturbing forces is solved iteratively in order to eventually arrive at an integrated orbit fitting the measurements best in the least squares sense. The foundations of this technique were laid down by William M. Kaula, an American physicist of Australian descent (1926-2000), considered to be the father of space-based geodesy.

Background on classical dynamic orbit determination: Conventional ground-based tracking systems seldom provide coverage from more than one direction at a time, and often provide no coverage. To supply the missing information for orbit determination, an orbit model

must be fit to the tracking data. The most precise orbit estimation strategies employ orbit models derived from detailed models of the forces acting on the satellite, a technique known as dynamic orbit determination. — The technique begins with a set of tracking measurements [e.g., GPS, SLR, Doppler, DORIS (along with a global network), VLBI, SST, SAR interferometry, altimetry measurements] along with models of the forces and satellite mass. Those models yield a model of satellite acceleration over time, from which, by double integration, a nominal or a priori trajectory is formed. To produce the orbit solution (state vector), the two constants of integration — the initial position and velocity — also known as the epoch state, are estimated (Ref. 1578).

In a simple and conventional approach, using only one tracking method, GPS receiver data may for instance be used to obtain a fast onboard navigation solution with moderate accuracy. An improved but more complex solution would be to use GPS code and/or carrier measurements. In addition, various tracking intervals may be used in either approach, like batch processing or continuous tracking. This example demonstrates that the choice of orbit determination is depending on the accuracy requirements and the amount of effort to be invested.

Satellite tracking and orbit determination are essential elements of practically all satellite missions. Knowledge of the spacecraft position at any time is a requirement for all operational planning activities. There are several application areas in EO (geodesy, geodynamics, atmospheric sciences, constellation navigation, etc.) with accuracy requirements for the Precise Orbit Determination (POD). Examples are:

- For altimetry satellites, the orbit determination results are an essential part of the scientific data - by providing the link between the range observation made by the altimeter instrument and the terrestrial reference frame. The accuracy requirements for the Precise Orbit Determination (POD) of altimeter satellites, such as TOPEX/Poseidon, Jason-1, Envisat, and ICESat are therefore several orders of magnitude higher than for most other satellites. Any errors in the orbit determination also directly affect the accuracy of their scientific products. All altimeter-carrying satellites have therefore been equipped with high-precision tracking capabilities, such as SLR, DORIS and GPS (combinations).

<table>
<thead>
<tr>
<th>Tracking system</th>
<th>TRA-NET</th>
<th>SLR</th>
<th>DORIS</th>
<th>PRARE</th>
<th>GPS</th>
<th>Orbit error</th>
<th>Launch Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement precision</td>
<td>RR 2-10 mm/s</td>
<td>Range 0.5-5 cm</td>
<td>RR (RangeRate) 0.35-0.5 mm/s</td>
<td>Range + RR 2.5 cm, 0.25 mm/s</td>
<td>Phase 0.2-0.5 cm</td>
<td>cm</td>
<td></td>
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<tr>
<td>Seasat</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>30</td>
<td>27.6.78</td>
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<tr>
<td>GEOSAT</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>10</td>
<td>12.3.85</td>
</tr>
<tr>
<td>ERS-1</td>
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<td>no</td>
<td>failed</td>
<td>no</td>
<td>5</td>
<td>17.7.91</td>
</tr>
<tr>
<td>Topex/Poseidon</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>2</td>
<td>10.8.92</td>
</tr>
<tr>
<td>ERS-2</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>4</td>
<td>21.4.95</td>
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<tr>
<td>GFO</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>failed</td>
<td>no</td>
<td>5</td>
<td>10.2.98</td>
</tr>
<tr>
<td>Jason-1</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>2</td>
<td>7.12.2001</td>
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<tr>
<td>Envisat</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>3</td>
<td>1.3.2002</td>
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<tr>
<td>ICESat</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>5</td>
<td>1.13.2003</td>
</tr>
<tr>
<td>CryoSat</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>3</td>
<td>8.10.2005 launch failure</td>
</tr>
<tr>
<td>Jason-2</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>2</td>
<td>2008</td>
</tr>
</tbody>
</table>

Table 98: Tracking methods used for various altimeter missions (Ref 1785)

- Radio occultation instruments flown on LEO spacecraft. For precision analysis of GNSS radio occultation data, especially at altitudes between 30-60 km, LEO and GPS satel-

lite velocities have to be known to about 0.1 mm/s or better. This requires POD techniques. An example is the MetOp (Meteorological Operational Satellite) mission of EUMETSAT which carries the GRAS ((GNSS Receiver for Atmospheric Sounding) instrument. In GRAS POD, the target accuracy for orbit (10cm) and clock offset (1ns) has to be obtained based on 10-minute datasets and within a few minutes of processing time. Only a sequential algorithm can achieve this.

- POD techniques are being required for constellation maintenance services such as COSMO/SkyMed, ROCSat-3/COSMIC, etc.

**Gravity field models:** Satellite laser ranging (SLR) data has been an integral part of Earth gravity model development since the days of the earliest GEM (Goddard Earth Models) in the 1970s. SLR data have contributed both directly in the form of tracking of the multiplicity of satellites that have made up these solutions, and indirectly in the definition and stabilization of the terrestrial reference frame. The evolution of the SLR technology required improvements in modeling and yielded ever-refined models.\(^{1786}\)\(^{1787}\)\(^{1788}\)

The launch of the Lageos-1 (launch May 4, 1976) satellite contributed greatly to early SLR technology by providing an unambiguous measurement of range, with well-calibrated system biases. This SLR data formed the core of state-of-the-art gravity models developed at NASA/GSFC – starting with GEM−5 (Goddard Earth Model−5) in 1983, GEM−9, and GEM−L2.

Note: At the time of the Lageos launch, lasers with a precision of 40 cm provided the bulk of the tracking support. The next generation of lasers, using pulse-choppers, delivered data at the precision of 2−5 cm.

Uncertainties in the Earth’s gravity field have long been the major error source in orbit determination of altimetry satellites. A great improvement in gravity field modeling was made possible by past altimeter missions, with their high accuracy satellite tracking and altimeter measurements. This has reduced the radial orbit error from meters in the 1980’s to a few cm nowadays. The effect of the Earth’s gravity perturbations decreases rapidly with the orbit altitude. The effects on TOPEX/Poseidon and Jason-1 at 1336 km, are therefore much smaller than on GEOSAT, GFO, ERS and Envisat, at roughly 800 km.

Gravity field models are generally generated using tracking data from a variety of satellites at different inclinations and altitudes, combined with surface gravity and altimeter measurements. For this reason, the gravity-induced orbit error of a certain satellite for a certain model, depends heavily on how much tracking data of this satellite (or other satellites in the same or similar orbit), have been used in the generation of this model. Therefore, so-called tailored models have been generated to push the orbit accuracy to its limits. Examples of these are (see also 1.8.1.2 for gravity field models):

- **JGM-1 (Joint Gravity Model) effort,** developed by NASA/GSFC started in 1982.\(^{1789}\)
  This model, along with other model and tracking system improvements, resulted in a prelaunch radial orbit accuracy of T/P on the order of 13 cm. The JGM-1 model was developed before the launch of TOPEX/POSEIDON (T/P) and was the result of a multi-year effort to improve the Earth’s gravity model by a new inversion of tracking data on over 30 satellites, altimeter data from Seasat and GEOSAT, and direct gravity measurements on the Earth’s surface (land and marine gravimetry).

- **JGM-2 of NASA/GSFC.** A post-launch tuning/adjustment of the JGM-1 gravity model (after the launch of TOPEX/POSEIDON ) resulted in JGM-2.


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- JGM-3. An update to the JGM-1 and JGM-2 models developed at NASA/GSFC and the University of Texas (inclusion of more tracking data on T/P, and especially the inclusion of about 40 days of GPS tracking). Combined with improved tide models based on the T/P altimeter data, and some additional refinements of the orbit determination strategy, the current orbit accuracy of approximately 2 cm was achieved. [Marshall et al., 1995].

- DGM-E04 for ERS-1/2. DGM stands for DUT/DEOS Gravity Model, with DUT (Delft University of Technology) and DEOS (Delft Institute for Earth-Oriented Space Research), Delft, Netherlands. DGM-E04 is based on precise, preliminary, or near-realtime orbits using SLR and crossover tracking data. [R.Scharroo, P.Visser, “Precise orbit determination and gravity field improvement for the ERS satellites,” Journal of Geophysical Research, Vol. 103(C4), April 1998, pp. 8113-8127]

- The GRIM5-C1 model [developed in a joint GFZ (GeoForschungsZentrum) and GRGS (Groupe de Recherches de Géodésie Spatiale) effort] represents the current state of the art in long wavelength gravity field modelling for POD, providing improvements over earlier models for both the TOPEX/Poseidon and ERS orbits. [T.Gruber, A.Bode, C.Reigber, P.Schwintzer, R.Biancale, J.-M.Lemoine, “Grim5–c1: Combination solution of the global gravity field to degree and order 120,” Geophysical Research Letters, Vol. 103(C4), April, 2000, pp. 8113-8127]

During the last decade (1990s) orbit errors of altimeter satellites have come down by more than an order of magnitude, and more advances are expected when new gravity models based on CHAMP, GRACE and GOCE data have been produced.

The conventional POD technique is a ground-based offline batch process in which the various tracking elements are collected and analyzed a posteriori. The CHAMP project provides RSO (Rapid Science Orbit) on an operational day-by-day basis with position accuracies of < 10 cm. As of 2003, USO (Ultra-rapid Science Orbit) products (i.e. atmospheric soundings) of CHAMP are delivered with a time delay slightly above 3 hours after reception. [B.Tapley, M.Watkins, J.Ries, G.Davis, R.Eanes, S.Poole, et al., “The JGM-3 Geopotential Model,” Journal of Geophysical Research, Vol. 101, 1996, pp. 28029-28049]

Precise GPS tracking of a LEO spacecraft requires at least one onboard GPS receiver as well as processing of both GPS observables, namely the carrier phase and pseudorange measurements in a relative positioning approach. In this setup, parallel GPS measurements are being required simultaneously at terrestrial GPS observing sites. The terrestrial receiver-to-spaceborne receiver measurements are then incorporated into a classical orbit determination estimation algorithm (a posteriori analysis). For both carrier phase and pseudorange observables, there are offsets of the receiver and GPS (transmitter) satellite clocks from GPS Time and there are further delays due to the troposphere and ionosphere as well as smaller effects due to multipath and receiver noise. Measurement combination and differencing can almost entirely remove the timing offsets and the ionospheric and tropospheric delays but increases the noise of the resultant observables and also reduces the measurement strength. In the phase measurements, the initial phase is unknown by an integer number of cycles. This can be determined by the carrier phase triple difference. [R.Scharroo, P.Visser, “Precise orbit determination and gravity field improvement for the ERS satellites,” Journal of Geophysical Research, Vol. 103(C4), April 1998, pp. 8113-8127]

Three basic strategies are in use at the start of the 21st century to determine precise orbits using GPS. These are 1) dynamic, 2) kinematic, and 3) hybrid strategies:

1794) The conventional ground-based POD technique has been or will be implemented for many missions such as: TOPEX/Poseidon (launch Aug. 10, 1992), Jason-1 (launch Dec. 7, 2001), CHAMP (launch July 15, 2000), GRACE (launch Mar. 17, 2002), CryoSat (launch Oct. 8, 2005 – but launch failure), ROCSat-3/COSMIC (launch Apr. 14, 2006), GOCE (launch 2007), and TerraSAR-X (launch June 15, 2007)
1) In the dynamic strategy, a mathematical model for the forces acting on the LEO are used to produce a nominal trajectory using a nominal spacecraft state vector. A more accurate trajectory is then found by selecting the LEO state that best fits the GPS tracking measurements in a least squares sense. As long as the dynamic models are adequate, the effect of noisy instantaneous tracking measurements on the solution are reduced for longer data arcs.

2) In the kinematic strategy, the rationale is that the actual path of the LEO may be closer to the precise GPS position estimates than the trajectory determined by a dynamic model. The LEO dynamic and spacecraft models are completely removed, thus explaining why the kinematic strategy is otherwise known as a non-dynamic strategy. The spacecraft state and a process noise vector representing three force corrections can be estimated at each measurement time in a Kalman filter formulation. Theoretically, a radial position of about 3 cm may be achieved with this approach from one day’s worth of data. The method relies on the precision of the GPS observations and the relative location of the LEO and terrestrial receivers with respect to the GPS constellation and the continuous GPS satellite tracking from the spaceborne GPS receiver. 1797)

3) The hybrid strategy combines the strengths of dynamic and kinematic approaches. The idea is to combine tracking observables from several high-precision measurement techniques such as GPS, SLR, DORIS, etc. The T/P (TOPEX/Poseidon, launch Aug. 10, 1992) spacecraft of NASA pioneered this concept. In addition to its GPS receiver, the T/P spacecraft has been tracked with TDRS (Tracking Data Relay Satellite), DORIS (onboard the S/C) and SLR (Satellite Laser Ranging). A posteriori analysis of the tracking information from the four sources has demonstrated a satellite position determination capability in the < 5 cm range. Many other projects followed this hybrid POD approach.

Future orbit determination developments are heading towards a real-time POD service. However, this requires to install the differential orbit improvement process onboard the spacecraft (i.e., migration from batch mode to filter mode). The RADARSAT-2 satellite of MDA/CSA (planned launch 2006, chapter D.35.4) is probably the first mission to employ a real-time onboard POD software package in combination with its dual-frequency LAGRANGE GPS receiver (a 12-channel instrument which produces pseudorange and Doppler phase measurements). An orbital filter is used to combine the GPS measurements with high fidelity orbit models.

1.8.3.9 Gravitomagnetism, frame dragging and gravitational lensing

Gravitomagnetism describes the general relativistic curvature of space-time around massive bodies, like Earth. By its very nature, gravitomagnetism refers to the hypothetical analog of magnetism predicted for a moving mass that would cause geodetic spin precession (i.e., a change in the orientation of a spinning mass’s axis). The gravitomagnetic field is one of the most important predictions of Einstein’s Theory of General Relativity, which has no Newtonian counterpart, it emerges as a consequence of mass-energy currents. 1798) Gravitomagnetism is the tendency for a massive spinning body to apply a torque to nearby objects. The fundamental principle of general relativity asserts that accelerated reference frames and reference frames in gravitation fields are equivalent. General relativity states that clocks run slower in strong gravitational fields (or highly accelerated frames), predicting a gravitational redshift. It also predicts the existence of gravitational lensing. 1799) gravitational waves, and gravitomagnetism.

1798) http://scienceworld.wolfram.com/physics/Gravitomagnetism.html
There are three main effects of gravitomagnetism: 1800)

1) Precession of a gyroscope. In the field of a body rotating with angular momentum, a gyroscope at a distance r precesses with an angular velocity. A gyroscope orbiting Earth tends to tilt away from the plane of its orbit because the Earth is dragging it. Einstein referred to this effect as **frame dragging** in which the orbit of a small body orbiting around a rotating massive one is slightly perturbed by the rotation.

2) Precession of orbital planes (nodal precession of a spinning top, also referred to as geodetic effect). According to Einstein’s Theory of General Relativity, a large body like Earth warps local space and time (spacetime) much like a marble would dent a bed sheet it is lying on. This is known as the geodetic effect (a consequence of the geodetic effect is that it gradually changes the spin direction of a gyroscope). For a gyroscope orbiting near the Earth, this distortion leads to a tilting of the gyroscope’s spin axis in the plane of the orbit. This effect is predicted by general relativity theory to be 150 times larger than the frame dragging. 1801) Examples of nodal precision: 1) The whole orbital plane of a satellite is itself a kind of enormous gyroscope dragged by the gravitomagnetic field; 2) Earth itself is a perturbed spinning gyroscope, each spin around the sun lasts one year, and each gyration around the nutation cone (cone angle of 23.45º) takes 26,000 years.

3) Precession of the pericenter. This is known as the Lense-Thirring effect, first predicted by two Austrian physicists Josef Lense (1890-1985) and Hans Thirring (1888-1976) in 1918. 1802) They calculated the advance of the pericenter and line of nodes of a particle orbiting a rotating mass – due to frame dragging. They proposed that the rotation of planets and stars or any rotating mass twists the structure of spacetime near that mass. Not only is local spacetime curved near the sun, it is twisted by the sun’s rotation.

Background: In Einstein’s Theory of General Relativity (gravity), the concept of inertial frame has only a local meaning, and a local inertial frame is “rotationally dragged” by mass-energy currents. In other words, moving masses influence and change the orientation of the axes of a local inertial frame (e.g., a gyroscope). Hence, an external current of mass, such as the spinning Earth, “drags” and changes the orientation of gyroscopes. This is the “rotational dragging of inertial frames,” or “frame dragging” as Einstein referred to it -- the spin of a body must change the geometry of the universe by generating space-time curvature. Simply stated the phenomenon says that all celestial bodies that rotate, such as the sun, or the Earth, create a force that pulls space towards them (also referred to as gravitomagnetic orbital perturbation). The theory implies that Earth’s rotation should influence the motion of its orbiting satellites. Obviously, the effect of frame dragging is most pronounced near massive, fast spinning objects in the universe.

Since Albert Einstein published his Theory of General Relativity in 1916, several experiments have been discussed and proposed to measure the rotational dragging of an inertial frame by a spinning body. The first examples of direct measurements are:

- In the 1990s, an Italian team (CNR/IFSI, University of Rome, University of Pisa, etc.) performed an analysis of the orbits of Lageos-1 (launch May 4, 1976) and Lageos-II (launch Oct. 22, 1992), using existing laser ranging observations (3.1 years of measurement data) along with a highly accurate modeling technique (JGM-3 and EGM-96 gravity models) and the 1994 version of GEODYN II (an orbit determination program of NASA/GSFC). The

1799) Note: Gravitational lensing is an important tool for the study of the distribution of dark matter in the universe. Gravitational lenses produce multiple images of single astronomical objects.


result of the analysis was that the gravimagnetic field has changed the point of perigee of the satellite Lageos-II by about 11 m during the observation period of 3.1 years (the plane of the orbits of LAGEOS I and II were shifted by about 2 m/year in the direction of the Earth’s rotation). Both Lageos satellites are in MEO orbits (Lageos-II altitude of 5900 km, inclination = 52.65, period of 3.758 hours). \(^{1803}\) \(^{1804}\)

- In November 1997, astronomers using NASA’s RXTE (Rossi X-ray Timing Explorer) spacecraft observations made a startling discovery: evidence that supports this effect known as frame dragging. The astronomers found evidence to support frame dragging by observing a binary star system in which a normal star feeds the disk of accreting matter spiraling into the event horizon of a black hole. \(^{1805}\) \(^{1806}\)

- **First direct measurement of the frame dragging and geodetic effects and their magnitudes is being provided by GP-B (Gravity Probe-B).** \(^{1807}\) The objective of GP-B mission of NASA (launch Apr. 20, 2004, flying at an altitude of 640 km and an inclination of 90\(^\circ\)) is to measure with great accuracy the phenomenon on orientation of the axes of spin in orbiting gyroscopes (four superconducting gyroscopes are flown on GP-B, see E.12). GP-B monitors any drift in the gyroscopes’ spin axis alignment in relation to its guide star, IM Pegasi (HR 8703). GP-B provides a drag-free environment to compensate for all non-gravitational disturbances acting on the spacecraft. SQUIDs (Superconducting Quantum Interference Device), which are very sensitive magnetometers, provide the gyroscopic readouts. A SQUID has the capability to detect a field change of 5 x 10\(^{-14}\) Gauss within a few days, which corresponds to a gyro tilt of 0.1 milliarcseconds.

In 1959, the theoretical concept of a frame dragging experiment was independently conceived and formulated by Leonard Schiff of Stanford University and George W. Pugh of the Pentagon. According to calculations by L. Schiff, the frame-dragging effect (rotation of space-time) should turn the gyroscope with the Earth through an angle of 41 milliarc-seconds in a time period of one year (corresponding to 1.17\(^\circ\) x 10\(^{-5}\)). According to Einstein, a second, much larger change in spin direction, the geodetic effect, follows from the gyroscope’s motion through this spacetime curvature. The predicted effect for a gyroscope is a rotation in the orbit-plane of 6,600 milliarcseconds per year - quite a large angle by relativistic standards.

- ESA is defining a fundamental physics mission (under assessment as of 2003) called HYPER (Hyper-Precision Cold Atom Interferometry in Space). In the time frame 2008/10, HYPER will make the first map of the spatial contours of the gravimagnetic effect close to Earth (the aim is to measure whether any rotation is associated with the Earth’s gravitational field). \(^{1808}\) \(^{1809}\) It will achieve about 1% precision over a one-year measurement time. As they move in their orbit, atom gyroscopes (also referred to as quantum gyroscopes) with high sensitivity for rotation rates (10\(^{-12}\) rad/s at 1 Hz) will trace the latitudinal variation of the Earth’s drag with respect to an inertial reference provided by a guide star monitored by a high-performance star tracker PST (Precision Star Tracker). The mission will provide the first test of the prediction, which flows from Einstein’s general theory, that nearby space should be dragged round by the Earth’s spin.

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\(^{1806}\)http://www----tech.mit.edu/V117/N57/warping.57w.html

\(^{1807}\)Note: Gravity Probe A was a relativity experiment relating to the equivalence of gravitational and inertial mass, performed in 1976 by NASA and the Smithsonian Astrophysical Observatory (suborbital flight).


Gravitational lensing:

A gravitational lens is formed when the light from a very distant, bright source (such as a quasar) is "bent" around a massive object (such as a massive galaxy) between the source object and the observer. This process is known as gravitational lensing, and was one of the predictions made by Einstein’s general relativity.

There are three classes of gravitational lensing:

1) **Strong lensing**: where there are easily visible distortions such as the formation of Einstein rings, arcs, and multiple images.

2) **Weak lensing**: where the distortions of background objects are much smaller and can only be detected by analyzing large numbers of objects to find distortions of only a few percent.

3) **Microlensing**: where no distortion in shape can be seen but the amount of light received from a background object changes in time. Typically, both the background source and the lens are stars in the Milky Way.

**Gravitational microlensing** is an astronomical observation technique taking advantage of the gravitational lensing effect of a foreground compact mass, such as a planet or star, as it passes very close to the line of sight to a more distant source, such as a star or a quasar. As light from the source star streams toward Earth, the gravity of the intervening lensing star bends the light rays. This creates a significant increase in brightness during the weeks or months that the two stars are in close proximity. — The distinguishing characteristic between microlensing and other cases of gravitational lensing is that the multiple distorted images of the source which the lens may induce are not individually resolvable by optical telescopes. Instead, with microlensing a single apparent image is observed with a brightness given by the combined brightness of the individual images. 1810] Astronomers who constantly monitor dense star clusters have recorded several hundred microlensing events each year since the early 1990’s.

- A first test of gravitational light-bending was confirmed in 1919 during a solar eclipse (May 29, 1919), when the English astronomer Arthur S. Eddington (1882—1944) observed the light from stars passing close to the sun was slightly bent, so that stars appeared slightly out of position. The measurement involved an expedition to Principe Island in West Africa.

- In 1979, the first gravitational lens was discovered accidentally by Dennis Walsh, Bob Carswell, and Ray Weymann using the Kitt Peak National Observatory 2.1 m telescope (AZ, USA). The object became known as the "Twin Quasar" since it initially looked like two identical quasars; it is officially named Q0957+561.

- In 2005, astronomers (an international team of 73 collaborators from 32 institutions) used the technique of microlensing with a network of telescopes — thereby discovering an extrasolar planet (exoplanet), named OGLE—2005—BLG —390Lb, only 5.5 times larger than the Earth, orbiting a star in the Sagittarius constellation (20,000 light years away close to the center of the Milky Way). The OGLE (Optical Gravitational Lensing Experiment) project telescopes first observed the lensing event of the exoplanet on July 11, 2005 (it is the smallest and the most Earth—like exoplanet discovered to date). 1811) 1812] OGLE is a long—term (NSF and NASA funded) research project that began sky searches for stellar variability in 1997.

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1812] [https://www.gmxattachments.net/de/cgi/mail-view?m=741299671%2E2E1138271647&MSGNO=111%2Da004bb6e781aabcdab73bb43ccae7317&_f=att](https://www.gmxattachments.net/de/cgi/mail-view?m=741299671%2E2E1138271647&MSGNO=111%2Da004bb6e781aabcdab73bb43ccae7317&_f=att)
1.8.4 Introduction of quantum technology applications in spaceflight

At the start of the 21st century, a new class of enabling technologies promises to offer services for real applications which are based on quantum mechanic principles - a theory originally conceived by Max Planck in 1900 - with measurement dimensions on the atomic scale. Obviously, these applications have the potential to increase the measurement capabilities of new devices (with regard to accuracy, precision, and interpretation) by many orders of magnitude. Only fairly recent technology developments (since the 1980s) permitted the introduction of some spaceborne components, sensors, and experiments that utilize the new quantum technologies. In parallel, quantum technology applications are also being introduced into such fields as: quantum information technology (quantum computers, quantum cryptography, and communications), and nanotechnology in general. All these developments have propelled quantum mechanics into a multidisciplinary frontier research topic.

Some examples of quantum technology developments relating to new sensors or components in space applications are: 1813)

- **QWIP (Quantum Well Infrared Photodetector)**

  The field of quantum optoelectronics deals with electrically induced optical properties of nanometer-scale structures such as quantum dots, superlattices and quantum wells. When the dimensions of these structures become comparable to the wavelength of the electrons, or the photons they generate, their optical and electrical properties are modified. — The use of QWIP arrays to detect infrared radiation can be explained by using the basic principles of quantum mechanics. The quantum well is equivalent to the well-known “particle in a box problem” in quantum mechanics. QWIPs utilize the photoexcitation of electrons (hole) between the ground state and the first excited state in the conduction (valance) band quantum well. The quantum well structure is designed so that these photo-excited carriers can escape from the quantum well and be collected as photocurrent. QWIPs are being used as intrinsic infrared detectors in the spectral range 6-20 μm. See also chapter 1.2.8.1.

  The QWIP technology was developed in the 1980s by Barry F. Levine and his colleagues at Lucent’s Bell Labs (formerly AT&T Bell Labs) in close cooperation with NASA (GSFC and JPL). In the meantime, the QWIP infrared imaging detection technology has been and is being introduced into many observation applications such as in: fire fighting, volcanology, medicine, military surveillance and reconnaissance, astronomy, and general Earth observation applications; hyperspectral imaging is among them. 1814) In 2001, the QWIP technology was one of the new developments inducted into the US Space Technology Hall of Fame. 1815) In Feb. 2003, a NASA/GSFC team fabricated and tested the first large-format QWIP detector array of one million pixels, a GaAs semiconductor chip. 1816) 1817)

- **QGG (Quantum Gravity Gradiometry)**

  The experimental developments of laser cooling and manipulation of atoms, first introduced in the 1990s, have lead to an entirely new class of gravity sensors: namely the quantum gravity gradiometer (QGG) based on atom interferometry. Unlike any previously known gravity sensors, the quantum gravity gradiometer uses atoms themselves as drag-free test masses. At the same time, the quantum wave-like nature of atoms is utilized to carry out interferometric measurement of the effect of gravity on the atoms. The exquisite

1813) http://www.esa.int/SPECIALS/GSP/SEMU42ZO4HD_2.html
sensitivity potentially achievable with atom-wave interferometry holds great promise for
new gravity mapping and monitoring capabilities - higher measurement sensitivity, finer
spatial resolution, and temporal monitoring. 1818) 1819)

As of 2003/4, the goal of a NASA/JPL research team is to construct a viable laboratory
instrument based on these principles to be used eventually in a spaceborne mission in support
of geodesy applications.

As of 2006, NASA/JPL completed the development of a laboratory – based quantum gravi-
ty gradiometer based on atom interferometer technology (dual light—pulse concept). This
represents a first step towards a new spaceborne gradiometer instrument, which can signifi-
cantly contribute to global gravity mapping and monitoring important in the understanding
of the solid earth, ice and oceans, and dynamic processes. 1820)

Background: Light-pulse interferometers work on the principle of quantum-mechanical
particle-wave duality that when an atom absorbs or emits a photon, momentum must be
conserved between the atom and the light field. The wave-like nature of atoms is exploited
to construct an atom interferometer analogous to laser interferometers. John F. Clauser of
LLNL (Lawrence Livermore National Laboratory), Livermore, CA, first proposed using
an atom interferometer as a gravity sensor in 1988. 1821) In his conclusion he states: Practical
scientific applications of the proposed interferometer include measurements of the Lense-Thir-
ing and de Sitter precessions, measurements of the composition-dependent “fifth force,” ob-
servation of time delays of the gravitational fields of the sun and moon (and thus the speed of
gravitational waves), measurement of gravitational gradients, tests of the Equivalence Principle,
and measurements of energy shifts of the total energy of a free atom (such as those due to sym-
metry breaking effects). Important practical applications of such devices occur in the fields of navi-
gation, geology, surveying and the analysis of structures. – However, his idea could not be fully
realized until subsequent advances in laser cooling and manipulation of atoms were avail-
able. S. Chu and M. Kasevich of Stanford University first demonstrated the measurement of “g” using a light-pulse atom interferometer in 1992. 1822)

In the 1990s and later on, matter-wave interferometry has shown its potential to be an ex-
tremely sensitive probe for inertial forces. Photons carry momentum, when an atom ab-
sorbs/emits a photon, its momentum changes accordingly. In a quantum gravity gradiometer,
the atoms themselves are being used as test masses. At the same time, the quantum nature of
atom as matter-wave is utilized to carry out interferometric measurement of the effect of gravity
on the atoms.

- Quantum gyroscopes

The quantum gyroscope is a concept proposed at NASA/JPL (Jon Dowling) in 1997. Cal-
culations suggest that the two-input port optical quantum gyroscope ought to be about 10^8
times more sensitive to rotations than a one-input port optical gyroscope. 1823)

The measurement of rotation (or spin) is closely tied to gyroscopic measurements since the
principle is based on the conservation of angular momentum. SQUID (Superconducting

1818) N. Yu, J. M. Kohel, J. Ramirez-Serrano, J. R. Kellogg, L. Lim, L. Maleki, “Progress towards a space-borne quan-
tum gravity gradiometer,” Proceedings of NASA ESTC (Earth Science Technology Conference), Palo Alto, CA,

1819) N. Yu, J. M. Kohel, L. Romans, L. Maleki, “Quantum Gravity Gradiometer Sensor for Earth Science Applica-
tions,” Proceedings of NASA ESTC (Earth Science Technology Conference), Pasadena, CA, June 11--13, 2002,
URL: http://esto.nasa.gov/conferences/estc--2002/Papers/B3P5(Yu).pdf

1820) J. M. Kohel, N. Yu, J. R. Kellogg, R. J. Thompson, D. C. Aveline, L. Maleki, “Quantum Gravity Gradiometer
Development for Space,” Proceedings of the Sixth Annual NASA Earth Science Technology Conference (ESTC
2006), College Park, MD, USA, June 27--29, 2006, URL: http://www.estc.nasa.gov/conferences/ESTC2006/pa-
pers/b4p1.pdf

1821) J. F. Clauser, “Ultra-high sensitivity accelerometers and gyroscopes using neutral atom matter-wave interfer-

1822) M. Kasevich, S. Chu, “Measurement of the gravitational acceleration of an atom with a lightpulsed atom interfer-

1823) http://cism.jpl.nasa.gov/program/RCT/QuantCompUD.html
Quantum Interference Device), is a fairly new detector type most sensitive for magnetic field detection, in particular with superconducting technology. A solid-state magnetometer formed by the parallel circuit of two Josephson junctions is called a direct current or a DC-SQUID. In practical SQUID measuring instruments, by means of a negative feedback with an additional coil, the flux through the SQUID loop is held constant. The strength of the feedback current necessary for this is then a measure of the magnetic field to be measured.

In 2001, the phenomenon of quantum interference was also demonstrated in a liquid state experiment, namely in a superfluid SQUID at UCB (University of California, Berkeley). The double-path experiment demonstrated that quantum interference is identical to the interference between light waves, electrons, atomic beams and electrical currents in solid superconductors. In the experimental setup, the superfluid SQUID geometry, analogous to the superconducting DC-SQUID configuration, provided the rotation detection (analogous to a gyroscopic detection) in the superfluid; the quantum phase shift was controlled by using the rotation of the Earth. Hence, a superfluid SQUID couples to rotation measuring minute changes in rotation; the technology may for instance be used as a detector of absolute rotation measurement. The sensitivity of the superfluid SQUID technology gives rise to the development of a quantum gyroscope. This is of vital interest for future missions in geodesy (detecting minute gravitational deviations, etc.). The ESA mission HYPER (Hyper-Precision Cold Atom Interferometry in Space), under definition in 2004, may be able to use this new technology.

Rotation measurements are also being considered in spin electronics applications to enable manipulations of the electron charge and spin. The ability to manage electron spin is expected to lead to improvements in electronic systems and devices used in photonics, data processing and communications applications.

- Applications of improved atomic clocks

ACES (Atomic Clock Ensemble in Space) is an ESA-selected nadir-oriented instrument to be flown on ISS (launch expected in the 2006 time frame). ACES is a laser-cooled cesium atomic clock, exploiting the microgravity conditions onboard ISS to reach unprecedented precision not achievable on Earth. In fact, a cold atomic clock works more accurately under weightlessness than under Earth’s gravity. The laser cooling is used to reduce the thermal velocity of atoms to a few cm/s, corresponding to a temperature of about 1 K.

Background on laser cooling. The technology of laser cooling began with the development of a set of tools using laser beams to slow atoms down, cooling them to within a millionth of a degree above absolute zero (the atoms actually relinquish their heat energy to laser light and thus reach lower and lower temperatures). At these cold temperatures, cesium atoms are left with a residual velocity of only 1 cm/s. This slowing of atoms allows longer observation times to study the atoms’ behavior. When a laser-cooled vapor (like cesium) is taken to microgravity, the observation time is increased considerably because the cold and slow atoms will not fall out of the observer’s view as quickly as they do under the influence of the Earth’s gravity. The small residual velocity makes for instance cesium atoms attractive candidates for precision spectroscopy in atomic clocks.

Laser cooling techniques have also been used to cause a cloud of atoms to condense into the Bose-Einstein state, a new state of matter similar to superfluid helium. The BEC (Bose-Einstein Condensate) occurs when atoms at a particular temperature and pressure, on the removal of some energy, fall into lock-step with one another.

Background on BEC: The Bose-Einstein condensate is a purely quantum form of matter, first predicted by Albert Einstein and the Indian physicist Satyendra Nath Bose in 1924.

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1825) R. Sanders, “Quantum interference demonstrated for first time in liquids as physicists make superfluid analog of superconducting SQUID, a potential ultrasensitive gyroscope,” July 5, 2001, URL: http://www.berkeley.edu/news/media/releases/2001/07/05_SQUID.html
Normally, light appears to heat things up (through absorption of light by the material). However, it is possible, in some cases, to use light to cause materials to give up more energy than they absorb, causing them to cool. Basic research with laser cooling of atoms was first done in the 1980s by Steven Chu of Stanford University, Claude Cohen-Tannoudji of Collège de France, and William D. Phillips of NIST (National Institute of Standards and Technology), Gaithersburg, MD. However, it took until 1995 when the first BEC was created and observed by the three scientists in a laboratory at the University of Colorado. For this work the physicists listed above were awarded the 1997 Nobel Prize in Physics.
1.9 Satellite Orbits

Newton’s laws of motion provide the basis for orbital mechanics. A satellite’s orbit is generally defined by six independent parameters (see Table 99). For remote sensing satellites the most important parameters are: a) mean radial distance with regard to the Earth’s center of mass, referred to as semi-major axis [the radial extremes are designated by perigee (min) and apogee (max) above the Earth’s surface]; b) inclination (angle between the Earth’s equatorial plane and the spacecraft’s orbital plane (major axis); and c) by the time, or period, it takes to complete one orbit about a central body like Earth. The orbital period increases with the mean altitude of the orbit, so a satellite in LEO moves faster than a satellite in MEO, and still faster than a satellite in GEO.

In general, Earth orbits are elliptical; circular orbits are a special case of elliptical orbits (providing on average a constant-altitude observation geometry, a constant orbital speed, as well as a constant signal strength). Satellites in non-circular orbits (i.e., eccentricity > 0) move faster when they are closer to the Earth (i.e. at perigee), and slower when they are farther away (i.e. closer to apogee).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_E$</td>
<td>6378 km, the average Earth equatorial radius</td>
</tr>
<tr>
<td>$T_{GEO}, T_{GSO}$</td>
<td>Earth rotation period = 24 h (in mean solar time)</td>
</tr>
<tr>
<td>$n_{sun}$</td>
<td>Mean motion of the fictitious mean sun, $n_{sun} = 0.9856,\text{day}^{-1}$</td>
</tr>
<tr>
<td>$\frac{d\theta}{dt}$ (theta-dot)</td>
<td>Theta-dot is the sidereal rotational rate of the Earth $= 360.9856,\text{day}^{-1}$; consequently the Earth sidereal rotation period is 23 h 56 m 4 s.</td>
</tr>
<tr>
<td>Orbital revolution</td>
<td>A revolution or period is defined as the time from one perigee to the next</td>
</tr>
</tbody>
</table>

**Keplerian Elements**

- **a**: Semi-major axis (or mean orbital radius)
- **e**: Eccentricity: defines the shape of the orbital ellipse, if $e=0$ the orbit is circular
- **i**: Inclination of orbital plane to equatorial plane. The orbital plane always goes through the center of the Earth; $i=0^\circ$ (equatorial orbit), $i = 90^\circ$ (polar orbit)
- **$\Omega$ (Omega = RAAN)**: Right ascension of ascending node; the longitude of the ascending node at which the orbit crosses the equator northbound; RAAN is an angle, measured at the center of the Earth, from the vernal equinox to the ascending node. For some orbits the right ascension of the ascending node ($\Omega$) may move as much as $6^\circ$/day.
- **$\omega$ (omega)**: Argument of perigee: the angle between the ascending node and the perigee; for some orbits the argument of perigee ($\omega$) may move as much as $12^\circ$/day.
- **$T_0$**: Epoch, time at which the orbital elements are defined

**Special Orbits**

- **SSO (Sun-synchronous Orbit)**: $\omega$ (omega-dot) = $n_{sun}$; most near-Earth SSOs have inclinations between 97º and 103º. SSO is characterized by synchronizing the rate of change of ascending node ascension to the rate of the Earth rotation around the sun
- **GEO (Geostationary Orbit)**: $n = \theta$ (where $n$ is the mean motion of the satellite), and in addition: $i$ (inclination) = 0, and $e$ (eccentricity) = 0
- **GSO (Geosynchronous Orbit)**: $n = \theta$ (where $n$ is the mean motion of the satellite)
- **Molniya-type orbit**: $\omega$ (omega-dot) = 0 (i.e., no secular drift of the perigee), with $i = 63.43^\circ$ (generally orbits of 12 hour periods with very long times in apogee. The ground track for the northern hemisphere loops back on itself in a narrow pattern that enables multiple observing opportunities per orbit

Table 99: Overview of some orbital parameters/definitions and special type orbits

Obviously, an infinite number of possible orbits can be defined for a spacecraft in Earth orbit. However, a number of special Earth orbit types (or classes) evolved since the early space age to cover particular observational and/or operational characteristics such as: LEO (polar, SSO, etc.), MEO, GEO (GTO, GSO), HEO (Molniya, etc.), and Halo orbits (these are briefly covered in the following chapters). Generally, the observation coverage of a geographical area increases with increasing observation distance from Earth (but the spatial resolution decreases with increasing distance).
In general, the LEO-type observation provides high spatial resolution with low temporal resolution – while GEO-type observation provides for low spatial resolution, but high temporal resolution. Note: The GEO observation occurs at a distance of about 45 times farther away than the LEO observation (considering an average LEO altitude of 800 km).

From a legal/management point of view, all orbits represent a natural space resource to be shared by all participants, with some orbits of rather limited capacity. The ITU (International Telecommunications Union) is the entity which regulates for instance the use of GEO (Geostationary Orbit) traffic of satellites (allocation of GEO position - only 360º of orbital arc are available in the equator plane) as well as of the radio frequency spectrum for all orbits of airborne and spaceborne vehicles (another natural space resource of very limited capacity to be shared by all). 1826)

### 1.9.1 LEO (Low Earth Orbit)

The general altitude range of LEOs is < 2000 km above the Earth’s surface with orbital periods of about 90-120 minutes (in general all inclinations are possible). The orbital velocity of a LEO spacecraft with regard to an observer on Earth is generally in the order of 7-8 km/s (requiring fast observation schemes; this involves also coping with large Doppler shifts for communication needs and other measurement services). 1827) 1828) The circular LEO is the most common and natural orbit for Earth observation, in particular in the altitude range of about 200-900 km with orbital periods of about 90-105 minutes. The polar orbit, and in particular the sun-synchronous orbit, are special LEO subclasses.

The very first satellites, like Sputnik-1 and most successors, had LEO orbits and were launched in an eastward direction (thereby gaining a boost with the Earth’s rotation), and obtaining an inclination of the launch site’s latitude. - To achieve a polar orbit requires more energy, thus more propellant, than does an orbit of low inclination. A polar orbit cannot take advantage of the “free ride” provided by the Earth’s rotation, and thus the launch vehicle must provide all of the energy for attaining orbital speed. 1829)

The vast majority of LEO spacecraft, orbit at altitudes of \( \leq 1000 \) km. The 1000 km altitude limit represents a ceiling of a region, in which the atmospheric drag is still being felt for a long-term decaying orbit (the decay may actually last for centuries for spacecraft in orbits close to the limit). All spacecraft in orbits with perigee altitudes > 1000 km, and without any onboard deorbiting means, must be considered as “eternal debris” at EOL (End of Life). In most space applications, drag is considered an unwanted disturbance related to atmospheric density changes. These changes are induced by solar extreme ultraviolet irradiance (EUV) variations, i.e., one of the effects of space weather.

The class of LEO satellites can only provide intermittent coverage of a geographical area (considering a single spacecraft). The observation coverage from LEOs is limited by the FOV (Field of View) of the satellite’s observation instruments. A nadir-viewing spacecraft with its payload FOV (Field of View) can only see a small portion of the Earth’s surface instantaneously, namely the footprint, resulting in a coverage geometry of observation swaths (normally the width of the imagery on Earth’s surface) by the various instruments in a continuous observation support mode (and provided by the spacecraft’s orbital motion). This

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1826) Note: ITU is an UN agency since 1947 to cover standards for a wide range of telecommunication services

1827) Note: From a viewpoint of orbital mechanics, circular orbits are only on average “circular,” referring to average conditions over long-term periods (1000 years or so). No satellite is in reality orbiting in a circular orbit. The nature of Keplerian elements is variable: this means the semi-major axis on a circular orbit \( (e=0.0) \) is actually varying by about 20 km for satellites in LEO. Naturally, this affects to some extend the observation geometries with the additional effect of polar oblateness.

1828) Note: Satellites [Ofeq series of IAI (Israel Aircraft Industries)] launched from Israel (Palmachim Air Force Base south of Tel Aviv) orbit from east to west, as opposed to the traditional west to east direction, as Israel can only safely launch rockets to the west, over the Mediterranean Sea.

1829) http://www.geo-orbit.org/sizepgs/geo.def.html#anchor1302357
scenario results in a periodic observation coverage of a rotating Earth. Satellite contact periods with ground stations are generally limited to about 8-12 minutes, depending on the orbital geometry relation to a particular station.

Global LEO observation coverage was an early requirement in spaceflight. This led to new strategies in mission design concepts - in particular with regard to orbital plane inclinations and to orbital altitudes. Obviously Earth observation coverage is much more effective by a LEO spacecraft with a high inclination (say 90º, a polar orbit) than one with a low or even 0º inclination (i.e. an equatorial orbit). In a polar orbit (in which the satellite passes over or fairly close to the vicinity of both poles), the entire Earth is rotating underneath the orbital path of the satellite, thus permitting a global coverage in a minimum time of 12 hours (if slightly overlapping observation swaths can be provided). In this setup, the satellite’s orbit and the rotation of the Earth work together to allow complete coverage of the Earth’s surface, after it has completed one complete cycle of orbits. - In an inclined orbit of 60º, for instance, observation coverage can only be provided ranging from the equator up to the latitudes of ±60º. Hence, polar orbits (with inclinations close to 90º) turn out to be particularly useful for global mapping and surveillance functions.

The study of these general coverage schemes was of particular interest in the early phase of the space age and far beyond, opening up new vistas for various kinds of mission applications and service configurations.

### Figure 40: Schematic illustration of polar orbits and swath projections

- **Observation coverage** considerations in polar orbits, including SSOs (Sun-Synchronous Orbits) which are near-polar orbits: A spacecraft in a LEO polar or near-polar orbit (within an altitude range of about 200-2000 km) provides on average 16 to about 10 orbits per day (dictated by orbital mechanics). This corresponds to 25.7º of longitudinal separation between successive orbits related to the equator (Earth circumference of 360º divided by an average of 14 orbits at about 800 km altitude). In a single orbit, two swath widths should be added to the coverage, accounting for the northward (ascending) orbital path on one side of Earth and for the southward (descending) orbital path on the other side of the pole - all in one orbital revolution. However, if the orbit is also sun-synchronous, the ascending pass is most likely on the shadowed side of the Earth, while the descending pass is on the sunlit side. 1830 Hence, sensors recording reflected solar energy only, image the Earth’s surface on a descending pass of the orbit only, i.e. when solar illumination is available. In gener-

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1830 In general, SSOs may have any defined local time (equator crossing time) in either of their ascending or descending nodes. There is no rule that the ascending pass of an SSO has to be in the sun’s shadow.
al, each polar orbit experiences about 70% of sunlight exposure and about 30% of darkness or shadowing (in an average 100 minute orbit, this amounts to 70 minutes sunlight and 30 minute shade). 1831)

- Contiguous repeat coverage. Obviously, the observation geometry in a polar orbit is such as to provide contiguous repeat coverage on every orbital path at the poles as well as at high latitudes (in the polar regions). However, the sunlit swath projection requirements (of 25.7º longitude) widen constantly along the orbital path of a spacecraft flying over a rotating Earth, reaching twice per orbit a maximum in the equator plane with about 2860 km between adjacent orbits (Earth equatorial circumference of 40,000 km divided by 14 orbits). **This implies an observation swath width of at least 2860 km if a daily global overlapping coverage of the sunlit portion of the orbit is required.**

Active sensors which provide their own illumination, or passive sensors that record emitted (e.g. thermal) radiation, can also image the Earth’s surface on nighttime passes of the orbit. In Earth observation there are not many imaging instruments providing swath widths around 2900 km or more (they all deal with weather or environmental parameter observations). Some examples of sensors with a daily global coverage capability in polar orbits are:

- AVHRR (Advanced Very High Resolution Radiometer) of the NOAA/POES series and on the future MetOp series of EUMETSAT (MetOp-A launch Oct. 19, 2006), provides a swath width of 2900 km (FOV of ±55.37º)
- OLS (Operational Linescan System) of the DMSP series has a swath of 2960 km (FOV= ±56.25º)
- SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) of the OrbView-2 mission of ORBIMAGE (launch Aug. 1, 1997) provides a swath width of 2800 km in LAC (Local Area Coverage) mode; FOV = ±58.3º.
- MSU-MR (Low Resolution Multispectral Scanner), flown on the Meteor-3M series of Russia (launch of Meteor-3M-1 on Dec. 10, 2001), provides a swath width of 3000 km
- VIIRS (Visible/Infrared Imager and Radiometer Suite) of the future US NPOESS series provides a swath width of 3000 km (corresponding to a FOV of ±55.84º
- OMPS (Ozone Mapping and Profiler Suite) instrument of NPOESS provides also global daily maps of the amount of ozone in the vertical column of the atmosphere (in UV range).

All of the above instruments provide a global daily overlapping coverage in their VNIR bands of reflected solar energy (imagery of visible bands); in addition, the instruments provide a twice-daily global overlapping coverage in their respective SWIR/MWIR/TIR bands of emitted radiation (OMPS is excepted which has only a UV/VNIR spectral range).

In general, the swath widths of observation instruments do not add up easily to exact integral parts of orbital coverage cycles. It means, there are coverage gaps between two adjacent orbits. In these cases, the interval of time required for the satellite to complete its orbit cycle is not the same as the **revisit or repeat period.** The revisit period is defined for a specific site and represents the minimal time interval (in days) between two imaging opportunities of this specific site. The ground track repeatability is defined by the time period (in days) between the satellite revolutions having the same ground track.

Quick revisit times of a particular area (with preference to “daily” and not something like 16 days) are often a much wanted requirement of an imaging mission. However, a more frequent coverage of a given area can only be provided from LEO orbits at higher altitudes (say 3000 km) providing considerably wider ground swaths (or from a constellation of spacecraft). On the other hand, a higher orbit for a given instrument means also a coarser resolution of the imagery. Current technology requires a compromise for an optimal solution. But the not so far future will also permit these higher orbits at fairly good resolutions of the imagery.

1831) http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter2/chapter2_2_e.html
Another development, namely that of directional instrument pointing or spacecraft pointing (also referred to as “body pointing”), must be considered for event coverage or for commissioned imaging coverage of particular surface regions. The pointing agility of a spacecraft, introduced mostly since the 1990s with increasing capabilities, led to the introduction of FOR (Field of Regard) coverage. FOR designates the angular coverage capability beyond (and including) the swath - it allows the imaging of nearby events of interest that happen to be just outside the regular (generally nadir-centered) swath.

Background on the introduction of some observation schemes:

- The US satellite Discoverer-1 (launch on a Thor vehicle from VAFB on Feb. 28, 1959, apogee = 968 km, perigee = 163 km, inclination = 89.7°, period = 96 min) was the first spacecraft in polar orbit. It flew a military payload. This was followed by the “Transit” navigation satellite series of the US Navy. Starting with the launch of Transit-5A-1 (and follow-up satellites of the series) on a Scout vehicle from VAFB, CA, on Dec. 18, 1962.

- In the field of Earth observation, the orbital strategy of polar orbit was introduced with Nimbus-1 (launch Aug. 28, 1964), then with TIROS-9 (launch Jan. 22, 1965). The polar orbit enabled the provision of full repetitive global coverage. Depending on sufficient swath width, some sensors (such as AVHRR of the NOAA POES series with a swath > 2900 km and OLS of the DMSP series with a swath of 3000 km) were able to provide daily global coverage, while other sensors needed several days for a repeat cycle.

- Coverage from a LEO constellation of spacecraft in the same orbital plane. This technique is being employed in some EO missions for quick revisit times on a global scale. In this context, “revisit” refers to the capability to fly again over a given geographic site and to image the site under different conditions (e.g., with a varying incidence angle). In general, all S/C of a constellation (of 4-5 S/C) are being positioned in the same orbital plane and phased in equal distances around the orbit. The S/C fly actually in the same orbital arc in an Earth frame, which means that the successive observation swaths are generally overlapping (due to Earth rotation) and adding to the overall swath width of the constellation. Some examples of constellation observation coverage are:
  - The US-German GRACE constellation (launch March 17, 2002) consists of two S/C in a polar co-planar orbit at distances of 170-270 km apart. The intersatellite range is measured very accurately between the freely moving S/C to derive high-resolution models of Earth’s gravity field.
  - As of 2004, the international DMC (Disaster Monitoring Constellation), built and managed by SSTL, consists of four microsatellites from various countries [AlSat-1 (Algeria), BILSAT-1 (Turkey), NigeriaSat-1 (Nigeria), and UK-DMCSat-1 (UK)] in the same orbital plane. All S/C fly an optical sensor payload of medium resolution and a fairly wide swath providing rapid coverage (daily revisits are possible).
  - The ROCSat-3/COSMIC constellation is a joint project of NSPO (Taiwan) and UCAR (USA), consisting of 6 microsatellites all in a single orbital plane. A launch took place on April 14, 2006. The objective is to collect atmospheric remote sensing (occultation data from GPS signals) for operational weather prediction, climate, ionospheric (space weather monitoring), and geodesy research.
  - The COSMO-SkyMed mission of ASI consists of a total of 4 spacecraft in the same orbital plane (launch of the first S/C on June 8, 2007, constellation complete in 2008) carrying SAR instruments (observations in the microwave region).
  - The RapidEye constellation of RapidEye AG employs 5 S/C in the same orbital plane (launch 2007) to perform observations in the optical region.

1.9.1.1 Sun-Synchronous Orbit (SSO), a LEO subgroup

- In general, a near-Earth SSO (also referred to as heliosynchronous orbit) is a special case of the near-polar orbit. Sun-synchronous orbits are made possible by the fact that the
Earth is not a perfect sphere. In an SSO, the daily rotation of the orbital satellite plane (with respect to the equatorial plane) is identical to the mean motion of the fictitious sun around the Earth - which in turn is identical to the mean motion of the Earth around the sun. The effect of the rotation of the orbital satellite plane is due to the oblateness of the Earth [i.e., the SSO orbit design is such that the Earth’s mass inhomogeneities cause the slight orbit precession of about 0.9856º per day (Ω) to the east, equivalent to the daily revolution rate of Earth around the sun]. Hence, SSO observations are locked into a fixed (solar) time of the day. Note: All satellite orbits, at any inclination other than exactly 90º, are affected gravitationally by the fact that the Earth is not a perfect sphere.

Figure 41: Schematic of two successive sun-synchronous orbits of a S/C 1832)

Some characteristics of SSOs are:
- The most important characteristic of a sun-synchronous orbit is the provision of **repeat observations** (same sun illumination angles and viewing geometry) of a given Earth surface region at the same time of the day (due to same latitudinal crossings), improving considerably the conditions for data analysis. The orbital plane of an SSO always presents the same aspect with respect to the sun.
- An SSO provides also a good power provision for the spacecraft; the nearly constant sunlight ratio of the satellite on each orbit implies a near constant solar energy supply for the satellite platform. As near-polar orbits, SSOs permit also global observation coverage.
- All sun-synchronous orbits are retrograde orbits (i.e., they have inclinations in the range 90º ≤ i ≤ 180º). In retrograde orbits, the projection of the satellite’s position onto the equatorial plane revolves in the direction opposite to Earth’s rotation (i.e. a retrograde orbit has a westward motion or precession on consecutive orbits). 1833)

Note: Orbital mechanics permits to define high-altitude SSOs with maximum inclinations of 180º (the latter orbital plane is of course in the equator plane). However, these orbits are of little observational interest due to their very limited range of coverage in the equator plane only. 1834)
- Assuming that orbital altitudes of ≤ 1000 km are considered to produce too much residual drag, the minimum inclination available for SSOs will be about 100º. Lower inclina-

1832) Courtesy of EUMETSAT
1834) Information on the topic of orbital mechanics for the various orbit types was kindly provided by Friedrich E. Jo- chim of DLR/GSO.
tions, which are closer to polar orbits, would lead to SSOs at altitudes below 1000 km. SSOs with inclinations between 90º and 96º are not possible because they would require negative orbital altitudes.

- The closer a circular SSO approaches a polar orbit, the lower will be the orbital altitude. The SSO has indeed become the most widely used orbit for Earth monitoring applications due to its special observation characteristics. An SSO for observational imagery is generally circular within an altitude range of about 300-900 km (most SSOs have 700-800 km circular orbits), a radial distance permitting fairly good ground resolutions for optical as well as microwave instruments. The time of nodal equator crossing may of course be defined for any time of the day; however, most missions usually select this time between mid-morning and mid-afternoon on the sunlit side of the orbit.

Some examples of the sun-synchronous orbit are:

- **The first SSO in a military program** was realized on the early classified DMSP (Defense Meteorological Satellite Program) series of DoD. The code name of the spacecraft was P35-2 with a launch on Aug. 23, 1962. The orbit of P35-2 was: perigee of 578 km, apogee of 752 km, inclination of 98.5º, period of 98.1 min, spacecraft mass of 91 kg. The COSPAR designation of P35-2 was: 1962-A-Omicron-1 (also known as Ops-3502 and FTV-3502).

- **The first SSO in a civilian program** was realized on TIROS-9 of NASA (launch Jan. 22, 1965), using an elliptical orbit with an apogee of 2582 km, a perigee of 705 km, an inclination of 96.4º, and a period of 119.2 minutes. This was followed by TIROS-10 (launch July 2, 1965). TIROS-10 had already a near-circular SSO with an apogee of 837 km, a perigee of 751 km, an inclination of 98.65º, and a period of 100.76 minutes. The SSO retrograde orbit drifted westward at about 1º/day.

- All Landsat missions (launch of LS-1 on July 23, 1973) featured SSOs with an average nominal orbital altitude of 905 km for LS-1, LS-2, and LS-3. The follow-up missions had nominal altitudes of 705 km and a sun-synchronous orbit.

- The SPOT satellite series of CNES (in continuous operation since 1986) uses SSOs, so do all commercial imaging missions as well as many other missions in Earth observation.

- A fairly uncommon SSO is the one selected for the ST5 (Space Technology 5) mission of NASA, a launch took place on March 22, 2006. ST5 has an elliptical orbit with a perigee at about 300 km and an apogee of about 4500 km, the inclination is 105.6º (period of 136 minutes). The objective is to measure the effect of the sun’s activity on Earth’s magnetic field.

- **The dawn-orbit** (or dawn-dusk orbit) is a special case of the sun-synchronous orbit (normally at local equator crossing times of 6 AM or at 6 PM) where the satellite trails the Earth’s shadow. When the sun shines on one side of the Earth, it casts a shadow on the opposite side of the Earth — this shadow is nighttime. The dawn-dusk plane represents an orbit 90º to the noon-midnight plane — thus, the sun vector is nearly perpendicular to the orbit plane during the entire mission. Because the satellite never moves into this shadow, the sun’s light is always on it, i.e. like perpetual daytime. Since the satellite is close to the shadow, the part of the Earth the satellite is directly above is always at sunset or at sunrise; that is why this kind of orbit is called a dawn-dusk orbit.

A dawn-dusk orbit allows a satellite to always have its solar panels in the sun, obviously a great advantage for a power-hungry spacecraft with active instruments like SARs, lidars, or scatterometers. In addition, a dawn-dusk orbit simplifies the satellite design since no solar panel steering mechanism is needed to maintain normal incidence to the sun; also the solar array utilization efficiency increases, and the battery size decreases. Besides, a satellite in

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1835) Note: The path of the dawn-dusk orbit along the terminator is somewhat “theoretical.” Throughout a year, portions of the orbit will be at times in the sun’s shadow due to ecliptic effects of the sun’s motion and the eccentricity of Earth’s orbit.
dawn-dusk orbit experiences a very stable thermal condition, one side of the satellite being permanently illuminated by the sun, the opposite side always facing deep space.

[Note: Spacecraft with sun-synchronous orbits using other nodal crossing times than dawn-dusk (say at 10:00 hours) experience an **ecliptic phase** once per orbit (moving into the shadow of the sun); during this period the spacecraft must rely on its battery power to maintain operations].

Some examples of spacecraft placed into sun-synchronous dawn-dusk orbits are:

- The MAGSAT spacecraft (also referred to as Explorer 61) of NASA (launch Oct. 30, 1979, the satellite remained in its orbit for seven and a half months until June 11, 1980) was probably the first satellite in a dawn-dusk orbit for observational reasons. Since magnetic fields from the magnetosphere are a disturbing factor in such a mission, a factor that strongly depends on the orientation of the orbit relative to the sun’s direction, a dawn-dusk orbit was selected which kept the orbit’s orientation relative to the sun stable. The effect was that observational disturbances also stayed more or less the same throughout the mission.  

- The Astrid-1 microsatellite of IRF-K (Swedish Institute of Space Physics in Kiruna) with a launch Jan. 24, 1995 employed a dawn-dusk orbit during the initial phase of its mission.

- The RADARSAT missions of Canada (launch Apr. 11, 1995, and the follow-up RADARSAT-2 with a launch in 2007)

- The QuikSCAT mission of NASA (launch June 19, 1999) with the SeaWinds scatterometer aboard uses a dawn orbit with a nodal crossing time at 6:00 hours.

- The COSMO-SkyMed constellation of ASI, Italy (launch of first satellite on June 8, 2007)

- The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission of ESA (launch in 2007)

- The TerraSAR-X1 mission of DLR/EADS-Astrium (launch June 15, 2007)

- The ADM-Aeolus mission of ESA (launch 2008).

- Starting in the mid-1990s, the LEO space region is also heavily being used by the communications industry, providing the services of the “Big LEO” and “Little LEO” constellations.

### 1.9.1.2 Exact repeat orbits (a LEO subgroup)

Orbits designed with repeating (or subrecurrent) ground tracks follow specific objectives in some types of missions (Earth observation missions or rendezvous and docking missions). The exact repeat orbit concept covers identical groundtracks at a given repeat cycle, representing a tradeoff between duration of repeat cycle and track spacing.  

In Earth observation, the limited observation capability of single LEO missions, in particular for geodetic applications (objective: provision of large-scale high-resolution measurements of ocean topography), has led to exact repeat pass designs to obtain surface grids for measurement correlations (i.e., cross-track sampling is pre-determined by the exact repeat orbit pattern). Measurements of ocean topography by radar altimetry inevitably involve a tradeoff between spatial resolution and temporal resolution; improvement of one results in degradation of the other. In single-pass interferometric SAR applications, the nearly exact repeat orbit allows formation of an interferometric baseline. Exact repeat orbit missions play also

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1836) http://www--istp.gsfc.nasa.gov/Education/wloopolar.html
an important role in Earth gravity model studies. 1838) A future approach to this coverage-limited problem may be the use of a satellite formation with coordinated orbits.

Some application examples of exact repeat pass missions in Earth observation are:

1) **Altimetry missions.** In altimetry missions, the exact repeat orbit represents an excellent reference to relate measurements from various altimeter missions (on space-time scales). In fact, all altimeter missions, maintained in a repeating orbit configuration, facilitate the separation of sea height variations from the geoid. Exact repeat orbit altimeter measurements provide a grid of crossover points for the estimation of the ocean current velocity vector (the finer the grid - the better). - A crossover is defined as the intersection of the satellite ground track with itself. 1839) At this location, the two crossing passes (one ascending and one descending) provide independent sea level measurements at the same place but at different times. Crossover differences contain information about uncertainties in the satellite ephemeris and therefore enable correction of radial orbit error. Orbit-corrected crossover differences form the basis for studies of sea level variability, both in a statistical sense and for computation of sea level time series. Tide model studies represent another type of crossover difference application.

Altimeter data makes ocean currents detectable as slopes in the sea surface. Hence, the ocean currents can be detected and monitored. Small-scale features are visible as well, like eddies, which are generated by the large-scale currents such as the Gulf Stream. Satellite tracking and altimeter data are also being used to improve the long wavelength component (>1000 km) of the global geoid models. - In general, perturbations in the satellite orbit result in excursions from the “exact repeat” ground track in the order of ±1 km about the nominal repeat path. This misalignment leads to an error in the estimates of sea surface height variations because of the local slope in the geoid.

Some examples of exact repeat pass altimeter missions are:

- **The GEOSAT (Geodetic Satellite) altimeter mission of the US Navy (launch March 12, 1985, built by JHU/APL) consisted of two mission phases.** 1840) The first one was the classified Geodetic Mission (GM); mission duration = 18 months (until Sept. 1986). GM was based on a 23-day near-repeat orbit which was permitted to drift, ultimately producing a tightly spaced ground track pattern. The second mission phase is known as the ‘Exact Repeat Mission’ (ERM), which was unclassified; it started Oct. 1, 1986 and ended in January 1990. In ERM, the orbit was changed to an exact repeat cycle of 17.05 days for the observation of geodetic parameters of the oceans (dense map of marine geoid, surface height data for assimilation into numerical models and mapping the progression of El Niño in the equatorial Pacific).

- **The GFO (GEOSAT Follow-On) satellite (launch Feb. 10, 1998)** 1841) retraces the orbit of the GEOSAT altimeter ERM (Exact Repeat Mission) mission phase at 800 km altitude, 108° inclination, 0.001 eccentricity, 101.4 min period, latitudinal coverage of ± 72°. The objective is to obtain a dense global grid of altimeter data (crossover points) for use in the areas of geodesy (Earth’s gravitational models), the study of fronts and eddies, winds, waves and ice topography, physical oceanography in the ERM. The 17.05-day exact repeat orbit of GFO retraces the ERM ground track within ± 1 km.

- **The TOPEX/Poseidon (T/P) altimeter mission of NASA/CNES (launch Aug. 12, 1992) uses a circular non-sun-synchronous orbit; 1334 km altitude, 2 hour period, an inclination of 66°, 10-day exact repeat orbits. T/P represents the first dedicated satellite radar altimeter**

1838) Note: A subrecent orbit means that after a certain number of days, the satellite repeats its original orbit. This orbit enables the satellite to observe the same area at regular intervals.
1839) http://www.nodc.noaa.gov/General/CDR—detdesc/crossover.html
mission optimally designed for scientific study of the ocean. \(^{1842}\) The instrument measurement accuracy of the dual-frequency altimeter onboard T/P improved by more than a factor of two and the orbit accuracy improved by more than an order of magnitude, resulting in an overall measurement accuracy of about 4 cm. The T/P orbit configuration was chosen specifically for measuring the large-scale SSH (Sea Surface Height) field for studies of ocean variability on monthly and longer time scales. This dictates an orbit with approximately a 10-day repeat period in order to minimize temporal aliasing of mesoscale variability at the measurement.

- Jason-1 mission of NASA/CNES (launch Dec. 1, 2001). The Jason-1 operational orbit follows an “exact repeat ground track” (or a frozen orbit) every 127 revolutions in ten days with the same characteristics as those of T/P (identical orbital tracks (about a minute apart) to perform cross calibration). In this tandem setup, Jason-1 is located one minute ahead of T/P. Both missions are providing high-resolution topography measurement data sets.

Note: A “frozen orbit” is characterized by keeping (or trying to keep) constant the argument of perigee and eccentricity of the orbit, in such way that, to a given latitude, the satellite always passes at the same altitude, benefiting the data users due to this regularity (by making the measurements more consistent). With a frozen orbit, the variation in geodetic height over the same location on successive orbits can be held to a minimum.

- The altimeter crossover data of the ESA missions ERS-1 (35-day repeat and 168-day repeat interleave mission phases), and ERS-2 (35-day repeat) may also be used (in combination with satellite tracking data) for Earth gravity model studies.

- The ICESat (Ice, Cloud and land Elevation Satellite) mission of NASA (launch Jan. 13, 2003) features an exact repeat orbit with a repeat cycle of 183 days to enable uniform sampling of the surface with high resolution. The sensor complement consists of a) GLAS (Geoscience Laser Altimeter System) to measure ice sheet topography, cloud heights, planetary boundary layer heights, and aerosol vertical structure; b) two GPS Blackjack receivers; c) a laser reflector array for ground-based SLR measurements.

2) **Interferometric repeat pass missions (InSAR).** In the general repeat pass interferometry concept, the scenes are acquired at different times, so there is a time difference as well as viewing geometry to consider (baseline). The passes must have rather similar viewing geometry in order to allow extraction of the relative phase difference. This usually requires that the satellite be on an exact repeat orbit. The small difference in viewing geometry allows the extraction of topographic information, in the same way as with a single pass interferometric system (such as SRTM). The superposition of repeat pass imagery provides interference fringes representing the effects of topography and/or motion. \(^{1843}\)

Temporal decorrelation and atmospheric distortions limit the performance of conventional repeat pass interferometry. Repeat pass observations imply significant time lags of several days up to several weeks between the acquisitions of the two interferometric channels. Hence, temporal decorrelation is expected to become a major issue, especially at shorter wavelengths. Hence, a general problem in LEO SAR observations is to minimize the InSAR repeat periods. Wide instantaneous accessibility does not necessarily minimize the repeat time; rather, extensive cumulative (orbit—averaged) accessibility is desired to reduce the orbit repeat period required for global coverage.

Some examples of interferometric repeat pass missions are:

- The SRL-1/2 missions of NASA/DLR/ASI in 1994 (April 9-20 for SRL-1 (STS-59), Sept. 30–Oct. 11 for SRL-2 (STS-68), also referred to as SIR-C/X-SAR missions, see J.23)

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employed two-pass (and repeat pass) interferometry for topographic mapping (detection of topographic surface change in SRL-1 and SRL-2). The SRL-2 11-day mission had an orbit with a nominal altitude of 215 km and an inclination of 57º. This resulted in a slightly drifting orbit for the first 6 days, almost exactly duplicating the SRL-1 orbit for one day (at times to within 10 m). For days 7-11, the orbit was lowered to a 1-day exact repeat orbit (200 km). The SLR-2 mission permitted for instance the analysis of active lava flow (surface change imagery) on the Kilauea volcano in Hawaii.

- ESA’s ERS-1/2 tandem mission (start in Aug. 1995, end in May 1996). The prime objectives were focused on the collection of SAR data pairs for exploitation in interferometry, together with the synergistic use of instruments on the two platforms. The configuration was that of two-pass measurements of a single-antenna SAR platform (the same SAR instrument on both satellites observing the same area on the ground), permitting the superposition technique of imagery (in data processing) of fairly close repeat tracks. The C-band SAR instruments of the ERS-1/2 and RADARSAT-1 (launch Nov 4, 1995, 24-day exact repeat orbit) missions demonstrated the ability to detect cm-scale surface strain over large contiguous areas. In this context, RADARSAT-1 provides large-scale coverage of the Arctic sea ice cover on a 3-day basis with its wide-swath ScanSAR mode (460 km).

- ESA’s Envisat mission (launch Mar. 1, 2002) operates in a 35 day exact repeat pass cycle of 501 orbits with an inclination of 98.5º (sun-synchronous orbit of 800 km). Envisat has the same ground track as ERS-2 (within ± 1 km) with its orbit 30 minutes ahead of ERS-2. This orbital configuration permits repeat pass observation studies for its active sensor complement [RA-2 (Radar Altimeter-2), ASAR (Advanced SAR); a) as a single mission, and b) as a tandem mission with ERS-2. This orbit pattern has sub-cycles of 3 and 17 days, providing global coverage, with correspondingly coarser sampling, at these intervals. 1844)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TerraSAR−L (L-band)</th>
<th>ALOS (L−band)</th>
<th>RADARSAT-2 (C-band)</th>
<th>TerraSAR-X (X-band)</th>
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</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>23.8 cm</td>
<td>23.6 cm</td>
<td>5.55 cm</td>
<td>3.1 cm</td>
</tr>
<tr>
<td>Chirp bandwidth</td>
<td>80 MHz</td>
<td>14 MHz</td>
<td>30 (100) MHz</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Peak power (rad.)</td>
<td>4740 W</td>
<td>2000 W</td>
<td>1650 W</td>
<td>2260 W</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>3.5% (7%/2)</td>
<td>3.5% (7%/2)</td>
<td>3% (6%/2)</td>
<td>9% (18%/2)</td>
</tr>
<tr>
<td>Rx noise figure</td>
<td>2.5 dB</td>
<td>4 dB</td>
<td>4 dB</td>
<td>4.5 dB</td>
</tr>
<tr>
<td>Losses (atmosphere, swath, )</td>
<td>&lt;5 dB (for 40 km swath)</td>
<td>&lt;5 dB (for 40 km swath)</td>
<td>3 dB (for 25 km swath)</td>
<td>6 dB (split antenna)</td>
</tr>
<tr>
<td>Antenna size</td>
<td>11 m x 2.86 m</td>
<td>8.9 m x 3.1 m</td>
<td>15 m x 1.5 m</td>
<td>4.8 m x 0.7 m</td>
</tr>
<tr>
<td>Co-registration</td>
<td>1/10 pixel</td>
<td>1/10 pixel</td>
<td>1/10 pixel</td>
<td>1/10 pixel</td>
</tr>
<tr>
<td>Quantization (BAQ)</td>
<td>4 bit</td>
<td>4 bit</td>
<td>4 bit</td>
<td>4 bit</td>
</tr>
<tr>
<td>Orbital height</td>
<td>629 km</td>
<td>691 km</td>
<td>798 km</td>
<td>514 km</td>
</tr>
<tr>
<td>Repeat cycle</td>
<td>14 days</td>
<td>46 days</td>
<td>24 days</td>
<td>11 days</td>
</tr>
</tbody>
</table>

Table 100: System parameters of some LEO repeat pass missions (see Ref. 518)

3) Tracking missions in geodesy.

- The objective of ESA’s GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission (launch 2007) is to obtain a high-accuracy, high-resolution model of the Earth’s static gravity field, represented by spherical harmonic coefficients complete up to degree and order 300, which corresponds to a shortest spatial half-wavelength of < 70 km. The GOCE mission requirements call for an SSO (Sun-Synchronous Orbit) circular exact repeat orbit. 1845) The GOCE measurement system is based on a sensor fusion concept: satellite-to-satellite (SST) tracking in the high-low mode (hl-SST) using GPS, plus onboard satellite gravity gradiometry (SGG). This data contains abundant information about the

1844) http://envisat.esa.int/dataproducts/ra2−mwr/CNTR1−1−4.htm
gravity field of the Earth on a near-global scale (except for the polar gaps due to the sun-synchronous orbit configuration), from very low (derived mostly from hl-SST) to high (derived mostly from SGG) frequencies.

1.9.2 GEO (Geostationary Earth Orbit)

A geostationary orbit is a circular orbit in the equatorial plane (inclination = 0º) revolving about the Earth in the same direction and with the same period as the Earth’s rotation. A satellite in GEO remains fixed with respect to an observer on Earth. A geostationary orbit is a special case of the geosynchronous orbit (GSO), both have a period equal to the Earth’s rotational period, namely the sidereal day which is 23 h 56 m 4 s in length or 1436.1 minutes (the sidereal day refers to the rotation of Earth in inertial space). However, the synodic rotation rate of a satellite in GEO or GSO (i.e. the rotation rate with respect to the sun) is exactly 24 hours. GEO refers to a special orbit in which a satellite appears to be stationary over a point on the Earth’s surface i.e., the actual geocentric longitude of the S/C remains constant. The orbital velocity of the spacecraft is 3.075 km/s to match the rotation speed of the Earth at GEO altitude. To ensure that a satellite remains over a particular point on the Earth’s surface, the geostationary orbit must also be circular (zero eccentricity) and have zero inclination, i.e. the orbital plane must be coincident with the equator plane. In general, all geostationary orbits are geosynchronous, but not all geosynchronous orbits are geostationary.

The radial distance of GEO is approximately 35,786 km above the Earth’s surface. The orbital radius of GEO is 6,6107 R_E (with R_E = 6378 km) or about 42,164 km from the Earth’s center of mass. This is consequently the altitude at which the ‘centrifugal force’ caused by the rotation of the Earth is equal to its ‘gravitational attraction.’ A spacecraft in GEO requires stationkeeping services (N-S as well as E-W) caused by the following influences or perturbations:

- Lunar and solar gravitational perturbations. The gravitational attractions of the sun and the moon, the solar radiation pressure and the slight misalignment between the centrifugal force and the Earth’s gravitational force disturb the sought-after ‘equilibrium.’
- The GEO plane is not identical with the Earth’s orbit plane in the ecliptic. The Earth’s orbital plane has an inclination of about 23.45º to the ecliptic.
- The noncircular shape of the Earth’s equator causes satellites to be slowly drawn to one of two stable equilibrium points along the equator, resulting in an east-west libration (drifting back and forth) about these points.

The daily orbital motions (pendulum-like swings) of a GEO spacecraft are in the order of about 0.05 arcsec in N-S as well as E-W. Stationkeeping implies periodic orbital maintenance maneuvers, involving energy consumption. - The GEO concept is quite extensively utilized by meteorological and communication satellites (as well as by broadcasting satellites). It is indeed the most crowded orbit of all due to the fact that only one geostationary plane is available, namely the equator plane.

- The GEO geometry provides some special features and capabilities for Earth observation, for communication as well as for other applications:

- GEO offers a fixed-position relation between the satellite and the ground; hence, a continuous viewing/service capability of the same large footprint is given, the entire viewable Earth disk subtends an angle of 17.4º, representing 42% of the Earth’s surface (howev-

1846) Note: The terms “geosynchronous” and “geostationary” are not synonymous: geosynchronous specifies only the orbit period, while geostationary also specifies the shape and orientation of the orbit. Historically, the geostationary orbit was simply abbreviated with “GEO.” I stick to this abbreviation. This leaves the acronym GSO to the more general type orbit designation of “Geosynchronous Orbit.” It so happens that these two terms are often interchanged in the literature.

er, the polar regions of the Earth are not accessible from GEO). Obviously, the best coverage of GEO satellites is given in the equatorial regions.

- Three evenly spaced S/C in GEO can provide a continuous **global coverage with the polar regions excepted** (coverage to about ±70º of latitude max is possible with distortions increasing with latitudes). The useful imaging disc for a GEO satellite reaches up to about 60º of latitude in either hemisphere, but only at the sub-satellite longitude.

- GEO provides in particular a synoptic view [or the “big picture”], a different perspective in scale and quality of Earth observations distinct from coverage-limited LEO observations. Certain large-scale phenomena and/or features (weather patterns, circulations, etc.) can best be observed from GEO due to its panoramic viewing capability of Earth; i.e., coverage of entire large-scale processes (cyclones) embedded within neighboring structures.

- The observation distance from GEO to Earth’s surface, about 36,000 km, is 45 times farther away than from LEO (considering an average LEO orbit of 800 km). This large distance ratio remains a challenge for remote sensing applications in terms of proper spatial resolutions for Earth surface imagery (implying tougher design constraints on imaging instruments). In the field of meteorology, this “GEO resolution deficiency” has led to a combined approach of LEO and GEO observations to obtain a more “global view.”

- For communications, the large distance causes in particular signal roundtrip delay times. Another advantage of GEO location is that antennas in the ground segment need no apparent motion to follow the S/C.

- GEO offers a continuous view of the diurnal cycle. It supports also frequent observations of highly variable parameters like precipitation

- Time-lapse imaging is possible (due to constant position) for repetitive measurements, permitting the capture of weather pattern imagery, etc.

- The GEO position supports the use of long integration times (making possible faint signal acquisition)

- For weather forecasting, the observations from a GEO location offers a short-notice warning capability – while the observations from LEO weather satellites (polar orbiting) are being used for longer-term forecasting.

- A spacecraft in GEO is not eclipsed by the Earth but is in sunlight continuously, 24 hours a day, due to its high orbit of 36,000 km altitude (the apparent sun traverses an angle of ±23º perpendicular to the Earth’s equator, the spacecraft’s orbital plane). The only exceptions are several days around the **seasonal equinoxes**, March 21 and September 22, when the satellite will be eclipsed briefly around midnight (i.e., Earth is between the sun and the spacecraft), for up to an hour and 12 minutes.

Example of equinox observation consequence: The viewing geometry design of the current GOES satellite series of NOAA (GOES-I-M and N-P) is such that sunlight may directly impinge on the optical path of its observation instruments which may lead to a degradation of radiometric accuracies. To avoid such damage, data is neither sensed nor provided during these periods - termed the “keep out zones” by NOAA. The combined impact on the current GOES series is a 3-4 hour loss of data for 10 to 12 days before and after each equinox.

- The periodic GEO position maintenance function is referred to as “**station-keeping**” to adjust the drift and orbit of a GEO spacecraft. Orbital perturbations are introduced by the solar radiation pressure as well as by the gravitational effects of the sun and moon.

- It should also be noted that a spacecraft launch into GEO is generally much costlier than a launch of the same spacecraft into LEO. Simply stated, it takes considerably more energy to transport a satellite into GEO, requiring a much larger launch vehicle.
Historical background: The concept of a geostationary orbit seems to have several independent authors - men of vision and imagination:

a) The Russian school teacher and visionary, Konstantin E. Tsiolkovsky of Kaluga, Russia (1857-1935, referred to as the father of astronautics), suggested around 1895 of putting a “celestial castle” at the end of a spindle-shaped cable, with the “castle” orbiting the Earth in a geosynchronous orbit (i.e. the castle would remain over the same spot on Earth). In Tsiolkovsky’s tower (also referred to as “space tower”), an elevator would ride up the cable to the “castle.” Konstantin Tsiolkovsky wrote numerous science and science-fiction articles on space travel at the turn of the century (19th to 20th).

b) Hermann Potocnic [Dec. 22, 1892 - Aug. 27, 1929, born in Pola (Pulj), Moravia, Austrian-Hungarian Empire, an engineer (Vienna) and retired captain of the army] published his concepts of future space travel in a book with the title: “Das Problem der Befahrung des Weltraums - Der Raketen-Motor,” Richard Carl Schmidt & Co., Berlin W62, 2. Auflage, 1929. He used the pseudonym of Hermann Noordung for the publication, since he was afraid to be ridiculed by his peers. In the book (page 98), Noordung proposed a stationary orbit of a space station (referred to as “Raumwarte” for astronomical observations) at radius 42,300 km from Earth center (or about 35,900 km above the surface), in the equator plane, with a chosen orbital speed of about 3080 m/s - resulting in a free orbit with an angular velocity equal to that of Earth rotation. An orbiting body would seem to be stationary over a certain point at the equator.

c) Arthur C. Clarke (born Dec. 16, 1917 in Somerset, England) published an article in 1945 with the title: “Extra-terrestrial Relays: Can Rocket Stations Give World-wide Radio Coverage?” (Wireless World, Oct. 1945) where he described the principles of satellite communication in geostationary orbit. Clarke suggested that if a satellite were placed above Earth’s equator at just the right height - 35,888 km - it would orbit Earth exactly once in 24 hours - and seem to stay put in the sky above some point on the ground. In 1947, Arthur C. Clarke proposed how three satellites, suspended in orbits 35,888 km above the equator, could serve as relay platforms for the entire Earth. He cautioned that the concept was based on the theory that microwave radio signals would not bounce off the atmosphere like shortwave signals, something that wasn’t known for certain in 1947.

- Syncom-2 (launch July 26, 1963 on a Thor Delta vehicle, built by Hughes Aircraft Corp., now Boeing Satellite Systems, Inc.) of NASA was the first successful experimental communication satellite to achieve geostationary orbit. Positioned over the Atlantic, it demonstrated the feasibility of geostationary satellite communications. Syncom-2, designed for 1 year lifetime, remained operational through 1966 (decommissioned in April 1969). Note: Syncom-1 (launched Feb. 14, 1963) achieved GEO orbit but contact was lost after it was placed in orbit (electronics failure).

- Intelsat-2 (commonly called “Early Bird”) was the world’s first commercial communications satellite in GEO (launch April 6, 1965, the S/C was built and operated by Comsat an international government-chartered organization). The spacecraft (mass of 39 kg) provided the first scheduled transoceanic TV service and was operational for 3.5 years (mostly demonstration of technology). Intelsat-2 supported 240 telephone links or one television channel. In 1969, Intelsat completed the first global GEO communication network deployment consisting of three spacecraft.

- The objective of ATS (Applications Technology Satellite) program, a series of six NASA S/C, was to explore and test new technologies and concepts for communications, me-
teorological and navigation satellites (investigation of the geostationary orbit environment). Note: ATS-2 and ATS-4 were MEO satellites, the rest of the ATS program were GEO satellites.

- In the 1990s the geostationary orbit (GEO) has indeed become the most densely populated orbit of satellites. This is due in particular to the needs of the communication industry as well as to some GEO weather satellites [USA (NOAA), Europe (EUMETSAT), Japan (JMA), Russia (Planeta/HYDROMET), India (ISRO/IMD), China (NSMC/CMA), etc.]. Over the years, spacecraft removal from GEO has become a necessity at EOL (End of Orbital Life) to avoid havoc with neighboring operational spacecraft. A common spacecraft retirement practice from GEO is to boost it into a slightly higher orbit. Occasionally, retired communication satellites are also moved into inclined orbits. However, this practice involves again a twice daily crossing of the equator plane.

1.9.2.1 GSO (Geosynchronous Orbit)

A geosynchronous orbit is one with an orbital period matching the rotation rate of the Earth (sidereal day). However, the definition of a geosynchronous orbit says nothing about the shape of the orbit, or the orientation of the orbital plane with respect to the equator. Hence, the orbit can be highly elliptical, and/or it can be inclined with respect to the equator, and still be synchronous with the Earth’s rotation. This general nature of a GSO implies there is no fixed position relationship relative to an observer on Earth. Several GSO configurations are possible:

- Circular GSO with an inclination. A GSO satellite with an eccentricity of zero and an inclination different from zero is not stationary when observed from the Earth. This particular orbit has the property of remaining stationary over a particular meridian (there is no longitudinal precession for successive orbits but variable latitudinal motion along the meridian). An inclined circular orbit provides a ground track describing the slim figure 8 (see Figure 42). An inclination of 50º causes a latitudinal displacement of ±50º during one orbital period (one sidereal day). The subsatellite velocity of this orbit varies from 2600 m/s at the equator to about 1100 m/s at the inclination maxima (±50º latitude). This GSO subgroup is also sometimes referred to as IGSO (Inclined Geosynchronous Orbit). In an IGSO, the subsatellite track crosses the equator plane in either the ascending or descending node in exactly 24 hours of mean solar time.

- Non-circular GSO within the equator plane. This orbit provides a daily E-W ground track.

- Non-circular GSO with an inclination. A more general ground track is provided.

So far, there has not been much use of satellite observations or operations in GSO. Nonetheless, there are plenty of potential applications from GSO for the future. Some early examples of S/C in GSO are:

- IUE (International Ultraviolet Explorer), a joint astronomical mission of NASA, ESA, and PPARC (Particle Physics and Astronomy Research Council) UK, was launched Jan. 26, 1978. IUE featured an elliptical inclined GSO over the Atlantic Ocean as its nominal operating orbit: the initial orbit was at 32,050 km x 52,254 km with an inclination of 28.6º and a period of 23.927 h; at mission end the orbit was: 36,360 km x 48,003 km with an inclination of 35.9º. IUE remained operational until its hydrazine was deliberately vented, its batteries drained and its transmitter turned off on Sept. 30, 1996.

- The US DoD communication minisatellite pair LES-8 [Lincoln (Laboratory) Experimental Satellite-8)] and LES-9 (tandem launch of both S/C on Mar. 15, 1976) were placed

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1852) http://iuearc.vilspa.esa.es/IUE/about_IUE.shtml
1853) http://satobs.org/seesat/Mar---1999/0311.html
into inclined GSOs with 14º inclination. Their respective inclined GSO longitudinal positions were at 94.5º W, and at 103º W, respectively (end of operation in Jan. 1996). LES-8/-9 were the first cross-linked military satellites. A Ka-band ISL (Intersatellite Link) utilized tracking antennas to maintain the link with the other spacecraft as it moved through its figure-eight track.

Figure 42: A lemniscate of a geosynchronous orbit with an inclination of 60º (image credit: F. Jochim, DLR)

Figure 43: Orientation of GEO and inclined GSO in space (at maxima)

- The ACTS (Advanced Communications Technology Satellite) mission of NASA (launch Sept. 1993) was maintained as a GEO satellite until 1998 (far exceeding its planned demonstration period of 2 years). After 5 years of successful demonstrations, the satellite’s
north-south stationkeeping was discontinued in Aug. 1998. The system is now operating in an inclined orbit that increases at a rate of 0.8°/year.  

- The Milstar-2 communication satellite constellation of DoD (in orbit by 2003) employs a low inclination GSO (Geosynchronous Orbit) configuration. The constellation features jam-proof communications between fixed-site, mobile, and portable terminals. Launch of Milstar-2-4 on April 8, 2003 from Cape Canaveral, FL, USA.

- The SDO (Solar Dynamics Observatory) research mission of NASA (planned launch 2008) employs a circular GSO of 28.5° inclination.

- Galileo constellation of Europe. In addition to a MEO constellation, a circular inclined GSO overlay was considered in the early planning phase of GalileoSat (Europe’s space segment of a navigation constellation), but this option was eventually dropped for economic reasons.

- GSO may, for instance, be used in the future for SAR observations from geosynchronous altitudes. Initial proposals of a SAR mission concept from an inclined circular geosynchronous orbit, referred to as “GEOSAR,” were already published by Kiyohide Tomiyasu in 1978 and 1983. An advantage of the GSO concept is that it provides relative observation velocities of the target area with respect to the SAR instrument, required for SAR imaging.

1.9.2.2 GTO (Geosynchronous Transfer Orbit)

GTO is an elliptical orbit with perigees usually between 250 - 600 km, an apogee of about 36,000 km and an initial period of about 11 hours. A standard GTO is an orbit which requires the minimum energy to reach geostationary altitude. In the normal case, GTO is the short-term initial orbit (or parking orbit) of a S/C after launch to be placed into GEO by a sequence of orbit raising maneuvers that are executed by the satellite’s own propulsion system to circularize the elliptical orbit eventually into GEO. Orbit raising maneuver: At GTO apogee, the payload usually fires an onboard motor (commonly referred to as “apogee boost motor”) to circularize the orbit and adjust the inclination to zero. Most GEO satellites (weather and/or communication) go through this procedure.

Secondly, GTO may be used as a long-term observation orbit, usually selected by S/C with payloads that measure the harsh solar radiation environment. GTO implies that a S/C passes through the Van Allen radiation belts [these are regions located at about 1.4-1.5 RE (inner) and 4.5-6 RE (outer) where many energetically charged particles from the solar wind are trapped in the Earth’s magnetic field] four times per day, causing them to be exposed, in a twelve month period, to levels of radiation equivalent to about 8-10 years in GEO or in LEO. GTO gives also exposure to other environmental effects such as atomic oxygen erosion at perigee and electrostatic charging at apogee. - The accelerated life testing of radiation effects provided by GTO is a unique opportunity to evaluate for instance new technology solar panels quickly and cost-effectively.

- Examples of S/C in long-term GTO are: CRRES of NASA/DoD (launch July 25, 1990, A.13); STRV-1a and -1b of DERA, UK (launch June 17, 1994, M.41); STRV-1c/1d of

DERA (launch Nov. 16, 2000); MDS-1 of JAXA (launch Feb. 4, 2002; the MDS-1 operations were terminated on Sept. 27, 2003, after 18 months of operations that were planned for a mission life of 1 year).

- The GTO turns out to be a very frequented initial orbit due to the many launches of communication satellites— for further advancement into GEO. This frequent “access to space” offers of course many opportunities for small secondary payloads. However, for most of these potential secondary missions, GTO or GEO orbits are not acceptable or “non-ideal” for their mission requirements. Hence, solutions must be found for the secondary payloads to transfer from a GTO into an SSO (Sun-synchronous Orbit) or into something in-between that turns out to be more acceptable to the secondary mission.

1.9.3 MEO (Medium Earth Orbit)

MEOs are defined for an altitude range of about 3000 km to about 25,000 km above the Earth’s surface. MEO orbits provide considerably longer contact times with the user on Earth’s surface, as well as much larger footprints than spacecraft in LEO (the nadir velocity decreases with altitude and the swath width increases). Spacecraft in MEO may offer higher ground resolutions in imagery than those from GEO (due to its lower altitude).

A MEO disadvantage is the long-term exposure to the Van Allen radiation belts (requiring proper shielding). MEO orbits are mostly circular and may be designed for any inclination. The orbital periods of MEO satellites range from about 3 to 15 hours and more. The spacecraft with orbits of 12 hours are also referred to as semi-synchronous. In the communication industry, MEOs are also referred to as ICO (Intermediate Circular Orbit); the service of these satellites is being used in communications because of shorter signal propagation delay times than those from GEO. Examples of typical MEO S/C are:

- Some laser ranging satellites (passive systems) such as: LAGEOS-1 of NASA (launch May 4, 1976, altitude 5900 km). ETALON-1 of USSR (launch Jan. 10, 1989, altitude about 19,000 km).
- **Navigation satellite constellations** of GPS (GPS-1 launch Feb. 22, 1978, altitudes of about 20,000 km, period of about 12 hours) and GLONASS (GLONASS-1, -2, -3 launch, Oct. 12, 1982; altitudes of about 19,000 km, period of about 11.25 hours). Prior to the GPS constellation, the launch of NTS-2 (June 23, 1977) had a MEO orbit of 13900 km. - The Galileo navigation constellation of ESA will also be deployed into MEO (launch 2008) at near-circular orbital altitudes of about 23,600 km. In case of the GPS constellation, the selected 12 hour period of MEO is resonant with the Earth’s rotation rate (2 orbits/day), so the orbit track repeats itself each day. Full and continuous Earth coverage of a MEO constellation is given by positioning the various spacecraft into several orbital planes. Examples:
  - The GLONASS constellation of nominally 24 S/C has three orbital planes (8 satellites are equally spaced in each plane with a 45º argument of latitude displacement)
  - The GPS constellation of nominally 24 S/C has six orbital planes (24/6 constellation) with a 60º separation within a plane
  - The Galileo constellation will feature 27 S/C (nominally) in three orbital planes (symmetrical 27/3/1 Walker constellation).

- Some communication satellites in MEO: Telstar-1 (launch July 10, 1962) and Telstar-2 (launch May 7, 1963) of AT&T (American Telephone & Telegraph) company are considered the first experimental communication satellites in MEO. Telstar-1 delivered the first television transmission across the Atlantic in 1962. Because Telstar-1 was placed into an elliptical MEO that varied from low to medium altitudes, the satellite was visible contemporaneously to Earth stations on both sides of the Atlantic for only about 30 minutes at a time. - A much more recent entry into MEO communications is the Inmarsat-P constellation (provision of a hand-held telephone system), consisting of 12 satellites in two MEO planes of 10,335 km altitude.
• The introduction of new and improved observation (instrument) technology offers the potential to provide eventually also high spatial, temporal and spectral resolution environmental data from MEO orbits. At the start of the 21st century, the MEO orbit is being studied and considered by NOAA and other agencies (EUMETSAT) for future integrated concepts of environmental satellite missions. For instance, a MEO constellation of 4 S/C (circular altitude of 10,400 km, 6 hour orbit) would be capable of viewing Earth’s polar regions on a continuous basis, 24 hours a day, seven days a week. – An obvious advantage of MEO (over GEO) is the fact that it allows a range of observations configurations with sufficient coverage and spatial resolution for passive microwave radiometry.\textsuperscript{1859} \textsuperscript{1860} \textsuperscript{1861} \textsuperscript{1862}

1.9.4 HEO (Highly-elliptical Earth Orbit)

A HEO is greater than a GEO. If the HEO period turns out to be greater than a day, it is referred to as “supersynchronous.” A typical HEO is highly inclined, has a perigee of about 500 km and an apogee of 5-10 R\textsubscript{E} and more. The observation objectives in HEO orbits involve mainly investigations of the energy transport between the sun and the Earth in the interplanetary plasma (energetic particle fluxes, etc.), solar-terrestrial interactions (in particular in the auroral regions), as well as magnetic field studies. Some examples of satellites in HEO are:

The IMP-4, -5, -6, -7 and -8 (Interplanetary Monitoring Platform series of NASA - also referred to as Explorers 34, 41, 43, 47, and 50, respectively). IMP-4 was launched on May 24, 1967 (apogee of 34 R\textsubscript{E}, perigee of 250 km). IMP-8 was launched Oct. 26, 1973. HEOS-1A (Highly Eccentric Orbit Satellite) of ESRO Launch Dec. 5, 1968. HEOS-1A orbit of 424 km x 223 428 km, 28.3\textdegree. A number of the Prognoz spacecraft series of the USSR (magnetospheric research, etc.) had apogees ranging from 200,000 - 800,000 km (or about 30-125 R\textsubscript{E}) such as Prognoz-6 (launch Sept. 26, 1977, Prognoz-7 (launch Nov. 11, 1978), and Prognoz-9 (launch July 1, 1983). Onboard the Prognoz-9 spacecraft was also the Relict-1 experiment to investigate the large-scale anisotropy of relict radiation. The ISEE-1 and -2 satellites (K.19) had a joint launch on Oct. 2, 1977 (apogee at 23 R\textsubscript{E}). The AMPTE satellites (IRM, UKS, CCE, see K.4) were launched on Aug. 16, 1984. GEOTAIL, launch July 24, 1992. WIND, launch Nov. 1, 1994. INTERBALL (launch of Tail probe Aug. 3, 1995, Auroral Probe launch Aug. 29, 1996). POLAR, launch Feb. 24, 1996.

Equator-S, launch Dec. 2, 1997. The Chandra X-ray Observatory of NASA, launch on Shuttle flight STS-93 on July 23, 1999. The Chandra HEO is 16,000 km x 133,000 km, inclination of 28.4\textdegree and a period of 3809 minutes (63.5 h orbit).\textsuperscript{1863} The XMM (X-Ray Multi-Mirror Mission - Note: XMM was officially renamed to “Newton” in Feb. 2000) of ESA, launch Dec. 10, 1999 with an Ariane-5 vehicle from Kourou, has an operational orbit of: perigee = 7000 km, apogee = 114,000 km, an inclination of 40\textdegree and a period of 47.86 hours. The IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) mission of NASA/GSFC (launch Mar. 25, 2000), has a polar orbit of: perigee = 1000 km, apogee = 7 R\textsubscript{E}

\textsuperscript{1863}The Chandra X-ray Observatory is named in honor of the late India-American Nobel Laureate Subrahmanyan Chandrasekhar (born Oct. 19, 1910 in Lahore, India (now Pakistan), died Aug. 21, 1995 in Chicago, IL). In the 1930’s, Chandra, as he was known then, showed that stars whose mass was 1.4 times greater than the sun would eventually collapse into objects which we now know as black holes. In 1983, Chandra was awarded the Nobel prize in physics for his studies of the physical processes important to the structure and evolution of stars.
The location of the apogee changes during the course of the two-year mission, both in latitude and, because of the Earth’s revolution about the sun, in local time. The Cluster-II mission of ESA (launch Aug. 9, 2000, 4 satellites) features polar HEOs with perigees of 19,000 km and apogees of 119,000 km (period of 57 hours). The DSP (Double Star Project) of CNSA (China) and ESA (launch of DSP-1 on Dec. 29, 2003) has an equatorial orbit with a perigee of 570 km and an apogee of 78,970 km (~12 RE), inclination = 28.5°, Kepler period of 20.91 hours. The DSP-1 objective is to study Earth’s magnetic tail. DSP-2 (launch July 25, 2004) has a polar orbit with a perigee of 700 km, an apogee of 39,000 km, and an inclination of 90°.

### 1.9.4.1 Molniya-type orbits (a HEO subgroup)

Molniya-type (also Molnya spelling) orbits represent a special HEO class used for communication as well as observation services. These HEO orbits are chosen in such a fashion that maximum service provision (coverage and viewing time) can be provided to a particular high-latitude region of the Earth (including the polar regions).

Note: Molniya means ”lightning” in Russian. The Molniya-type orbit is named after the first launch vehicles, Molniya, that were capable of transporting a satellite into this particular HEO orbit. There is also a series of Soviet/Russian spacecraft, named Molniya, flying in Molniya orbits.

Prominent examples are the numerous Molniya-type orbits (apogee of 39950 km, perigee about 500-800 km); they are characterized by long orbital periods (12 hours, making them semisynchronous), a high eccentricity (0.7 - 0.75) and an inclination of approximately 63.4° - whose apogee (in excess of 8 hours by far the longest duration period of the orbit) occurs always in the intended region, namely the northern hemisphere for extended-period communication coverage services (a quasi zenithal system over the region to be covered).

Compared to LEO systems, a smaller number of satellites is required for limited areas or regions, which is one of the principle merits of this system. - The orbital period of half a sidereal day enables a Molniya-type spacecraft to follow the same ground track (repeating ground tracks) on each orbit. This represents an important criteria for high-latitude service provision. The spacecraft thus appears in the same relative position in the sky during each pass. Since the orbital period is half a day, apogee occurs twice per day, typically once over Russia and once over Canada. The 63.4° inclination is essential to the stability of the Molniya orbit, keeping the argument of perigee fixed. And because $\omega$ is fixed, the apogee stays at a given latitude. Due to the equatorial bulge of the Earth, this inclination results in no rotation of the line of apsides and maintains the apogee high above the northern hemisphere (and the perigee always in the southern hemisphere). - All HEOs, including Molniya-type orbits, experience large Doppler shifts, due to the relatively large movement of a satellite in HEO with respect to an observer on the Earth. Hence, satellite systems using this type of orbit need to be capable of large Doppler shifts. 1864) 1865)

The first prototype Molniya spacecraft was launched in 1964. The launch of the Molniya-1 satellite series occurred April 23, 1965 (over 20 spacecraft of the series were launched until 1974), followed by the Molniya-2 series with first launches in 1972 and countless S/C of the Molniya-3 series (first launch in 1974). The Russian Tundra satellite system fits also into this class. Tundra employs 2 satellites in two 24 hour orbits separated by 180° around the Earth, with an apogee distance at 53,622 km and a perigee at 17,951 km. The Molniya series represents also the first communication satellites of the former USSR. Until 1983, the Soviet

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Union maintained a Molniya ("lighting") constellation of four Molniya-3 communication satellites. The operational constellation was eventually increased to 16 satellites. 1866)

![Orbit Types](image)

**Background:** The original design of the Molniya-type HEO orbits in the early 1960s is considered to be a remarkable accomplishment in orbital mechanics pioneered by Russian engineers to deliver satellite services to high-latitude locations. Most Molniya orbits have orbital inclinations of about 63.4° in order to reduce or eliminate rotation of the line of apsides (major axis of the ellipse) due to gravitational perturbations. This prevents their apogees from drifting away from their initial latitude. [Note: 1868] The perigee of the orbit literally moves along the plane of the orbit at a rate dependent on the inclination. This condition is known as the “rotation of the apsides.” It turns out that at two special inclinations, the apsidal rotation rate is zero. These inclinations are either at 63.4° or at 116.6° (complementary angle). If a satellite is at 63.4° inclination, and the perigee is in the southern hemisphere, the perigee will remain in the southern hemisphere.

A spacecraft in a Molniya orbit lingers for instance over Russia for about 8 hours per day. This implies that an orbital configuration of at least three satellites in sequence can provide a continuous coverage of Russia (or any other large land mass). The Russian Molniya orbits have arguments of perigee (ω) at or near 270° so that the resulting observation coverage was highly biased toward the northern hemisphere. Spacecraft in Molniya orbits also have repeating ground tracks, thus providing steady coverage with some station-keeping requirements. The Molnya orbits are in general less stable than geostationary orbits. 1869)

Other examples: The Chinese mission SJ-4 (launch Feb. 8, 1994) used a Molniya orbit of 210 km x 36,125 km. The TWINS dual-spacecraft mission of NASA (planned launch in 2004) employs also Molniya-type orbits to achieve long periods in apogee. The US military

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1866) [http://www.fas.org/spp/guide/russia/comm/elliptical/molniya.htm](http://www.fas.org/spp/guide/russia/comm/elliptical/molniya.htm)
1867) [http://www.geo-orbit.org/sizepgs/geodef.html](http://www.geo-orbit.org/sizepgs/geodef.html)
1868) [http://users2.ev1.net/~mmccants/faq/Chapter-04.txt](http://users2.ev1.net/~mmccants/faq/Chapter-04.txt)
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has been using Molniya-type orbits for some of its classified surveillance satellites since the early 1970s. For instance, six first generation SDS (Satellite Data System) data relay satellites of DoD were launched from 1976 to 1987 (the SDS are being used for real-time data relay from reconnaissance gathering satellites which are out of range from US tracking stations). The AMSAT-Oscar-40 spacecraft, also referred to as AMSAT-3D (launch Nov. 16, 2000, Kourou), was initially inserted into GTO and then into a Molniya orbit (1000 km x 47000 km) with an inclination of 63.4º to provide long communication times for its users in the northern hemisphere. - The long-term use of Molniya-type orbits has also generated its share of debris in these orbits; still, at the start of the 21st century there is an undiminished demand for Molniya-type orbits in communication and reconnaissance applications.

Naturally, HEO constellation designs with other orbital periods than 12 hours (Molniya type) are possible (say, 8 hour period, etc.). Consequently, they provide other observation characteristics. - Molniya-type orbits (as well as all HEOs) experience the same harsh space environment as GTOs with daily passes through the Van Allen radiation belts.

It turns out that the 8 hour Molniya orbit is much more suitable for Earth observation than the 12 hour orbit (used for communications), providing a lower apogee (27,263 km at apogee for an 8 hour Molniya orbit versus 39,950 km for a 12 hour Molniya orbit). Hence, the 8 hour orbit is not as technically demanding on the EO instruments. A constellation of 3—4 satellites in an 8 hour Molniya orbit (which is actually an elliptical MEO) could provide 24 hour real-time high latitude coverage of critical areas of the northern hemisphere.

![Figure 45: Overview of Molniya orbit parameters (image credit: NASA/GSFC)](image)

NASA/GSFC is considering the semisynchronous Molniya orbit for polar region observations since 2004. A single satellite in a Molniya orbit would allow to extend GEO-type imaging (i.e. over extended periods) all the way to the north pole for a total of 16 hours per day. Two satellites would ensure 24 hour coverage of the entire northern hemisphere, and four satellites would extend the continuous coverage to the entire globe.

The MOI (Molniya Orbit Imager) of GSFC is a concept for a high—latitude quasi—geostationary mission that would be ideally suited for multitemporal imaging e.g. for satellite
winds purposes without most of the disadvantages of the LEO (Low Earth Orbit) imagers. In the Molniya orbit, imaging is performed during the roughly 500 minute apogee dwell period (67% of the total duration of the orbit) when the satellite is above the curved line in the left panel of Figure 45. \(1870\)

Since the Molniya orbit is longitudinally “blind” — i.e. all regions of the high northern latitudes are imaged about equally well regardless of where exactly the apogee points are located — a mission in this orbit is an excellent candidate for international collaboration.

1.9.5 Halo orbits (orbits around the Sun/Earth Lagrangian Points, L1 or L2)  
Background: Libration points (also referred to as “Lagrangian points”) in space are defined as points where the gravitational forces due to two or more bodies (the sun, or planets) balance, and thus where a spacecraft can be positioned in equilibrium at zero velocity (the gravitational pull of the two large masses precisely equals the centripetal force required to rotate with them). The description of “libration points” results from the fact that a body (or a spacecraft) will oscillate or “librate” at these points, retaining the same average position relative to the two large bodies they orbit with.

The Italian born (Turin, 1736) mathematician Joseph-Louis Lagrange (later French mathematician, he died in Paris in 1813) showed, that there where five equilibrium solutions to the “three body problem” where one massless body is submitted to the gravitational field of two massive bodies. They are called Lagrangian points or libration points. In 1772, Lagrange received the prize of the Paris Academy of Sciences for proving mathematically that five positions of net zero-force exist in a rotating two-body gravity field [he shared the prize of the “three-body-problem” solution with Leonard Euler (1707-1783) of Switzerland].

The Lagrangian points are particular solutions of the equations of motion applied to the “Problem of Three Bodies” in an orbital plane of two massive bodies in circular orbits around a common center of gravity and a third body of negligible mass. The equilibrium or libration points represent singularities in the equations of motion where velocity and acceleration components are zero and the gravitational forces are balanced. *Lagrange deduced that any object, such as a satellite, placed in the vicinity of such a libration point (Lagrange point), will be stationary with respect to the reference frame in which the two large bodies are rotating.*

The equations of motion always yield five points at which the third body can remain at equilibrium. Three of the points are on the line passing through the centers of mass of the two massive bodies - L3 beyond the most massive body, L2 beyond the less massive body, and L1 (the point through which the mass transfer occurs) between the two bodies. The points L1, L2, and L3 are also known as the collinear libration points (on the same axis of the mutually rotating system such as the Sun-Earth line). The other two points, L4 and L5, are located at the two points in the orbit of the less massive component which are equidistant (equilateral triangle) from the two main components, as illustrated in Figure 46. \(1871\)\(1872\)\(1873\)

- **Sun-Earth system** (actually the Sun-Earth/Moon barycenter system): The L1 and L2 locations are just about **1.5 million km** from Earth (in the direction Earth - sun), in which the Sun/Earth gravitational forces are balanced (the L1 distance from Earth corresponds 1/100 the distance Earth-Sun). The L1 point is located towards the sun and provides a continuous full-disk view of the sunlit half of the Earth as well as of the sun; the L2 point is away from the sun (on the opposite side of Earth, i.e., in the direction of the universe) and pro-
vides a complementary continuous view of the night side of the Earth. The first three Lagrangian points of the sun/Earth system, namely L1, L2 and L3, lie along an axis with Earth and the sun, with L3 on the opposite side of the sun from Earth. The other Lagrangian points, L4 and L5, are in the same orbit plane around the sun as Earth; however, L4 is 60° ahead of Earth while L5 is trailing Earth by 60°.  

The stability of L1 and L2 orbital position (saddle points in the orbital computation) can be maintained for a duration of about 23 days, while L3 maintains stability for about 150 days. The triangular libration points L4 and L5, forming an equilateral triangle with one large mass, are the most stable points of the system. Whenever the mass ratio of the two large bodies exceeds 24.96, then these points remain permanently quasi-stable. The stability properties of L4 and L5 makes these locations in the Sun-Earth system as collectors of cosmic debris (also referred to as “Trojans”).

- **Earth-Moon system:** The distance from the moon center of mass to L1 is 61,350.3 km. The distance from the moon center of mass to L2 is 61,347.5 km. The distance from Earth's center of mass to L3 381,666.3 km (L3 lies on the opposite side of Earth in the Earth-Moon system; L3 has the distinction that the moon can never be seen from its position).

For the Earth-Moon system, the ratio between the mass of the Moon and Earth is about 1:81. For such large mass ratios, the L4 and L5 points can probably be considered as fairly “stable” - an error in position results not in an unstable orbit, but in a stable “libration orbit” around the actual point. However, from safety considerations, it should be pointed out that the collinear points (L1, L2) of the Earth-Moon system are much less suitable and stable for spacecraft positioning than those of the Earth-Sun system. Small deviations from the Lagrangian points would require immediate station-keeping maneuvers. The configuration of the lunar libration points rotates around the Earth once each month.

**Lissajous and halo orbits about Lagrangian points:**

Lissajous orbits are named after the French physicist Jules-Antoine Lissajous (1822-1880) who studied the behavior of vibrations. He found that the curved lines on the screen would combine to make a figure of eight pattern (Lissajous curves).

A spacecraft may orbit around any of the libration points (quasi periodic orbit) which, using a simplified motion theory (circular restricted three body problem), can be depicted as a Lissajous curve. Lissajous orbits, typically involve displacements from the Sun-Earth line ranging from thousands to hundreds of thousands of km. – The halo orbit family is a special case of the Lissajous orbit where the period of motion along the three directions of space is equal. These solutions exist only for large excursions from the Sun-Earth line (>650,000 km), the corresponding period is about 6 months.. A spacecraft in a halo orbit around a Lagrangian point (say L1 of Sun-Earth system) describes huge loops around this L1 point such that its orbits resemble a so-called “halo” (i.e., a ring around an imaginary center, namely L1). Lissajous orbits are the natural motion of a satellite around a collinear libration point in a two-body system and require less momentum change to be expended for station keeping than halo orbits, where the satellite follows a simple circular or elliptical path about the libration point.

The L1 and L2 libration points of the Sun-Earth system offer the particular quality of providing stable thermal as well as illumination environments. Hence, both vicinities of L1 and L2 are
considered as very attractive regions for solving problems of solar-terrestrial physics. Spacecraft flown to either L1 or to L2 are generally considered to be in the class of “deep-space” missions.

- Observation characteristics from L1 in the Sun-Earth system:
  L1 is an ideal outlook point for Earth observations (in UV, VIS and up to TIR are all within current technological capabilities) as well as for monitoring of “space weather” parameters (the supersonic solar wind reaches L1 about one hour prior to reaching Earth). L1 is located outside the Earth’s magnetosphere (see Figure 47). L1 allows an uninterrupted view of the sun and requires infrequent spacecraft maneuvers to stay in orbit (low Δv for maintaining the spacecraft near one of the L1/L2 points, station keeping needs about 10 m/s per year). Also, the thermal environment of the spacecraft is very stable and smooth as the sun is always seen in the same direction. There is no eclipse in L1. The L1 perspective is also of particular value for studies of cloud properties at solar wavelengths, since there are no shadows from this vantage point. Another advantage of the L1 location is the existence of a very small gravitational force environment. This has implications for missions with extremely high performance requirements in disturbance forces.

- Observation characteristics from L2 in the Sun-Earth system:
  Views of the nighttime hemisphere from L2 can be of value for monitoring lightening on Earth. Objects at or near L1 and L2 experience the same gravitational force as the Earth itself, and thus become new “planets” with the same orbital period as Earth around the sun. In fact, a satellite at L1 or L2 executes a three dimensional elliptical orbit about the Lagrange point as the Earth, the moon, and satellite system orbit the sun. From L1 or L2, the Earth occupies almost the same 0.5° FOV (Field of View) as the sun does from Earth - although slightly smaller since the rim of the sun is visible from L2 (an advantage for limb scanning!). Twin observatories at L1 and L2 can observe every point on Earth continuously – a true synoptic coverage and a new way to look at Earth.

Note: In the Sun-Earth system the L2 point is about the same distance away as L1 but at the opposite side of the Earth (in the anti-sun direction). This implies that a spacecraft positioned at L2 is always located in the Earth’s shadow. An advantage of L2 is astronomical viewing (looking toward the universe) due to constant lighting conditions. L2 is also advan-
tageous for microwave radiation reception (radio signals) from the universe (encounter of much lower radio frequency interference levels than with observations made from Earth).

- The use of Lagrangian points as possible orbital locations for space missions was first recognized and studied by Guiseppe (Beppi) Colombo (Italy) and Robert F. Farquhar (USA) in the early 1960s.  

Examples of satellites in L1 halo orbits of the Sun-Earth system are:

- ISEE-3 (International Sun-Earth Explorer), NASA/GSFC, launch Aug. 12, 1978; ISEE-3 remained at L1 for 4 years, requiring less than 10 m/s difference in velocity to adhere to its orbit. ISEE-3 was the pioneering mission to a libration point, demonstrating that such orbits could be used as prime locations for solar observations.
- RELICT-2, an astrophysics mission of Russia. In 1990, this was the first mission concept that planned to use a lunar swing by to achieve a mission orbit solely around a libration point L2. Unfortunately, the RELICT-2 mission was never launched.
- WIND (NASA, launch Nov. 1, 1994; WIND was placed into a halo orbit in Nov. 1996). WIND made a considerable loop around L1 repeating this several times.

Figure 47: L1 location in Sun-Earth system relative to the magnetosphere (not to scale)

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1884) http://highorbits.jhuapl.edu/
SOHO (Solar and Heliospheric Observatory), of ESA/NASA, launch Dec. 2, 1995. L1 was reached in 1996. SOHO has set an unprecedented standard for solar observations.


Another planned mission into a halo orbit at L1 is the LISA Pathfinder mission of ESA (launch 2009), to operate in an L1-Lissajous orbit [advanced instruments: LTP (LISA Test Package), and DRS (Disturbance Reduction System)].

Examples of spacecraft missions to L2 in the Sun-Earth system are: (see Figure 46):

- WMAP (Wilkinson Microwave Anisotropy Probe) of NASA/GSFC with a launch June 30, 2001, L2-Lissajous orbit; the objective is to probe conditions in the early universe by measuring the properties of the cosmic microwave background (CMB anisotropy) radiation over the full sky. 1886)
- HSO (Herschel Space Observatory) of ESA (collaboration with NASA) and the Planck spacecraft of ESA, both missions with a planned launch in 2007
- JWST (James Webb Space Telescope) of NASA, ESA and CSA with a planned launch in 2013.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Agency</th>
<th>Launch date</th>
<th>Main mission objective</th>
<th>Location (H for Halo)</th>
<th>Lissajous size (x 1000 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISEE-3</td>
<td>NASA</td>
<td>1978</td>
<td>Solar wind</td>
<td>L1/H</td>
<td>670 x 120</td>
</tr>
<tr>
<td>WIND</td>
<td>NASA</td>
<td>1994</td>
<td>Solar wind</td>
<td>L1/H</td>
<td>(short stay at L1 only)</td>
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<td>SOHO</td>
<td>ESA</td>
<td>1995</td>
<td>Solar wind</td>
<td>L1/H</td>
<td>650 x 120</td>
</tr>
<tr>
<td>ACE</td>
<td>NASA</td>
<td>1997</td>
<td>Solar physics</td>
<td>L1/H</td>
<td>260 x 160</td>
</tr>
<tr>
<td>WMAP</td>
<td>NASA</td>
<td>2001</td>
<td>Astrophysics</td>
<td>L2</td>
<td>200 x 200</td>
</tr>
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<td>Genesis</td>
<td>NASA</td>
<td>2001</td>
<td>Solar wind sample return</td>
<td>L1/H</td>
<td>650 x 120</td>
</tr>
<tr>
<td>LISA Pathfinder</td>
<td>ESA</td>
<td>2009</td>
<td>Technology demonstration</td>
<td>L1</td>
<td></td>
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<td>HSO (Herschel Space Observatory)</td>
<td>ESA</td>
<td>&gt;2008</td>
<td>IR astronomy</td>
<td>L2</td>
<td></td>
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<tr>
<td>Planck</td>
<td>ESA</td>
<td>&gt;2008</td>
<td>Cosmology</td>
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<td>400 x 80</td>
</tr>
<tr>
<td>Eddington</td>
<td>ESA</td>
<td>&gt;2009</td>
<td>Search of exoplanets</td>
<td>L2</td>
<td></td>
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<tr>
<td>Gaia</td>
<td>ESA</td>
<td>&gt;2010</td>
<td>Astrometry</td>
<td>L2</td>
<td>100 x 100</td>
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<tr>
<td>JWST</td>
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<td>&gt;2013</td>
<td>Astronomy</td>
<td>L2</td>
<td></td>
</tr>
<tr>
<td>JASMINE</td>
<td>JAXA</td>
<td>&gt;2014</td>
<td>IR Astrometry</td>
<td>L2</td>
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</tr>
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<td>DARWIN</td>
<td>ESA</td>
<td>&gt;2015</td>
<td>Search of exoplanets</td>
<td>L2</td>
<td></td>
</tr>
</tbody>
</table>

Table 101: Overview of missions to L1/L2 Lagrangian points 1887)

1.9.6 Observation coverage of constellations

The general objective of a satellite constellation is to provide either a global coverage configuration on a continuous basis, or to improve the partial coverage situation (increased temporal coverage of the target area), as can be offered by a single spacecraft. Such constellation designs consist of a group of satellites with coordinated coverage, operating together under shared control, synchronized so that they overlap well in coverage and reinforce rather than interfere with one another.

1886) Note: In Feb. 2003, NASA renamed the MAP (Microwave Anisotropy Probe) mission in honor of David Wilkinson to WMAP (Wilkinson Microwave Anisotropy Probe).
Satellite constellation coverage and geometry - determining the minimum number of satellites needed to provide a service, and their orbits - is a field in itself and beyond the scope of this text. However, an interesting classical coverage concept is use of the **Walker constellation** for applications in remote sensing, navigation, and in the wide field of communication services.

The Walker constellation [1888] [1889] [1890] [1891]) is named after John G. Walker of RAE [Royal Aircraft Establishment at Farnborough, UK - later renamed to DERA (Defence Evaluation and Research Agency); as of July 2, 2001 DERA was renamed to QinetiQ]. Walker was a pioneer in studying Earth-coverage problems (in particular equal-area distributions) with various satellite constellation configurations. [1892]

In the early 1970s, Walker systematized and simplified the definition of orbital constellation design for the case of circular orbits by specifying the key parameters as T/P/F. The value 'T' is the total number of satellites; 'P' is the number of planes; and, 'F' is a phasing angle by which satellites in an adjacent plane lead their twin in the previous plane. The phasing angle 'F' is defined as 360º/T. The planes are equally spaced around, and equally inclined to, the equatorial plane. In a symmetrical constellation of T satellites, T/P satellites are evenly spaced on each orbital plane, and P orbital planes are evenly spaced through 360º of ascending node. The advantage of inclined Walker constellations is the permanent network topology in the space segment.

Walker introduced a measure, referred to as PU (Pattern Unit) = 360º/T, to calculate the phase angle (phase angle = F x PU). Example: T/P/F = 54/9/3; then PU = 6.667º; and the phase angle = 20º. [1893]

- Example 1 of a Walker constellation 27/3/1: In this case 27 satellites are in a symmetrical Walker configuration (in three orbital planes).
- Example 2: 18/6/1. In this case 18 satellites are distributed in six planes (Δ=60º), the phasing φ=20º (see Figure 48).

![Figure 48: Equal distribution of a Walker constellation 18/6/1](image)

In the early phase of the GPS constellation development, Walker proposed a six-plane, 18 satellite constellation (with all planes inclined to the equator and satellites equally spaced

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[1893] Information provided by Friedrich Jochim of DLR/GSOC.
within a plane) — a classic Walker constellation: 18/6/2 which was eventually selected and accepted by the US Air Force. Later on, this 18/6/2 concept was changed to 24/6/2 when technical studies showed that no 18 satellite constellation could avoid intermittent outages, as well as periods of large navigational errors. The six additional spacecraft in the constellation were simply referred to as “operating in-orbit spares.”

Although the coverage concept of Walker was first implemented with the GPS constellation in MEO, the general concept is valid in LEO, MEO or in GEO satellite constellations. The GPS constellation of 24 MEO satellites is a Walker type constellation: 24/6/2, a semisynchronous orbit with an inclination (early phase of the program) of 63º — however, the inclination decreased to 55º due to launch vehicle constraints. Examples are:

- The Galileo constellation of 30 MEO satellites (European navigation system under development, start of operations in 2009) is a Walker type constellation: 27/3/1, plus three active spares. This adds up to 10 satellites per orbital plane. The three plane approach offers an easier replenishment of satellites.
- The communication industry employs a number of LEO Walker constellations such as: M-Star (proposed by Motorola), Iridium (66 satellites in 6 planes), Orbcomm, etc.
1.10 Orbital maneuvering and encounters

Orbital maneuvering encompasses all orbital changes after insertion required to place a satellite in the intended orbit. The first satellite maneuvers most likely occurred on January 2, 1959, with the Soviet Luna-1 mission to the moon - requiring countless maneuvers, including circularizing to initial launch orbit, doing midcourse corrections, and so on. Although Luna-1 missed the moon by about 5000 km, the feat of orbital maneuvering was remarkable at this early stage of spaceflight (see also chapter 1.4.8.7). Later, on Sept. 12, 1959 (launch), the Soviet Union corrected some of their difficulties and crashed Luna-2 into the lunar surface, near the crater Archimedes. The crash (on Sept. 14, 1959) was intentional because retro-rocket technology for a soft landing hadn’t matured enough to be installed on a satellite. 1895)

- Close encounters/rendezvous of satellites with celestial bodies. The art of satellite navigation has evolved steadily over the years, resulting occasionally in close flyby maneuvers. Examples are:

  - The Giotto mission of ESA encountered Halley’s Comet 1986. The S/C encountered Halley on March 13, 1986, at a distance of 0.89 AU from the sun and 0.98 AU from the Earth and an angle of 107° from the comet-sun line. The actual closest approach of the S/C to Halley was measured at 596 km. During the Giotto extended mission, the spacecraft successfully encountered Comet P/Grigg-Skjellerup on July 10, 1992. The closest approach was approximately 200 km. 1896)

  - On July 29, 1999, the DS1 spacecraft of NASA/JPL successfully performed a close flyby of asteroid 9969 Braille using the AutoNav system. At about 27 km separation, it was far the closest flyby of an asteroid so far attempted. On Sept. 22, 2001, DS-1 encountered and flew by the comet Borrelly at a speed of 16.5 km/s. DS1 came within 2200 km of Borrelly's 10km long core, transmitting 30 black-and-white images of the coma.

  - The NEAR (Near Earth Asteroid Rendezvous S/C)/Shoemaker satellite of NASA, in orbit around asteroid 433 Eros since Feb. 14, 2000, experienced its closest encounter with Eros on Oct. 26, 2000. 1897) 1898) 1899) The flyby, with corresponding surface observation, occurred at an elevation of about 5 km, planned and supervised by the mission control center at JHU/APL. The NEAR/Shoemaker S/C then performed year-long observations of Eros (322 million km from Earth). On Feb 12, 2001, it was commanded by JHU/APL to land on the asteroid (the S/C was not built for landing). The final touchdown speed of the craft was about 1.7 m/s after some descent maneuvers. Six high-resolution MSI images (<10 cm) of the asteroid were acquired during the descent at altitudes of <500 m. All S/C instruments kept operating after touchdown. The GRS (Gamma Ray Spectrometer) was detecting key chemical signatures of a “planetesimal” - one of the original building blocks of planets - up to two weeks after touchdown when the mission was ended. NEAR/Shoemaker thus became the first spacecraft ever to land on an asteroid. Launched Feb. 17, 1996, the NEAR S/C was the first mission in NASA’s Discovery Program of low-cost planetary missions.

  - The Stardust sample return mission of NASA (launch Feb. 7, 1999) encountered Comet Wild 2 on Jan. 2, 2004 (the closest distance to the comet was about 300 km at a relative speed of about 21,960 km/h, Wild 2 has a nucleus of about 5 km in diameter). Return of interstellar as well as cometary dust particle samples to Earth in January 2006. The Stardust

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1896) http://nssdc.gsfc.nasa.gov/planetary/giotto.html
1897) http://spacescience.com/headlines/y2000/ast26oct_2.htm?list65492
capsule of 46 kg landed safely on a parachute in the Utah desert on Jan. 15, 2006. Scientists believe these precious samples will help provide answers to fundamental questions about comets and the origins of the solar system. The dust collection task (tiny specks of solid matter, called interstellar dust grains, that permeate the galaxy) started on Aug. 5, 2002. On Nov. 1, 2002, Stardust completed a close flyby of asteroid Anne Frank (within 3,300 km, Anne Frank is about 4 km in diameter) as an opportunity for a full dress rehearsal of procedures the spacecraft used during its Jan. 2, 2004 encounter with its primary science target, comet Wild 2. Comet Wild 2 was discovered in 1978, it has an orbit of 6.39 years somewhere between Mars and Jupiter.

- The CONTOUR (Comet Nucleus Tour) mission of NASA (launch July 3, 2002). The CONTOUR mission is scheduled to visit 3 comets within five years. The first planned stop is with comet Encke in Nov. 2003; in June 2006 (after repeated flybys of Earth to change trajectory) comet Schwassmann-Wachmann 3 is being visited; if the fuel supply permits, comet d’Arrest will be visited in Aug. 2008. Note: The CONTOUR S/C went silent on Aug. 15, 2002 as it fired an onboard rocket to leave Earth orbit. Ground controllers at JHU/APL had expected to establish radio contact with the S/C shortly after the engine fired, but so far they never received a signal. - An investigation board came to the conclusion that a possible cause for this accident was structural failure of the spacecraft due to plume heating during the embedded solid-rocket motor burn.

- The Rosetta mission of ESA (launch March 2, 2004). After a series of flybys, one of Mars and three of Earth (to gain enough speed), and encounters with at least one asteroid, Rosetta will rendezvous with comet Comet 67P/Churyumov-Gerasimenko in 2014 (at a distance of about 675 million km from Earth, corresponding to 4.5 AU). For 18 months, the satellite will then orbit the comet’s tiny nucleus (about 4 km in diameter) as it gets closer to the sun. During this period, the Rosetta orbiter will deploy a lander, named Philae, for a touchdown and study of the comet’s surface. The Rosetta orbiter has 11 observing instruments, while Philae has 10 instruments.

- The Deep Impact mission of NASA (launch Jan. 12, 2005). A mother-daughter dual spacecraft carries an impactor with a mass of 370 kg (flyby of mother S/C and observation of the impactor’s collision with the comet). The objective was to hit the nucleus of Comet 9P/Temple 1 in July 2005. The fairly large comet Temple 1 (of size 5 km wide and about 12 km in length) won’t be destroyed or deflected by the impactor.

Note: On July 4, 2005, Deep Impact smashed into Comet 9P/Temple 1. The two objects collided at a speed of 10 km/s. The force of this collision generated a tremendous amount of heat and light which served to illuminate the whole area for the Deep Impact flyby spacecraft. The impactor spacecraft was able to capture images of Tempel 1 as it approached, and the last image was taken at an altitude of only 30 km. Data from Deep Impact’s instruments indicate an immense cloud of fine powdery material was released when the probe slammed into the nucleus of comet Tempel 1. — The collision encounter of Deep Impact with Comet 9P/Temple 1 has been watched by a large number of spacecraft instruments (Hubble, XMM—Newton, Rosetta, etc.) as well as by many ground-based observatories around the world. 1901)

1.11 On-Orbit Servicing (OOS) missions

Space logistics, the ability of on-orbit service provision, is a natural consequence of high-value assets in space (like HST and ISS) as well as of ever increasing satellite fleets in all fields of space endeavors. Without any logistics, satellites have severe limitations affecting their operational life and functional capabilities. The conventional practice in spacecraft and instrument building puts very high demands on reliability resulting in redundant and expensive satellites. With this approach, a spacecraft may still be lost even if the majority of its components are operational. Redundancy in turn produces heavy spacecraft which require extra lift capacity for launch services. 1902 1903

Since the 1970s, several challenging projects around the world have already dealt with OSS supported either by astronauts (Hubble repair missions) or simply by automation and robotics concepts. The emerging technologies of the 21st century may change the conventional practices of the past (at least to some degree) with the introduction of on-orbit servicing technologies and capabilities, in particular with regard to unmanned autonomous satellite missions. The solutions offered by the space industry must be affordable in order to be accepted.

Limitations: There are many physical limitations associated with servicing satellites. The foremost constraint is related to energy needs to achieve orbit. In order to simply achieve LEO (Low Earth Orbit), the required energy, in terms of velocity change, is roughly 9,650 m/s. To achieve MEO (Medium Earth Orbit) this is in excess of 10,000 m/s. Finally, GEO (Geostationary Earth Orbit) requires at least 13,580 m/s. These figures assume launch from a ground-based launch facility with direct injection into the respective orbit. The next largest energy constraint is associated with on-orbit maneuvering. In those cases where orbit-raising, deorbit, or life extension is involved, large amounts of propellant may be required to complete a mission. 1904

Some examples of servicing or repair missions are:

- On NASA’s various Skylab missions (1973-1974), astronauts installed various new equipment (deployment of sunshades and a solar array) and repaired instruments and/or science experiments as well. The early experiences with OOS required space suited humans performing the servicing tasks through EVA (Extra Vehicular Activity) missions.

- Shuttle repair/servicing missions. The first Shuttle repair mission took place in April 1984 (STS-41C). The SMM (Solar Maximum Mission) S/C became the first satellite to be retrieved, repaired, and redeployed in orbit by a Shuttle crew (with the help of Canadarm-1). The STS-51A mission (Nov. 8-16, 1984) retrieved two commercial satellites Palapa B2 and Westar-6 (Palapa B2 and Westar-6 were launched on STS-41B on Feb. 4, 1984 and had failed to reach proper orbit). A further Shuttle repair mission occurred on the Discovery flight STS-51-I (Aug. 27-Sept. 3, 1985). The primary mission of the crew was to deploy three commercial communications satellites and to retrieve and repair SYNCOM IV-3 which was deployed during the STS 51-D mission in April 1985 and had malfunctioned. In addition, a middeck materials processing experiment was flown. A rendezvous maneuver was successful in meeting the ailing SYNCOM IV-3 spacecraft; the malfunction was repaired - permitting commands from the ground to activate the spacecraft’s systems and eventually sending it into its proper geosynchronous orbit. The repair activity involved the first manual grapple and manual deployment of a satellite by a crew member.

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- **Hubble servicing missions.** HST (Hubble Space Telescope) was launched April 24, 1990 on Shuttle flight STS-31. However, after Hubble’s deployment, scientists realized that the telescope’s primary mirror had a flaw called “spherical aberration.” The outer edge of the mirror was ground too flat by a depth of 4 μm. This aberration resulted in images that were fuzzy because some of the light from the objects being studied was being scattered. Without periodic onboard servicing, HST would have been a disaster and would not have produced all of the great science it has. 1905)

- **SM-1 (Service Mission-1).** 1906) The first Hubble repair mission was launched Dec. 2, 1993 on STS-61. Installation of COSTAR (Corrective Optics Space Telescope Axial Replacement). In addition, SM-1 included the installation and replacement of other components including: solar arrays, solar array drive electronics, magnetometers, two rate sensor units, two gyroscope electronic control units, etc.

- **SM-2.** The second Hubble service flight was on STS-82 (Feb. 11-21, 1997). The installation of new instruments extended Hubble’s wavelength range into the near infrared for imaging and spectroscopy, allowing to probe the most distant reaches of the universe. The replacement of failed or degraded spacecraft components increased efficiency and performance. The newly installed instruments were: STIS (Space Telescope Imaging Spectrograph), NICMOS (Near Infrared Camera and Multi-Object Spectrometer).

- **SM-3.** HOST (Hubble Orbital System Test). The third Hubble service flight was on STS-95 (Oct. 29 - Nov. 7, 1998). This Shuttle mission provided a unique opportunity to test key pieces of new Hubble hardware before they would be installed in the telescope. By flying in an orbit similar to Hubble’s, the Shuttle allowed engineers to determine how the new equipment on HOST would perform on the telescope. HOST engineers monitored the effects of radiation on Hubble’s new hardware, including an advanced computer, digital data recorder, and cryogenic cooling system. All the new technologies on the HOST platform performed up to expectation.


- **SM-3B.** A routine servicing mission to HST took place Mar. 1-11, 2002 on STS-109. Installation of ACS (Advanced Camera for Surveys), built by Ball Aerospace for NASA and consisting of three cameras in the spectral range of 0.12-1.0 μm. The WFC (Wide Field Camera) uses a CCD area array of 16 Mpixel (4096 x 4096). The second is a HRC (High Resolution Camera) using a 1024 x 1024 CCD array and a high sensitivity in the UV. The third camera, the SBC (Solar-Blind Camera), is a far-ultraviolet, pulse-counting array that has a relatively high throughput at 121 nm. SA-3 (Solar Array-3) installation and PCU (Power Control Unit). Installation of a new experimental cryocooler for NICMOS (70 K cooling to revive its IR vision, and extend its life by several years).

- **SM-4.** Another HST servicing mission was planned for 2005. This included the installation of WFC3 (Wide Field Camera 3). WFC3 replaces WFPC1 and 2 (Wide Field Planetary Camera). In addition, installation of COS (Cosmic Origins Spectrograph) and replacement of COSTAR of SM-1. COS is a medium resolution spectrograph specifically designed to observe into the near and mid ultraviolet. In addition, refurbishment of Hubble’s vital attitude control gyro (only two of the six gyros are currently in operation).

1905) Note: When originally planned in 1979, the Large Space Telescope program called for return to Earth, refurbishment, and re-launch every 5 years, with on-orbit servicing every 2.5 years. Hardware lifetime and reliability requirements were based on that 2.5 year interval between servicing missions. In 1985, contamination and structural loading concerns associated with return to Earth aboard the Shuttle eliminated the concept of ground return from the program. NASA decided that on-orbit servicing might be adequate to maintain HST for its 15 year design life. 1906) http://hubble.nasa.gov/servicing-missions/
Note 1: NASA cancelled the next serving mission (SM-4) of the Shuttle and all follow-up flights to Hubble as of mid-January 2004 due to budgetary problems and to safety concerns. It means that Hubble will remain in orbit as long as it can fulfill its duties, then be brought back into Earth’s atmosphere, with reentry expected in 2011. The JWST (James Webb Space Telescope) mission is considered to be the successor of Hubble with a planned launch in 2013.

Note 2: NASA is reconsidering its decision on the SM-4 mission to Hubble as of May/June 2004 due to mounting pressure from the Hubble community and from Congress — to keep the Hubble mission alive until JWST is definitively in orbit. — A possible robotic mission scenario is considered referred to as HRSDM (HST Robotic Servicing and Deorbit Mission). To extend the scientific mission of HST, the robotic mission must launch by the end of 2007 to be of any use. This timing constraint represents a great challenge for the readiness of HRV (HST Robotic Vehicle). — In Jan. 2005, NASA awarded a contract to MDA (MacDonald Dettwiler and Associates Ltd.) to investigate a potential solution for a robotic servicing mission to rescue HST.

Note 3: On Oct. 31, 2006, NASA Administrator Mike Griffin announced new plans for a Hubble repair mission, SM-4 (Servicing Mission—4), for the fall of 2008. The 11-day Hubble flight is designated as STS—125 and slated to launch aboard the Discovery orbiter. The concept adopted is an astronaut-led Shuttle mission to Hubble (which voids the robotic servicing mission concept that was studied earlier). The overall objective of SM-4 is to extend the operational life of Hubble at least until 2013.

- The various service flights (1987 to 2000) to the Russian MIR Station were used to service/repair some onboard hardware.
- Servicing of a stranded commercial communications satellite (Intelsat 603) by Shuttle flight STS-49 (May 7-16, 1992, inaugural voyage of Shuttle Endeavour). The task required crew EVA (Extra Vehicular Activity) capturing Intelsat 603 and hauling it into the cargo bay (it took a couple of days of troubleshooting to complete the capture task). The crew then attached a new booster to its base and Intelsat 603 was redeployed into GEO. Intelsat 603 continued its operational service life until 2002 when it was replaced by Intelsat 905 (launch June 5, 2002 on Ariane-44L).

Background: Intelsat 603 was launched on Mar. 14, 1990 by a Titan-3 vehicle. Human error led to a mis-wiring of the Titan 3’s second stage and the satellite so the two would not separate. The only way to save Intelsat 603 was to separate the S/C from its attached upper stage. Unable to reach its intended orbit, Intelsat 603 was left stranded in a useless orbit for two years.

- The ISS (International Space Station) build-up era in LEO began in 1998. Service flights to ISS are being provided by the USA and by Russia on a continual basis. The total fleet of vehicles, which will perform RVD/B (Rendezvous and Docking/Berthing) maneuvers with the ISS includes:
  - US Space Shuttle (manned missions)
  - Russian Soyuz spacecraft (manned missions)
  - Russian Progress spacecraft (unmanned autonomous resupply vehicle). See description of Progress below.
  - ATV (Automated Transfer Vehicle). ATV is an ESA unmanned autonomous cargo resupply vehicle, put into orbit by the Ariane-5 launcher. The ES ATV version of the Ariane 5 has been designed to place ATV into a 300 km circular low Earth orbit (LEO) inclined to 51.6°. First launches are expected to start in 2007.

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- HTV (H-II Transfer Vehicle) of JAXA, Japan (unmanned autonomous vehicles).
All unmanned autonomous vehicles have the capability for resupply, to remove waste from
the station and re-boost the station to a higher altitude to compensate for atmospheric drag.
Hence, the ISS turns out to be the most important application of RVD/B technology
introduction in the first two decades of the 21st century.

- The capability of on-orbit servicing is of course not limited to Shuttle or Soyuz flights
(based on manned servicing techniques developed in the 1980s) resulting in very high ser-
vice bills for a single mission. Neither is OOS limited to the current (Progress) and future
generation (ATV, HTV) of unmanned autonomous spacecraft.

Examples: Small robotic spacecraft in combination with new technologies may in fact be the
answer to potential future servicing mission capabilities in such fields as: a) mission repair,
b) maintenance and scheduled repair, c) replenishment of consumables, and d) preplanned
product improvements and upgrades. The OOS mission architecture will consist of a set of
required hardware elements, software programs, protocols, and operational procedures. First experiments with on-orbit servicing have already been conducted.

- SVS (Space Vision System). SVS is a Canadian-built camera system, sponsored by CSA
and NASA with its maiden flight (prototype) on Shuttle STS-52 (Oct. 22 - Nov. 1, 1992).
Since then, SVS has completed four Shuttle flights. The Shuttle mission STS-88 (Dec. 4 - 15,
1998), an assembly flight with the module Unity to ISS, marked the first operational use of
SVS. The primary objective of SVS is to help astronauts perform so-called blind mates of
the space station modules. SVS is a computer-aided vision system that works in conjunction
with four stationary cameras located inside the Shuttle’s cargo bay and two cameras at-
tached to the robotic arm itself. 1910

- AERCam (Autonomous EVA Robotic Camera), a free-flying space camera (of NASA/
MSFC). The first demonstration occurred on STS-87 (November 19 to December 5, 1997).
The free-flyer, a spherical vehicle of 33 cm in diameter and a mass of 16 kg, has a self con-
tained cold gas propulsion system giving it the capability to be propelled with a 6 degrees
of freedom control system. 1911) Onboard the free-flyer are rate sensors to provide data for an
automatic attitude hold capability. The AERCam “Sprint” version, also referred to as
AERCam-I, is flown under remote control (teleoperation with hand controllers by a crew
member). AERCam employs a pair of stereo cameras for vision feedback to the operator
(and ground). AERCam is powered by lithium batteries. Its electrical supply and nitrogen
supply (propulsion) are designed to last at least seven hours, the maximum length of a nor-
mal spacewalk.

- MiniAERCam (Miniature Autonomous EVA Robotic Camera). A spherical-shaped
free-flying space camera of about 19 cm diameter (NASA/MSFC) using dense packaging
and miniaturized components. Two digital cameras are aligned with the +X direction of the
vehicle. One of these cameras provides NTSC-standard color video, while the other camera
may be used for high-resolution still images. A third color video camera is positioned in the
+Y direction for an orthogonal view. MiniAERCam features two custom GPS antennas,
one on top and one on the bottom. 1912) 1913)
The avionics system includes a processor board, a video compression and imaging system, a
wireless ethernet (IEEE 802.11b), and a LED array for illumination. A communications an-
tenna is located near the top GPS antenna. Data buses include: RS-232, I2C, for instrumen-
tation, and LVDS (Low Voltage Differential Signaling) device interfaces. The vision subsys-

1911) http://spaceflight.nasa.gov/station/assembly/sprint/
tonomous Extravehicular Robotic Camera (MiniAERCam) Guidance, Navigation and Control System,” Proceed-
ing of the 26th AAS Conference on Guidance and Control, Breckenridge, CO, Feb. 5-9, 2003, Vol. 113 Ad-
vances in the Astronautical Sciences, Edited by I. J. Gravseth and R. D. Culp, AAS-03-015, pp. 187-205
system consists of three CMOS/APS imagers, an onboard video compression system, and an off-board video decompression and display system. The propulsion system employs Xenon. The MiniAERCam program was initiated in 2000, a functional prototype had been designed, developed, integrated and tested by 2002. The functional spectrum of MiniAERCam offers a) visual inspection of space vehicles (ISS), b) to serve as a test platform for evaluating algorithms and relative navigation for autonomous proximity operations, or c) to evaluate candidate sensors and technology. MiniAERCam has a mass of 4.7 kg and a power consumption of 18.2 W.

- Inspector platform family of EADS Astrium GmbH (formerly DASA). The program started in 1993 as a joint project of DASA/Space Infrastructure, RSC Energia, and The Boeing Company. The objective was to monitor events in space (docking maneuvers, etc.) and to extend the inspection capabilities for MIR as well as for ISS. At the start of the 21st century the Inspector family consists of X-MIR and three more service structures (ISS Inspector, Visitor, and Operator) in varying phases of development. 1914) 1915)

X-MIR Inspector was launched on its first demonstration flight to the Mir station on Oct. 5, 1997. The prime objectives were to verify the video navigation system and the visual inspection capabilities of X-MIR in the neighborhood of MIR. On Dec. 17, 1997, X-MIR started its demonstration flight as a free-flying observer service module, by orbiting MIR. The successful X-MIR demonstration lasted from 1997 to 1998 providing high-quality video imagery of MIR as well as of the docking sequences of the service vehicle Progress. X-MIR consists of: a) space vehicle, b) monitoring and control station, and c) transport launch container. X-MIR was remotely controlled from MCS (Monitoring and Control Station) onboard the MIR station. MCS consisted of a laptop PC, a video display, a video recorder and an electronic module for radio communications, power distribution and navigation. 1916)

The prime objective of the ISS Inspector is the inspection of the surfaces of the ISS or visiting transportation vehicles (US Space Shuttle, Proton vehicle, etc.). In 1997 NASA selected the Inspector for the AETD (Advanced Engineering and Technology) program. The prime objective of the Inspector for ISS services is the inspection of space vehicle surfaces (video and infrared observations), this includes the ISS and visiting spacecraft. The Inspector payload performs also leakage, contamination and radiation environment monitoring of the ISS.

The Visitor concept is a co-orbiting multi-purpose platform of ISS to be used for various payload operations in the fields of science observations, technology or commercial applications. Visitor is able to carry various kinds of payloads under very low gravity conditions. The payloads are mounted onto standard payload modules, referred to as ORU (Orbital Replaceable Unit) or onto ExPA (Express Pallet Adapter).

- SRMS (Shuttle Remote Manipulator System) of CSA, also known as Canadarm-1 on Shuttle, has enabled on-orbit servicing missions such as payload/satellite deployment, maneuvering, servicing and retrieval, Extra-Vehicular Activity (EVA) astronaut assist, Shuttle inspection and servicing, Orbit Replaceable Unit (ORU) manipulation, as well as on-orbit construction and assembly. In addition to the Palapa B2, Westar-6 and Hubble servicing missions, Canadarm has been involved in the International Space Station (ISS) assembly missions.

SRMS, built by MD Robotics of Spar Aerospace of Canada, is in service since 1981 in the Shuttle program of NASA. A total of five Canadarms have been built and delivered to NASA with delivery dates of: April 1981, January 1983, Dec. 1983, March 1985, and Aug. 1993. Canadarm-1, developed by SPAR Aerospace Ltd. of Canada as prime contractor to NRCC (National Research Council of Canada), was first flown and successfully operated on Columbia’s second mission, STS-2 (Nov. 12-14, 1981). Canadarm-1, with an arm length

1914) “The Inspector Product Family,” brochure provided by F. Steinsiek of DASA/Space Infrastructure, Bremen
1915) http://www.dasa.com/dasa/index_e.htm
of 15 m, has performed flawlessly for over 20 years although originally, it was designed for “only” a life of ten years. – Note: In 1999, MD Robotics of Spar Aerospace was acquired by MDA (MacDonald, Dettwiler and Associates) of Richmond, B.C, Canada.

- ROTEX (Robot Technology Experiment), an experimental robotic arm of DLR (Germany), was flown on STS-55 (Apr. 26 – May 6, 1993) to demonstrate on—orbit assembly of subsystems. ROTEX successfully completed multiple tasks that include replacement of a simulated Orbital Replacement Unit (ORU) and capture of a free—flying object via onboard and ground teleoperation and autonomous scripts. By accomplishing tasks from autonomous scripts during the experiment, ROTEX became the first autonomous space robotic system.

- SPSR (Space Portable SpectroReflectometer) of NASA (see J.26.5). SPSR is a small battery-powered instrument (16.7 kg) providing solar absorptance measurements on S/C surfaces. The instrument was flown to MIR during the Shuttle STS-86 mission (Sept 27 - Oct. 6, 1997). In early 1998, the SPSR was utilized during various EVA operations to check spacecraft surfaces for optical performance. SPSR was returned to Earth at the conclusion of the STS-89 mission (Jan. 22-31, 1998).

- ETS-VII, a Japanese technology demonstration satellite (launch Nov. 27, 1997) of NASDA. ETS-VII conducted a series of rendezvous, docking, and space robotic technology experiments. For instance, it conducted the first successful release, tracking, and capture of a subsatellite without help from the ground on Sept. 1, 1999. The ETS-VII system consists of two spacecraft: a chaser satellite (Hikoboshi), and a target satellite (Orihime). Some of the key experiments executed during the ETS-VII mission include: 1917)

- Visual inspection of onboard equipment by a robotic vision system
- ORU (Orbital Replaceable Unit) handling and simulated fuel supply experiments
- Handling of small equipment by ETS-VII small robot arm including the use of a taskboard handling tool
- Handling of truss structures
- An antenna assembly experiment
- Ground teleoperation of the ETS-VII robot
- Handling and berthing of the 410kg ETS-VII target satellite (Orihime) with ETS-VII robot on chaser satellite (Hikoboshi)
- Rendezvous and docking by the ETS-VII Orihime with Hikoboshi.

Engineers commanded the Orihime to float about 200 mm away from the Hikoboshi main satellite body. Then, using a robotic arm and grapple attached to the larger craft, Orihime was retrieved and held firmly in place. The entire capture procedure, including the activation of the robotic arm and extension, was conducted automatically without help from ground control computers.

Joint NASDA-DLR teleoperation experiments of the onboard robotic arm on ETS-VII were conducted in the time frame April 19-21, 1999. The GETEX (German Teleoperation Experiment) ground control system of DLR was installed at the Tsukuba Space Center and linked to NASDA’s robot experiment system. The following experiments were conducted:

- Evaluating the motion of the satellite attitude during onboard robot arm operations
- World model update for onboard robot operations
- Tele—manipulating the onboard robot using virtual reality technology. 1918)

Previous automatic docking activities, such as those conducted with the Russian Soyuz and Progress S/C, have used either operator assistance or ground control computers. On Oct.

30, 1967, the USSR accomplished the first docking of two unmanned satellites in LEO (Cosmos-186 and Cosmos-188).

- MMS (Mobile Servicing System) of ISS provided by CSA Canada (also known as Canadarm2). MMS is a robotics system consisting of the elements SSRMS (Space Station Remote Manipulator System), SPDM (Special Purpose Dextrous Manipulator), and MBS (Mobile Base System). In April 2001, SSRMS was flown and installed on ISS. The system will be used to assemble and maintain the ISS (International Space Station). Both systems, Canadarm and Canadarm2 were built to service existing infrastructure in space.

- MEPSI (MEMS-based PicoSat Inspector), a technology validation flight (one of six precursor flights) of AFRL on STS-113 (Nov. 23 to Dec. 4, 2002, see M.40). MEPSI, built by The Aerospace Corporation and JPL, contains a pair of MEMS-based picosats (each with a mass of about 1 kg) in a launcher that ejects the two tethered picosats from the spacecraft (16 m tether). The launch system is mounted to a standard Shuttle-provided APC (Adaptive Payload Carrier). The total assembly is called PLA (Payload Launcher Assembly) with a mass of 8 kg. After release, the picosats operate on battery power for several days to complete mission objectives (demonstrate the launch system, establish communications between the two picosats and the ground system). The long-term goal is to establish an autonomous inspection capability. The launch of the second MEPSI mission, along with MEPSI-2A and -2B, took place on Shuttle flight STS-121 (July 4, 2006). The mission goals include: 1) to demonstrate a MEMS Inertial Rate Measurement Unit (IRMU), and 2) to demonstrate a MEMS Transmit/Receive (T/R) switch.

- XSS-10 (Experimental Spacecraft System-10), a demonstrator microsatellite (31 kg) of the US AFRL (Air Force Research Laboratory), was launched on Jan. 29, 2003 as a secondary payload to the GPS satellite (2R-8) on a Delta-2 launch vehicle from KSC. XSS-10, a demonstration of inspection (live video) of the second stage of the Delta-2 launcher (total operation of a day, see M.52.1). Shortly after reaching orbit, the XSS-10 maneuvered about 200 m away from the second stage vehicle, and then approached it taking live video of the target vehicle. XSS-10 featured its own propulsion system, however, no re-docking was involved. The XSS-10 operations were successful and fulfilled all primary mission objectives.

- XSS-11 (Experimental Spacecraft System-11) is a further development of AFRL (launch April 11, 2005). The minisatellite of about 145 kg launch mass is envisioned to explore, demonstrate and flight-qualify some microsatellite technologies. Emphasis is being placed on autonomous on-orbit operations. One of the future mission goals is to collect samples of rocks and soil from Mars and return them to Earth for analysis. Note: After launch (April 11, 2005), the spacecraft underwent an extended checkout period to verify all functions of components and subsystems. The spacecraft accomplished significant mission milestones by rendezvousing three to four times with the upper stage of the Minotaur launch vehicle at distances between 1.5 km and 500 m. So far, XSS-11 has already completed more than 75 natural motion circumnavigations of the expended rocket body. The fuel consumption and efficiency is good, and the spacecraft is expected to be operational for another year.

- Inspection services during launch and early-orbit phases are already practiced with onboard miniature cameras providing visible proof to the mission operators of such functions as stage separation, antenna deployment, secondary vehicle deployment, and many other onboard activities and events. An example of inspection services is TEAMSAT (M.45), an ESA/ESTEC low-cost satellite demonstrator mission (launch Oct 30, 1997) with VTS (Visual Telemetry System).

1919) G. Budris, “Integrating Secondaries on Delta II (Overview of XSS-10),” Proceedings of the IEEE Aerospace Conference, Big Sky, MT, March 6-13, 2004
The SNAP-1 nanosatellite mission of SSTL (Surrey Satellite Technology Ltd), UK, with a launch on June 28, 2000 (along with Tsinghua-1 of China) is equipped with MVS (Machine Vision System) permitting SNAP-1 to function as a remote inspector.

Most work on autonomous on-orbit assembly and serving has been confined to very high-value assets such as ISS. Servicing spacecraft developments considered for ISS are: a) CTV (Cargo Transfer Vehicle) of NASA; b) ATV (Automated Transfer Vehicle) of ESA, a cargo resupply vehicle for ISS to be launched by Ariane-5; and c) HOPE of JAXA.

OOS (On-Orbit Servicing) upgrade/refurbishment of a spacecraft configuration within the ISS Utilization Program. XEUS (X-ray Evolving Universe Spectroscopy) is an ESA long-term astronomy observatory in study/planning as of 1999-2003 and a potential successor to XMM-Newton (launch Dec. 10, 1999). XEUS will consist of two separate S/C, the MSC (Mirror S/C) and the DSC (Detector S/C), both in LEO and separated at a distance of 50 m (representing the telescope focal length) in FTO (Fellow Traveller Orbit). The mission profile of XEUS foresees several phases:

- An initial LEO observation mission slightly higher than that of ISS for a duration of 4-6 years. The initial configuration (XEUS-1) consists of an X-ray mirror S/C with a 1 keV effective area of 6 m² (diameter of 4.5 m²).

- Rendezvous and refurbishment of XEUS at ISS. After a period of operations XEUS-1 will visit the ISS to assemble/attach additional mirror elements that have already been transported to the ISS. In this way the initial mirror area of 6 m² will grow to 30 m² (10 m diameter at 1 keV). This will involve the use of ISS robotics such as ERA (European Robotics Arm) for the x-ray mirror assembly. The large aperture mirror required for XEUS is achieved through a new concept: the mirror is made up of segments, known as petals (each of these petals will be aligned using an active system). The assembly approach of XEUS at ISS makes it possible to accommodate an antenna of considerably larger mass, and therefore larger diameter and better surface accuracy.

- After the refurbishment and upgrade at the ISS, XEUS-2 will return to its FTO where it will continue its astrophysics program, but now with a much enhanced capability (XEUS-2 will be around 200 times more sensitive than XMM-Newton).

Generally, all OOS activities will be driven by the needs of the satellite owners/operators and the promise of resulting benefits. The overall service concept for OOS missions covers the following spectrum of applications:

- Re-orbiting: move of target to/in its target orbit
- Deorbiting: move of target to a graveyard orbit or initiation of a destructive reentry
- Salvage: refers to a salvage of a target (e.g., orbital station or non-destructive reentry)
- Maintenance: refueling or other resupply of the target
- Repair: diagnosis and correction or repair of failures or faulty units of a target
- Retrofit: upgrade and/or assembly of orbital replacement units of the target
- Docked inspection: system and fault diagnosis of the target using physical connectors
- Remote inspection: remote system and fault diagnosis of the target.

The Orbital Recovery Group, London, UK, is developing the ConeXpress ORS (Orbital Recovery System) with Holland’s Dutch Space (Leiden) to provide a way to extend the

1920) http://astro.esa.int/SA---general/Projects/XEUS/main/xeus_main.html
life of stranded orbiting communication satellites in GEO. ConeXpress is a relatively small servicing spacecraft (total mass of up to 1400 kg), formerly referred to as CX—OLEV (ConeXpress—Orbital Life Extension Vehicle), capable to dock with larger spacecraft (resupply of fuel and/or tug services to a stranded S/C).

The ORS tug—based concept employs the cone—shaped payload adapter design of EADS-CASA used on every mission of Ariane-5. Electric propulsion is used both for orbit transfer (from GTO to GEO) and stationkeeping. The European development team is composed of Dutch Space (ORS prime contractor), Kayser—Threde, DLR, SSC, Sener, and Snecma. The ORS program is also supported by ARTES-4 (Advanced Research in Telecommunications Systems), a PPP (Public Private Partnership) program of ESA. In Feb. 2006, a system PDR (Preliminary Design Review) was successfully conducted. The first launch of a ORS demonstration mission is scheduled for 2009.

• .The VGS (Video Guidance Sensor) flight demonstrations were flown on Shuttle flights STS-87 (Nov. 19 to Dec. 5, 1997) and STS-95 (Oct. 29 to Nov. 7, 1998)). The VGS system consisted of a video camera (CCD with 484 x 770 pixels) and dual-frequency lasers at 808 and 850 nm. The VGS package was mounted in the cargo bay of the Shuttle, it used the SPARTAN spacecraft, in close proximity of the Shuttle, as its optical target (SPARTAN was equipped with retroreflectors). The lasers illuminated the retroreflectors of the target, the reflected video images provided position information of the target and its distance from the Shuttle. The laser-video system offered improved accuracy over the use of radio frequency control systems for future docking maneuvers. VGS used five VME cards and two power supplies to drive and cool the lasers and camera and to capture and process the video frames into reflected spot coordinated. The VGS locked on when the Shuttle approached SPARTAN within a distance of 150 m. VGS was developed by NASA/MSFC as part of the future AR&C (Automated Rendezvous and Capture) system.

• Progress cargo ship. The Space Agency of Russia, Roskosmos, is providing an autonomous unmanned docking capability with its Progress spacecraft — servicing space stations. The Progress support concept is based on single-use cargo freighters (modified Soyuz capsules) — that fly unmanned as automatic, robot ships under remote control. The first Progress M cargo ship was launched in August 1989 toward the Mir space station.

Background: The Progress concept of resupply and disintegration on return into Earth’s atmosphere was developed by NPO Energia. It’s roots go back to the Salyut-6 space station era with a first servicing flight in January 1978. A total of 43 Progress flights of the original modification were launched toward Salyut-6 and Salyut7 space stations, and all successfully completed their missions.

Model Progress M1: A so-called “propellant” modification of the spacecraft was developed specifically for ISS (International Space Station), starting in 1998. RKK Energia “repackaged” the middle (refueling) section of the spacecraft to allow the delivery of more fuel to the ISS. The first M1 version of the Progress spacecraft was launched on Feb. 1, 2000 toward the Mir space station. On August 6, 2000, the first Progress spacecraft (M1-3) was launched toward the ISS.

Resupply flights to the ISS are scheduled on an average period of 8 weeks, taking about 2500 kg of goods to the station — food, fuel, water, clothing, office supplies, scientific experiments to be conducted, replacement parts, newspapers and mail from home, and other necessities.
The day after the disastrous loss of Shuttle Columbia (Feb. 1, 2003), Russia’s Progress M-47 flight completed its 100th launch in the series of unmanned automatic cargo carriers when it was blasted to space on Feb. 2, 2003, on a Soyuz-U rocket from the Baikonur Cosmodrome in Kazakhstan. At the ISS on Feb. 4, 2003, Progress M-47 docked automatically with the Zvezda module. The previously docked Progress M1-9 had been undocked on Feb. 1 2003, and deorbited to burn up in Earth’s atmosphere. 1928)

- **ROKVISS** (Robotic Components Verification on ISS) is a German (DLR) technology experiment, a light-weight manipulator system (the DLR industry partners were Kayser-\-Threde of Munich and EADS Space Transportation of Bremen). The objective is in-flight demonstration and verification of the ROKVISS functionality, a highly integrated modular robotic structure. ROKVISS is installed on the outside of the Zvezda Service Module of Russia at ISS. The verification includes the demonstration of the joint-elements, as well as the applicability of new robotic control modes for automatic operations for online closed-loop control by the human operator (tele-presence operational mode). 1929)

A flight of ROKVISS on a Progress service flight M−51 took place on Dec. 23, 2004. The ROKVISS functions and services are planned to be used on future manned and unmanned space missions for handling tasks such as maintenance, repair, assembly, etc.. The experiment basically consists of a robot, an attached pointer, a stereo video and a mono camera system. Since Feb. 2005, ROKVISS is operated by DLR using the Weilheim station (supported by ZUP, Moscow); operations will continue until Feb. 2007. 1930 1931)

- **DART** (Demonstration of Autonomous Rendezvous Technology) is a rendezvous demonstration mission of NASA (launch April 15, 2005). The objective is to test enabling (autonomous) technologies required to locate and rendezvous with other target spacecraft (client) — in particular, to perform and validate close proximity operations and its control between the DART vehicle and a passive target satellite in orbit. The DART spacecraft has been designed and built by OSC (Orbital Sciences Corporation) of Dulles, VA. Once in orbit, DART will rendezvous with with the target satellite MUBLCOM (Multiple Paths, Beyond-Line-of-Site Communications) of DARPA, a microsatellite launched May 18, 1999 and equipped with retroreflectors. Over a period of 24 hours, DART will perform several autonomous, close proximity operations with MUBLCOM, including station keeping, docking approaches, and collision avoidance maneuvers. DART employs AVGS (Advanced Video Guidance Sensor), a laser-based optical system (that works with cooperative retroreflectors on the target satellite) incorporating advanced optics and electronics. In addition, it receives a continuous GPS information stream broadcasted from the MUBLCOM satellite to track the satellite within a range of about 100 m. 1932) 1933)

Note: The DART maneuvers ended prematurely. A NASA investigation after the mishap found that DART had used up its pressurized nitrogen gas maneuvering fuel before it could complete the rendezvous. The investigation board determined that excessive thruster firings in response to incorrect navigational data caused the spacecraft to run out of thruster fuel during its approach, so it could not avoid the low – velocity collision with MUBLCOM. A DART design deficiency was that it couldn’t to receive commands from the ground. 1934)

1928) http://www.spacetoday.org/SpcStns/Progress100thFlight.html


1932) http://www1.msfc.nasa.gov/news/dart/

1933) http://www.orbital.com/AdvancedSpace/DART/

A DARPA-funded unmanned rendezvous and docking program is OE (Orbital Express). The overall objective of OE is to demonstrate autonomous on-orbit servicing in the time frame spring 2007 (launch March 9, 2007 of OE) using a system called ARCSS (Autonomous Rendezvous and Capture Sensor System). The mission scenario employs two spacecraft, the ASTRO (Autonomous Space Transfer and Robotic Orbiter) servicing spacecraft (under development at Boeing), and NEXTSat, the S/C to be serviced (under development at BATC). The basic requirement of ARCSS is to provide the parameters of: relative angle, range, position and attitude between the chaser (ASTRO) and client (NEXTSat) to the ASTRO GN&C (Guidance Navigation & Control) system. ASTRO and NextSat were part of a multiple satellite launch, referred to as the Air Force’s Space Test Program (STP-1). To line up with NEXTSat for docking, ASTRO will use a laser sensor system, as well as the AVGS (Advanced Video Guidance Sensor) first flown on DART. - As part of the technology demonstration, requirements call also for development of “industry standard servicing interfaces and protocols” that can be utilized by future spacecraft developers. The OE demonstration is also viewed under the aspect to provide eventually an alternate access capability for ISS logistic serving by commercial providers.  

1.12 Satellite Radionavigation Systems

Radionavigation refers to the determination of position, velocity and/or other characteristics of an object, or to obtaining information relating to these parameters, by means of the propagation properties of radio waves.

Radionavigation systems employ the concept of triangulation with line-of-sight radio signals from different satellites to find position - in the same fashion that angular measurements of distant stars were made (and are still being made) throughout the maritime navigation history to find position. Instead of angular measurements to natural stars, the new systems (GPS and GLONASS) introduced the concept of radio-ranging measurements (pseudoranges) as observables. In this triangulation scheme, the user’s receiver determines the distance from the user to each of several satellites. Since the positions of the satellites are known, either through previous publication or as part of the satellite’s broadcast information, the user’s position can be determined (only the satellite signals are needed).

The currently operational second generation of satellite radionavigation systems (GPS in particular, GLONASS), dual-use service systems for the military and civil communities, started nothing less but a revolution in navigation applications, permeating all facets of society, i.e., providing global services to those traditionally involved with navigation (aviation, shipping, space flight) as well as the ever-increasing segment of classical non-navigators [utility networks (gas, electricity, water, mobile phones, financial transactions, travel support, assistance for disabled people, road and railway transport services, etc.), steering of assembly lines in manufacturing, tracking and location-based services (farming, hazard tracking, emergency response, security services, information on points of interest, etc.), timing standard, etc.]. At the start of the 21st century, civil GPS applications far outnumber the military applications, both are beginning to play an increasing role in national economies.

Since neither the current GPS nor the GLONASS (nor the future Galileo) constellations are able to provide all aviation positioning requirements, so-called wide area augmentation systems are being developed to provide enhanced performance services of integrity, availability, and continuity monitoring on a regional scale. The topic of network service security (protection against unintentional signal interference and potential jamming threats or actions) is also an important upgrade aspect. The US WAAS (Wide Area Augmentation System) is expected to provide an initial operational service capability in 2003.

1.12.1 LORAN (Long-Range Navigation) and other pre-GPS systems

Land-based radionavigation came into existence with the development of the Decca Navigator system of Decca Radio and Television Ltd. of London, UK; it was initially used for guiding the leading minesweepers and landing craft in the Allied invasion of Normandy during World War II. The system was originally conceived by W. J. O’Brien (USA) in the time frame 1936-39 as a method of measuring the ground speed of aircraft for trial purposes, and was indeed originally called an “Aircraft Position Indicator.” The Decca system was one of the first to give the user a position, rather than a series of bearings. Decca is based around a chain of master transmitting stations, each one backed up by a trio of slave stations (low-frequency hyperbolic navigation system, it worked by comparing the phase difference of radiosignals emitted by several radio stations). DECCA services covered much of western Europe, parts of Canada, the Persian Gulf and the Bay of Bengal.

- LORAN is a ground-based hyperbolic radionavigation system (the term ‘hyperbolic’ refers to the reflected ionospheric transmissions) which uses the difference in the time of arrival of signals from individual transmitters to establish position. Historically, LORAN

1939) http://webhome.idirect.com/~jproc/hyperbolic/decca_hist.html
was developed at MIT (DoD funded) during World War II as a navigation aid, known as LORAN-A. The operation of LORAN-A was in the 1850-1950 kHz radio band. LORAN-A had a range of 1000 km. Later LORAN-B was developed to improve the accuracy of LORAN-A. The USCG (US Coast Guard) Coast Guard, a participant in the development of LORAN, took overall responsibilities for LORAN in the 1960's. In 1958 LORAN-C became operational; it was also used commercially for marine navigation. LORAN-C was designated as an approved navigation system for the coastal modes of maritime navigation. It provided excellent coverage and enjoyed widespread use along all US Coasts and the Great Lakes. In 1974, the LORAN-C system was transferred to civil authority (DOT). Later, FAA extended LORAN-C coverage to include the continental USA because LORAN applications are not limited to marine users. It can and has been developed and used by all modes of transportation as well as non-transportation applications such as radiosondes for weather balloons. Before the widespread use of GPS, LORAN-C attracted considerable attention from civil aviation users because of its Area Navigation (RNAV) capability. RNAV systems are aircraft navigation systems that can, at a minimum, calculate the aircraft position at any point in the service area.

LORAN-C is a long-range (in excess of 1850 km), low-frequency (90 -110 kHz) radionavigation system comprising transmitters, control stations, and SAM (System Area Monitors). The basic element of a LORAN navigation system is the LORAN chain, consisting of one master and two to six transmitter stations. A LORAN-C user receiver measures the time difference (TD) between the arrival of a pulse from the master transmitter and a secondary transmitter of a particular chain. Like any radionavigation system, LORAN-C depends fundamentally on precise time and frequency to deliver its services. LORAN-C transmissions consist of groups of eight or nine accurately timed and phase-coded pulses at a carrier frequency between 90 and 110 kHz. Each chain consists of a master and a number of slave transmitters.  

In the mid 1960's LORAN-D (a low power transportable system with a range of 1100 km) was developed by the USAF. - LORAN signals propagate as a ground wave, but sky waves reflected from the ionosphere are also received. - In the early 1990s, DoD declared that by the end of 1994, there would be no further military requirement for the system and authorized the transfer of LORAN-C assets to host nations for civil use. The USA planned to terminate LORAN-C operations on Dec. 31, 2000.

A rebirth of LORAN-C in Europe was initiated in 1992 as a result of an international agreement between the US and six European countries (Denmark, France, Germany, Ireland, the Netherlands, and Norway), known as NELS (Northwest European LORAN-C System). The NELS network, consisting of nine stations with a control center at Brest (France), started operations in 1999. In Europe the timing of all NELS stations, Master and Secondaries, are synchronized to UTC to allow “rho-rho” position finding. This way of timing also eases integrating Loran-C and GPS pseudoranges in a single position estimation algorithm. The performance characteristics of the NELS network are: absolute location accuracy of 100-460 m; repeatable accuracy of 20-100 m; availability per station of 99.9%; and availability per chain of 99.7%. A policy recommendation of IALA (International Association of Marine Aids and Lighthouse Authorities) states that the future use of radionavigation be based on complementary satellite and terrestrial systems.  

In 2000, the EC (European Commission) initiated a project called GLORIA (GNSS and LORAN-C in Road and Rail Applications) in the framework of the European IST (Information Society Technologies) program. The objective is to analyze the combination of LORAN-C/GNSS also with other systems, e.g., dead reckoning components. with respect to

1940) Note: The LORAN system was important to the development of GPS because it was the first system to employ time difference of arrival of radio signals in a navigation system, a technique later extended to the NAVSTAR satellite navigation system.

1941) G. M. Hermes, “NELS Status - Operational and political status,” GNSS 2003, Graz, Austria, April 22-25, 2003

1942) http://www.nels.org/userinfo.htm

possible improvements of the reliability and availability of the position determination. This combination is expected to strengthen the reliability and availability of position determination and opens the door to new applications and to major improvements in the redesign of existing road and rail applications. 1944) Lately, LORAN-C receives new attention due to the vulnerability of GNSS to all kinds of interferences. 1945) There are five significant breakthroughs that brought Loran-C into the current high-tech century: improved transmitter time-of-emission control accuracy, autonomous integrity messaging by the stations (blink), gained knowledge of the ASF (Additional Secondary Factor), the capability to broadcast data via Loran-C and, finally, the development of high-performance receivers that process all signals in view, irrespective in which chain these stations operate.

Eurofix (developed in the 1990s at Delft University of Technology) is an integrated Navigation system, which combines GPS and Loran-C. The Loran-C signals are additionally modulated to broadcast differential GPS and especially integrity information. 1946) A Eurofix user can correct and validate GPS observations and calculate his position. The accurate GPS position is then used to calibrate the Loran-C ranges to determine the unknown ASF. In case GPS becomes unavailable, for instance due to shadowing or interference, calibrated Loran-C can be used to continue positioning. The dissimilarity of the Loran and GPS signals decreases the probability that they both will be unavailable at the same time.

In 2002 the USA revised its LORAN-C plans. The FPR (Federal Radionavigation Plan) of DOT and DoD, reasserts the DOT policy to continue to operate LORAN-C “in the short term while evaluating the long-term need for the system.” Recently, there has also been research in modulating data onto LORAN-C for DGPS (Differential Global Position System) corrections and WAAS (Wide Area Augmentation System) broadcasts. LORAN-C may also be used to aid GPS in cases of weak signal availability. In the end, LORAN-C might become a redundant navigation system for GPS if all FAA performance requirements can be satisfied. 1947) 1948)

There are other radionavigation systems aside from LORAN: The US Omega [a global VLF (Very Low Frequency) band radionavigation system, developed in the post WW-II era], uses phase differences of continuous-wave radio signals (see Glossary on Omega). Further systems in the same class are: VOR/DME (VHF Omnidirectional Range/Distance Measuring Equipment), and TACAN (Tactical Air Communication and Navigation).

1.12.2 The Transit System

The first generation spaceborne operational radionavigation systems, Transit (Navy Navigation Satellite System, USA) and Tsyklon (USSR), were mostly reserved for military use; however, they were of pivotal importance due to the insights gained in the nature of navigation and the considerable advances in early space-age technology. The Transit constellation employed the concept of Doppler measurements. Unlike the purely geometry satellite triangulation, the “new dynamic satellite orbits” were computed by using Kepler’s laws of celestial mechanics and the gravity field of the Earth. These led to a trail of 3-D satellite coordinates, as a function of time, with Transit-Doppler measurements providing the ob-

servations. Together, they produced relatively quickly (i.e., within 30 minutes) geodetic
positions of ground points, without the need for an extensive network of satellite triangula-

ation. However, due to the substantial uncertainties in the values of the parameters of the
gravity field, and the other complex models affecting the motion of these satellites in the
1970s, these results were less accurate than those obtained by satellite triangulation. 1949
1950 1951)

The Transit and Tsyklon constellations were eventually followed by second generation naviga-
tion systems, namely GPS and GLONASS, which were again developed, built and oper-
ated by the military services; but their use was so revolutionary and universal, that the civil
community was permitted to use this new utility as well.

- Transit navigation program (US Navy, see H.6). 1952 The first operational US naviga-
tion satellite was Transit-1B (designed and built at JHU/APL), launched April 13, 1960
aboard a Thor-Able rocket from Cape Canaveral. Starting with Transit-5A-3 (launch June
16, 1963), each satellite in the series featured a gravity-gradient boom for stabilization and
had a total mass of about 55 kg (polar circular orbits at altitudes of about 1100 km). Transit is
generally credited with demonstrating the feasibility of using artificial satellites as naviga-
tional aids. By the end of 1962, a first position fix could be performed by a Polaris vessel. The
Transit system was used by the US Navy in 1964, it became fully operational in 1966 (12 S/C
constellation with seven operational and five stored S/C in orbit). 1953 1724 1954) The satel-
lites broadcast their signals on two frequencies: 150 and 400 MHz. The dual-frequency
method was introduced for the first time (on Transit-1B) to correct for ionospheric refraction
effects (the 2nd frequency enabled the distortion to be cancelled out). - The Navy’s Transit (2-D) navigation system allowed the user to determine position by measuring the
Doppler shift of the received signal (constant tone broadcast - the frequency of 150 MHz
was transmitted to correct for ionospheric delay). The 2-D system did not permit velocity
determination.

In 1967 the Transit system was released for non-military purposes, a benefit to broad ocean
navigation. The Transit series reached a peak utilization of about 100,000 commercial and
military users in the late 1980s. The Transit system was decommissioned on Dec. 31, 1996.
For over three decades the experience and use of the Transit system influenced consider-
ably the field of geodetic positioning techniques, in particular the development of the
emerging GPS (Global Positioning System).

One of the technologies required to make Transit possible was a considerable improvement
on time and frequency standards. To realize the fixed site survey accuracy of 1 m, the satellite
Doppler signal at 400 MHz must be measured to 0.0005 Hz (a resolution of 5 x 10^{-12}). In
1960, the best standards of frequency were only good to resolve 5 x 10^{-10} and could only
measure the 400 MHz carrier to 0.2 Hz. APL established a precision time and frequency
facility to support the necessary development of various equipment needed for Transit.

- Timation (Time Navigation) program. A US Navy satellite navigation system, initiated
in 1964, designed by NRL (Naval Research Laboratory), with the objective to explore the
idea of continuous navigation - of providing both accurate position and precise time to pas-
sive terrestrial observers (passive ranging). Timation-1, a small (39 kg) gravity-gradient sta-
bilized satellite, was launched May 31, 1967 (VAFB, Thor Agena-D) into a 810 km polar

1949) V. Ashkenazi, “GNSS: A Global Enterprise?,” Proceedings of GNSS 2003, Graz, Austria, April 22-25, 2003, Ple-
nary Opening Session: Keynote Presentation
No. 1, Special Issue, Spring 1995, pp. 109-164
1953) Note: Some benefits of satellite navigation are: precise, all-weather, worldwide availability, timekeeping capabili-
ty, and unified reference coordinates.
1954) Note: To achieve the required accuracy of the Transit system position measurement, APL had to develop a time
standard several orders of magnitude more precise than existing devices (time frame of 1958/59).
orbit (as a secondary payload, along with GGSE-4, -5, Calsphere-3, -4, NRL-PL-153, -154, and -159). Timation-2 was launched Sept. 30, 1969; both S/C flew with stable quartz oscillators. The STR (Side Tone Ranging) signals were transmitted with a continuous Doppler tracking beacon at about 400 MHz. The experience with the new time system of Timation was a technology demonstrator for future missions.

- In 1964, SAMSO (Space and Missile System Organization) of the USAF in El Segundo, CA initiated a parallel navigation system program to that of the Navy, referred to as ‘Project 621 B’, with the objective to use a constellation of satellites for navigation signal transmission from highly eccentric orbits of 24-hours periods. First signal propagation tests were conducted in 1969 using ATS-5 of NASA. Then in 1972, a four-channel airborne receiver was tested with signals transmitted from the ground (satellite signal simulation) at Holloman AFB, NM. The demonstration used a new type of signal, modulated with a PRN (Pseudo Random Noise) code, to provide ranging and timing data. The signal modulation technique used a repeated digital sequence of random bits - that permitted a navigation user device to detect a start (“phase”) of the repeated sequence. Recognition of the repeat sequence allowed to determine the range to the signal emitter (satellite). The PRN (spread spectrum) technology turned out to be a key ingredient for GPS signal ranging (see Glossary).

1.12.3 NAVSTAR/GPS (Global Positioning System)

GPS is the operational global navigation system of the US. The nominal space segment consists of the GPS satellites with an operational constellation of 24 satellites: 21 operational satellites plus three active spares. The GPS constellation is deployed at MEO (Medium Earth Orbit) altitudes of about 20,000 km, in six orbital planes (orbital plane separation of 60º), providing periods of about 12 hours (2 orbits/day). A ground repeat track of a GPS satellite is achieved in 1 sidereal day. See also chapter H.4 for a description of GPS.

Background: Start of the NAVSTAR/GPS program took place in April 1973 (a joint-services program on DoD direction) by merging of the Timation and 621 B programs. The proposed new system concept integrated the basic concept of Timation, employing passive ranging precision clocks (time-of-propagation measurements by the user), and the PRN signal technology of Project 621 B - for an eventual constellation of multiple satellites in circular orbits for global coverage. The new GPS measurement technique employs the “time difference-of-arrival” concept (requiring the simultaneous view of four satellites) rather than the Doppler shift of its predecessor system, Transit, to determine position.

- The first spaceborne atomic clocks were flown in the GPS pre-series concept validation program of NRL, referred to as NTS (Navigation Technology Program - previous name was ‘Timation’). NTS-1 (a renamed and modified Timation-2A satellite), a three-axis stabilized S/C, was launched on July 14, 1974 into a 13900 km orbit, the payload included two modified commercial rubidium oscillators (Efratom, Munich). The navigation signals were transmitted in L-band. NTS-2 was launched June 23, 1977 from VAFB and placed into a 12 hour (semisynchronous) orbit - later used by the GPS satellites. The NTS-2 payload included two cesium clocks (Frequency and Time Inc.) and the PRN code generator. The signals were in L-band and modulated with a PRN code. NTS-2 was actually the first test satellite that contained the basic system features of the soon-to-follow GPS satellites.

- Launch of the first GPS-series navigation satellite, called NAVSTAR-1 (built by Rockwell International), on February 22, 1978 and declared operational March 29, 1978 (see Table 581 of GPS launches). The first full GPS constellation with 21 operational satellites was reached in 1994. On February 17, 1995, the FAA announced that GPS is now operational and is an integral part of US air traffic control system. The US Air Force Space Command declared the GPS system operational as of July 17, 1995 for the international user community. The year 1995 is certainly a historic navigation event; for the first time in history, mili-
tary and civil users could access an all-weather, day-night, global positioning and timing system. – At the end of the 1990s, GPS rapidly became an integral component of an emerging global information resource and infrastructure. GPS is probably the best example of a technology which started its life as a military tool and then developed into a global multi-faceted civilian utility. The beneficial applications and influence of GPS are comparable to those of the PC, the mobile phone, internet, and electricity. GPS is a generous gift of the American people, without any service charge, to the whole world. (1955) (1956) (1957)

- All GPS satellite signal radiation of the GPS constellation (at 20,000 km altitude) is directed toward Earth, providing coverage in particular for “Earth-bound” users, this includes also S/C in the envelope of LEO and MEO orbits. Naturally, coverage will decrease with altitudes approaching those of the GPS constellation and beyond (GEO, etc.).

- With the deployment of the GPS constellation, the SA (Selective Availability) service has been used to degrade the GPS signal (L1) for the civil community while retaining the higher-accuracy signals for US and allied military forces (as well as for approved receivers of NASA satellite projects).

<table>
<thead>
<tr>
<th>S/C Generation &amp; (No of S/C)</th>
<th>Period of launches</th>
<th>Comment</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block I (11)</td>
<td>1978-1985</td>
<td>S/C were able to sustain on-board operations for up to 3.5 days between navigation message uploads from the ground.</td>
<td>Rockwell International, Seal Beach, CA</td>
</tr>
<tr>
<td>Block II (9)</td>
<td>Feb. 1989 - Aug. 1990</td>
<td>Incorporation of radiation-hardening capabilities is a significant improvement of the block-II design</td>
<td>Rockwell International, Seal Beach, CA</td>
</tr>
<tr>
<td>Block IIA (20)</td>
<td>Nov. 1990 - Nov. 1996</td>
<td>Normal operations were performed on a daily basis to account for orbital perturbations and to provide accurate ephemeris data</td>
<td>Rockwell International, Seal Beach, CA</td>
</tr>
<tr>
<td>Block IIR (21)</td>
<td>Jan. 1997 - GPS-IIR-9, 3.3.2003</td>
<td>Enhanced autonomous S/C operations (AutoNav) for up to six months; improved navigation accuracy</td>
<td>Lockheed Martin, Valley Forge, PA</td>
</tr>
<tr>
<td>Block IIR-M</td>
<td>GPS IIR-M1, 2004</td>
<td>Modernized Block IIR for 8 out of 21 in the series; M-code for military use, new civil L2 transmitters</td>
<td>Lockheed Martin, Valley Forge, PA</td>
</tr>
<tr>
<td>Block IIF (33)</td>
<td>2006</td>
<td>Crosslink communications within constellation, L5 signal capability,</td>
<td>Boeing Company formerly Rockwell</td>
</tr>
<tr>
<td>Block III (or GPS III)</td>
<td>2012 (next generation S/C)</td>
<td>Increase in GPS signal power</td>
<td></td>
</tr>
</tbody>
</table>

Table 102: Overview of GPS satellite generations

- **Removal of the SA (Selective Availability)** feature for the GPS constellation signal on May 2, 2000 (the SA levels were set to zero at 0400 UT). (1958) (1959) (1960) The Presidential Directive (of US President Bill Clinton) permits civil users worldwide general access to the highest-possible accuracy of GPS signals. Ionospheric effects are now the major source of signal error. - Background: A 1996 Presidential Directive promised to review the SA issue every year starting in 2000, and to remove SA in 2007 at the latest. **With the elimination of SA (May 2, 2000), the next largest contributor to the GPS positioning error is the signal delay caused by the Earth’s atmosphere.**

- The modernized GPS frequency plan contemplates a civilian three-carrier signal structure at frequencies L1, L2, and L5. The multi-carrier nature of these signals and the ex-

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1959) http://www.igeob.gov
pected increase in power over present transmitter levels will facilitate the use of “wide-lane” techniques to provide accurate ionospheric correction, precise delta-height observations, and potentially accurate wind speed estimations. Future upgrades of GPS include an increase in the emitted power and the addition of two new civilian signals, one at L2 (to measure ionospheric delay), and an entirely new L5 signal centered at 1176.45 MHz for aeronautical use (see H.4.1.5). The first upgrade will allow the correction of meter-level ionospheric errors down to the cm-level. In addition, a 5 dB increase in transmitted power at both L1 and L2 over the current specified values is expected. 1961) 1962) 1963) The new L5 signal is announced with 6 dB higher power than the current L1 signal, split into in-phase and quadrature components, to improve resistance and interference, especially from other pulse-emitting systems in the same band, as DME (Distance Measurement Equipment). Two other very attractive features of L5 are its high chip rate (10.23 MHz) and bandwidth (at least 20 MHz) and the fact that no data will be transmitted on the quadrature signal, thus allowing for easier processing and improved performance when used for remote sensing.

<table>
<thead>
<tr>
<th>Performance feature</th>
<th>Block II &amp; IIA</th>
<th>Block IIR</th>
<th>Block IIF (requirements)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr. of navigation signals</td>
<td>3 signals</td>
<td>3 signals</td>
<td>up to 5 signals</td>
</tr>
<tr>
<td>Signal power to user (combined L1 and L2)</td>
<td>-158.2 dBW L1 -166 dBW L2</td>
<td>-158.2 dBW L1 -166 dBW L2</td>
<td>-156.4 L1 C/A, -155.7 L1 P (dBW) -152.6 dBW L2</td>
</tr>
<tr>
<td>Space &amp; ground URE</td>
<td>2.3 m</td>
<td>1.2 m (AutoNav)</td>
<td>0.75 - 1 m crosslink navigation</td>
</tr>
<tr>
<td>Civil performance (2 dRMS)</td>
<td>100 m with SA 25 m w/o SA</td>
<td>100 m with SA 25 m w/o SA</td>
<td>&lt;10 m w/o SA (Selective Availability) and with ionospheric correction</td>
</tr>
<tr>
<td>Design life</td>
<td>7.5 years</td>
<td>10 years</td>
<td>15 years</td>
</tr>
<tr>
<td>Design flexibility</td>
<td>N/A</td>
<td>Auxiliary payload 45 kg, 90W</td>
<td>Auxiliary payload capacity up to 180 kg and 275 - 1000 W of power</td>
</tr>
</tbody>
</table>

Table 103: Performance parameter comparison of GPS satellite generations

1.12.4 GLONASS (Global Orbiting and Navigation Satellite System)

The Soviet/Russian GLONASS was initially designed mainly for military purposes. It consists of a nominal constellation of 24 satellites in three orbital planes (8 S/C per plane) with MEO orbital altitudes of 19,100 km (circular). The ascending nodes of the constellation are 120° apart. The period of a S/C is 11 hours and 15 minutes. A ground track repeat is achieved in 8 sidereal days. GLONASS observation data are available with the L1 signal of the standard accuracy without any selective availability. See also chapter H.3 for a GLONASS description.

- Launch of the first three GLONASS-series navigation satellites, called GLONASS-1, 2 and -3 (Cosmos 1413, 1414 and 1415 deployed), on October 12, 1982 (see chapter H.3 and Table 579). 1964)

Note: The first USSR navigation satellite, Tsyklon, was launched into a circular orbit of 750 km, on Cosmos flight 192, November 23, 1967. Tsyklon navigation was based on Doppler shift techniques. Tsyklon was followed by a six-satellite constellation with the name of Parus (also Tsikada-M). A virtually identical civilian navigation network with the name of Tsikada began deployments in 1976 with Kosmos 883, the constellation employs four orbital planes separated by 45°.

- The GLONASS constellation with 24 satellites was fully deployed in December 1995. But after 1995 to the end of 1998, the GLONASS constellation has been degraded due to

lack of the federal budget funding. In 1999, GLONASS became a dual-use system by Presidential Decree, with two agencies responsible for the system: namely the Ministry of Defense for the military side, and the Russian Aviation and Space Agency (Rosaviakosmos) for the civil side. In addition, GLONASS is open for international cooperation.

- In Aug. 2001, the Russian Government adopted and approved a long-term federal program of GLONASS sustainment and modernization, ensuring also the user equipment development as well as serial production. This governmental action represents in fact a first in Russian (and Soviet) history, namely that a specific space program experiences the phases of development, operational sustainment, and modernization in the framework of a dedicated federal program (with a budget and a 10 year planning horizon). Coordinator of all activities in the framework of the GLONASS Program now is Rosaviakosmos. The State Budget money dedicated for GLONASS flows through Rosaviakosmos and Ministry of Defense as equal partners. 

- As of April 2003, the GLONASS constellation consists of 12 satellites, 8 of which are operational and one is completing the flight tests. The current degraded constellation may experience signal outages in the order of 3-4 hours. However, In combination with GPS even now GLONASS use is improving the navigation quality. - The nearest launch of another three GLONASS satellites is scheduled for the second half of 2003. One of the three satellites will be GLONASS-M with extended lifetime to 7 years. Up to 11 GLONASS-M type satellites are expected to be deployed by 2006. A second signal (in frequency band F2) will be implemented in the M-series for improved location performance. - From 2005 onwards, plans call for a new generation of GLONASS-K satellites with extended performances, transmitting the third civil signal in the F3 frequency band (27 GLONASS-K in the time frame 2005-2012). Generally, the full (24 satellites) GLONASS constellation transmitting two civil signals will be available from 2010 onwards.

1.12.5 GPS and GLONASS, applications in space

- Position and time measurements with ground-based GPS and GLONASS receivers have been made with partial GPS and GLONASS constellations since the first launch in each constellation (first institutionally, then by the civil community as commercial receivers became available). The evolution of the GPS receiver: In 1978, Texas Instruments decided to make available one of the first GPS receivers for civil use. Its price tag was $153,000. In 1988, Magellan offered the first hand-held GPS receiver. Its cost was $3,500. In 1997, Magellan offered the first GPS receiver to break the $100 price barrier. Called the GPS Pioneer, it is a 12-channel, 7-ounce mobile unit powered by two AA batteries. The global GPS receiver market produced over 1 million units in 1997.

- Demonstration of GPS receiver position and velocity measurements from LEO satellites. The Landsat-4 (launch July 16, 1982) and Landsat-5 (launch March 1, 1984) spacecraft are flying the first experimental GPS receivers referred to as GPS PAC [GPS receiver and processor Package (the first onboard GPS receivers in history had to cope with a partial constellation of GPS satellites)].

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1966) http://gauss.gge.unb.ca/gradsunil/sgps.htm
tracking data is used for spacecraft time system synchronization and for post-event (on-ground) orbit determination. Despite the sparse GPS constellation in orbit, GPS/NAVSTAR demonstrated navigational accuracy of better than 50 m over 10- to 30-minute arcs on 88% of the revolutions. Two more GPS/NAVSTAR instruments were flown on two DoD host satellites with launches in 1983 and 1984, respectively. Since those early days, many GPS receivers have been installed on all types of satellites.

- **Introduction of the GPS carrier-frequency phase measurement technique.** In the pre-operational period of GPS service provision [Initial Operating Capability (IOC) of the GPS system was declared in December 1993], the civil user community had to live with measurement accuracies in the 50-100 m range provided by the SPS (Standard Positioning Service) signals. The pseudorange measurement technique (the intentional downgrading of GPS signal quality) for positioning services, introduced the errors caused by atmospheric effects and SA (Selective Availability). 1967) 1968)

In the early 1980s, two MIT radio astronomers (Counselman and Shapiro) suggested to the GPS user community, to use the **carrier frequency to make phase measurements**, instead of using the prescribed pseudorange modulation technique. This change in measurement technique opened up a window of greatly increased accuracies - namely centimeter-range GPS - provided one could resolve the so-called integer ambiguity (integer number of whole wavelengths). In response to this new opportunity, a number of commercial receiver manufacturers developed high-precision geodetic GPS receivers capable of relative positioning accuracies of a few centimeters. As a consequence, new applications became possible in such fields as geodesy, oceanography, land surveying, astronomy and many others. By 1987 it was known (within a small community) that unclassified “quasi-codeless” receivers with broad-beam antennas could recover dual-frequency GPS phase with the requisite millimeter precision, and that a strategy of concurrent observing from multiple sites would permit “double differencing” and related techniques to eliminate selective availability and other clock errors. Thus, in the 1990s, the technique of carrier-phase tracking of GPS signals has resulted in a revolution in land surveying as well as in other fields such as refractive occultation monitoring. 1969)

With regard to occultation monitoring, it was then a small step to see that analog techniques could be applied directly to occultation processing to remove clock errors. It thus emerged that the one-way GPS observing constraint, which at first seemed to demand stable clocks everywhere in the system, could be artfully adapted through concurrent observations to eliminate stable clocks altogether. This enabled both accurate retrievals and a reduction in instrument cost. Moreover, it was becoming clear that the basic techniques of GPS geodesy could be extended to provide orbit determination on the level of a few centimeters for LEOS spacecraft, adequate for occultation analysis. 1970)

- **Introduction of DGPS (Differential GPS) services.** 1971) DGPS is a further approach by the civilian GPS user community to overcome the large errors provided by pseudorange signal measurements. DGPS is fundamentally a relative positioning measurement approach, the GPS receiver may be on a moving platform (vehicle, ship, airplane or satellite). The

1968) Note: The pseudorange measurement technique is also referred to as “code-based GPS.” Code-based DGPS techniques use the GPS “pseudorange” measurement. Code-based DGPS removes certain errors from the pseudorange measurements to provide an accurate position solution. The pseudorange measurement is obtained by the GPS receiver locking onto a GPS satellite’s pseudorandom code. The GPS pseudorange measurement is essentially the difference between the time of transmission of the GPS signal from the satellite and the time of reception by the GPS receiver. The pseudorange measurement is an absolute range measurement between the receiver and the satellite, and therefore DGPS systems are relatively easy to implement.
1971) Note: The adjective “differential” refers to the fact that the user receiver is positioned with respect to the nearby reference or base station at a known location.
DGPS concept is based on the principle that a user is affected by satellite ephemeris, atmospheric propagation, SA, and clock synchronization errors to the same extent as a relatively nearby reference station. By predicting the reference receiver’s position to a high degree of accuracy, one can set up a system that can be used to calculate corrections to the pseudoranges measured to the various GPS satellites and to transmit these corrections to a multitude of users in the vicinity (100 km radius and more) of the reference station. The use of the DGPS technique (as well of RTK) provide relative positioning accuracies with respect to a reference system.

- Over the last decade (1990s) systems for DGPS started to expand from one reference station into integrated networks of reference stations. The distance between reference stations typically lies in the order of 50-70 km. Also, using the IGS (International GPS Service) ephemeris products rather than a broadcast navigation message to interpolate a higher accuracy satellite position and clock (<5 cm/0.1 ns) can improve the accuracy of position determination.

- Further advances by the civilian user community led to the development of RTK (Real-Time Kinematic) GPS tracking, enabling the receiver to make precise carrier-frequency phase measurements while in motion. The complication introduced with these measurements is the unknown cycle ambiguity, which needs to be resolved in order to exploit the millimeter carrier phase precision to the full extent for relative positioning. See also H.4.3, H.4.4.

The accuracy of RTK positioning is limited by the distance dependent errors from orbit, ionosphere and troposphere as well as station dependent influences like multipath and antenna phase center variations. In survey-type RTK applications with centimeter accuracy requirements, permanent reference station networks are being employed more frequently at the start of the 21st century. The advantages provided by these reference station arrays include improved modeling of the remaining tropospheric, ionospheric and orbit biases. Methods and concepts reflect the improvements in performance and reliability in some kind of closed system approaches. Standardization discussions underway within RTCM (Radio Technical Commission for Maritime Services) target the interoperability between the reference station systems and roving receivers from various manufacturers. Two examples of commercially available network-based RTK-positioning error correction techniques to roving users are: 1972) 1973) 1974)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Autonomous SPP (Single Point Positioning)</th>
<th>Differential or Relative Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPS (Standard Position Service)</td>
<td>PPS (Precise Positioning Service)</td>
</tr>
<tr>
<td>Measurement technique</td>
<td>Code</td>
<td>Code</td>
</tr>
<tr>
<td>Accuracy</td>
<td>8-10 m</td>
<td>6-10 m</td>
</tr>
</tbody>
</table>

Table 104: GPS horizontal positioning accuracies in different modes

- FKP (Flächenkorrekturparameter - or area correction parameter), developed at the University of Hannover. In this concept, FKP coefficients are computed for every satellite covering ionospheric, tropospheric and orbit effects (with regard to a specific network area and at specific time intervals, at least every 10 s). The measurement corrections, reduced by


the station-satellite slope distances of the reference stations, are then transmitted via RTCM messages Type 20/21 as well as the FKPs for interpolation via a customized RTCM type 59 message.

- VRS (Virtual Reference Stations) concept of Trimble (the VRS software consists of a network of Trimble GPS receivers communicating with a control center to calculate GPS error corrections that are applicable over a wide area). In this concept, the rovers also receive network information but additionally transmit, via NMEA (National Marine Electronics Association) messages, their approximate positions to a central computing facility. This facility calculates the station-satellite slope distances for the approximate positions and then, from the reference station observations, interpolates the corrections corresponding to a virtual reference station near the rover. These virtual measurements are unique to each rover and transmitted to them via RTCM messages of type 20/21 or 18/19. The concept of “virtual reference stations” allows to eliminate/reduce systematic errors in reference station data, i.e. allows to increase the distance to the reference station for RTK positioning while increasing the reliability of the system and reducing the initialization time.

- Determination of water level with an RTK GPS buoy.\(^{1975}\) An RTK-equipped buoy can potentially be used to accurately measure water level height above the WGS84 ellipsoid. The goal is to use this method eventually for such applications as: a) determination of water level to establish the separation between tidal datum and GPS datum; b) determination of water level for calibration of altimetric sensors on aircraft or spacecraft. Experiments with a RTK-equipped buoy of the US NAVOCEANO (Naval Oceanographic Office) over a period 2001-2003 provide encouraging results.

- Demonstration of GPS high-precision orbit determination. The GPSDR (GPS Demonstration Receiver) of Motorola was flown on two missions: EUVE (Extreme Ultraviolet Explorer, launch June 7, 1992, of NASA/GSFC) and TOPEX/Poseidon (launch Aug. 10, 1992) to demonstrate/validate accurate orbit determination with GPS data.\(^{1976, 1977}\) Two GPSDR instruments (dual-frequency receivers producing long cycle-slip free carrier-phase passes as well as pseudorange measurements) on TOPEX/Poseidon were the first spaceborne receivers obtaining high-accuracy range measurements and demonstrated DGPS techniques with a set of IGS (International GPS Service) ground reference stations. A comparison of orbit parameters from three independent techniques (retroreflectors for SLR, DORIS and GPS), all available on TOPEX/Poseidon, obtained GPS orbit differences <25 cm (3D rms). These results of GPS orbit reconstitution are indeed impressive in terms of accuracy.

- Spaceborne orbit determination with a GPS receiver (initial validation flight tests). The goal is the provision of a real-time service of autonomous onboard functions (orbit, etc.). The provision of mean orbital elements is a first step toward operational autonomy. The orbital elements are being used on the ground for ground station operations and other support functions; they are also being used onboard for S/C operations. In general, however, there are further functional services needed for autonomous onboard S/C operations, such as: position, velocity and time; GPS receiver data logging; S/C clock synchronization; data logging; instrument triggering by position; status monitoring, and more. - The introduction of onboard autonomy has certainly great potential of reducing operating costs of future missions.

Background: Orbit determination is generally based on two models, namely the dynamic model (describing the forces acting on the satellite), and the observation model (providing the relationship between the measurements of the tracking system). This requires consider-


able onboard processing and storage capability. A recursive Kalman filter algorithm provides a sequential approach to combine the inputs of both models, namely the satellite's motion (in the dynamic Earth model) with the GPS measurements (observation model) as they become available, resulting in best estimates of position and velocity (continuous comparison and update of actual with estimated values). 1978)

- PoSAT-1 (launch Sept. 26, 1993, built at SSTL, UK) is the first microsatellite to make use of a GPS receiver in orbit, and to autonomously determine its orbit through the processing of GPS data into orbital elements. 1979) 1980) The GNU (GPS Navigation Unit) consists of a TANS Vector-II 6-channel C/A code receiver of Trimble and is operated with a software package run on a Transputer Data Processing Unit (a T800 32-bit RISC microprocessor). The GNU is operated intermittently to conserve power. Some services demonstrated on PoSAT-1 are: a) orbital elements: they provide a prediction accuracy of 1-10 km for two weeks, and b) the variables of position, velocity and time can be requested at any time. While basic attitude determination on PoSAT-1 was performed with magnetometers and sun sensors, there was in addition a demonstration of attitude determination using the single GPS antenna of GNU.

- Since 1993 NASA/JSC was conducting different GPS experiments to validate concepts required to fly GPS as an in-line avionics component on Shuttle missions. The reason: an anticipated beginning of TACAN ground-station phase out in 2000 prompted the Shuttle program to reexamine the use of GPS as a TACAN (Tactical Air Communication and Navigation) replacement. 1981) 1982) A series of seven flights were conducted on Endeavour which started with STS-56 (April 1993) using a Rockwell Collins 3M receiver operating in SPS mode. The next phase of Shuttle/GPS operations used a PPS (Precise Positioning Service) receiver as a single string navigation device [Rockwell Collins MAGR/S (Miniaturized Airborne GPS Receiver/Shuttle)]. The first flight was on STS-79 (Sept. 16-26, 1996). During flight the navigation data was downlinked in real-time for display. During landing, the GPS system performance was compared to TACAN, the primary Shuttle navigation device. In the summer of 2002, the Shuttle program successfully completed an integration, ground test, and flight test effort to certify a GPS receiver for use on the Shuttle orbiters. The certification lead to use of a single GPS receiver on each orbiter along with three existing TACAN units. Eventually, NASA will replace the TACAN units with a GPS receiver on each orbiter.

- The REX-II satellite of USAF (see below, launch March 9, 1996) provides GPS-generated orbital elements in the downlink.

- The ORFEUS-SPAS-II free-flyer payload on Shuttle flight STS 80 (November 19-December 7, 1996) flew the first GPS Tensor receiver system (SS/L and LABEN) capable of providing onboard orbit parameters with an adapted Kalman filter algorithm along with Earth model software.

- The DORIS system of CNES, with a prototype payload first flown on SPOT-2 (launch Jan. 22, 1990) and later on TOPEX/Poseidon (launch Aug. 10, 1992), is a microwave tracking system (with the use of a global ground network). Successful long-term onboard orbit determination has been demonstrated with DIODE (Doris Immediate Orbit Determination), a DORIS software package first flown on SPOT-4 (Mar. 24, 1998, see H.7.1). Further DORIS/DIODE systems fly on Envisat, Jason-1, SPOT-5, etc.

- **GDGPS** (Global Differential GPS) system of NASA, and a subset of NASA’s Global GPS Network (GGN - some 40 reference stations), consisting of geodetic quality dual-frequency receivers. The GDGPS system, developed and operated by JPL (since 2001), combines innovative software and hardware components with advanced Internet technology to provide end-to-end capabilities for autonomous, real-time orbit determination, time transfer, and positioning, with an unprecedented level of accuracy (10 cm horizontal and 20 cm vertical for kinetic applications anywhere on Earth) and availability (at any time). [1983] [1984] [1985] [1986] [1987] This feature is particularly valuable in support of event monitoring functions and kinematic applications of equipment on Earth-orbiting satellites (also on airplanes and terrestrial vehicles) with positional accuracy requirements of centimeters to decimeters. The GDGPS analysis concept employs a state-space approach, where the orbits of the GPS satellites are precisely modeled, and the primary estimated parameters are the satellite epoch states. This approach guarantees that the corrections will be globally and uniformly valid. The system is geared toward users carrying dual-frequency receivers. The ground segment consists of the ground network of reference GPS receivers, the operations centers, and the Internet, which serves as the data communication channel between the reference network and the operations centers. - Note: One of the major advantages that dual-frequency receivers have over single frequency ones is that an on-the-fly (OTF) search can be performed quickly, due to the combination of L1 and L2 data resulting in the wide lane phase observable.

At the heart of the operations center is the GPS orbit determination process, where the Real Time GIPSY (RTG) software ingests the streaming GPS data and generates real-time estimates of the dynamic GPS orbits, one-second GPS clocks, and tropospheric delay estimates for each reference site. The estimated GPS orbits and clocks are differenced with the GPS broadcast ephemerides to form the global differential corrections. These differential corrections are then optimally packed to allow for efficient relay to the users. The correction data stream is made available to authorized users via several communication channels. The first is the open internet, where a user can connect to a TCP or UDP server running at the processing center. Remote users can establish such a connection through a broadband hookup (e.g. Ethernet), or through telephony, including wireless telephones such as provided by the Iridium system.

As of 2003, the GDGPS system processes real-time GPS data from a global network of more than 40 dual-frequency GPS ground sites. The utility has in particular been demonstrated in precise airborne navigation applications (support of InSAR, etc. with accuracies of 10 cm horizontally and 20 cm vertically for users anywhere in the world). In addition, the RTG flight software will be demonstrated on orbit and is being projected for a number of spaceborne missions. NASA is also considering TDRS broadcasts of the differential correction message.

- The first GPS attitude determination systems [1988] - proof-of-concept demonstrations were conducted on research aircraft, and on a commercial airliner.

- Three GPS attitude measurement flight tests were conducted in April/May 1991 on a DC-3 aircraft of Ohio University by using an Ashtech-3DF (Three-dimensional Direction

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1986) Note: The GDGPS system is also known under the name of **IGDG** (Internet-based Global Differential GPS)
Finding) 24-channel receiver configured in four 6-channel sections, and four microstrip patch antennas (fuselage and wing-tip mounted). Attitude data were computed, stored and displayed in real-time by two PCs.

- A Stanford University attitude demonstration was conducted with a Trimble TANS Vector GPS receiver on a Piper Dakota aircraft in 1991. Four strip-mounted antennas were used for attitude sensing. A 486 laptop computer provided both real-time display and data recording for post-flight analysis. 1989)

- On January 12, 1993, a flight experiment was conducted on a NASA/Ames King Air 200 aircraft 1990) with the objective to evaluate the dynamic response of a GPS attitude system. The attitude equipment consisted of two independent systems: INU (inertial Navigation Unit) and a six-channel C/A code GPS receiver (TANS Vector) and four microstrip patch antennas (fuselage and wing-tip mounted). Attitude data from both systems were recorded for post-flight analysis.

- On Dec. 10, 1994, a test flight of a TANS Vector receiver on board a DC-10 commercial airliner (United Airlines) demonstrated the potential for SATCOM antenna pointing, by providing aircraft attitude measurements (Note: Proper antenna pointing requires knowledge of aircraft position, satellite position and aircraft attitude). 1991) The aircraft used a Honeywell SATCOM system beam-steering antenna, two INS (Delco Carousel IV - the Carousel is a free azimuth INU which contains four-gimbal IRUs), a vertical gyro and a compass. In addition to the TANS Vector receiver, the aircraft was equipped with two modified TNL-8100 GPS receivers. The TANS Vector receiver exhibited expected performance during all phases of the test flight when compared to the reference measurements.

- Demonstration of spaceborne GPS orbit and attitude measurements. A number of tests for attitude determination with “prototype GPS receivers” have been carried out (or are planned) on Shuttle and on various commercial and military satellites. Table 105 lists a chronology of these instruments (see also chapter H.4.3.4).

- The RADCAL spacecraft of the USAF (launch June 25, 1993) 1992) performed the first known attitude determination experiment using GPS carrier-phase measurements with two TANS Quadrex GPS receivers (see D.36). The CRISTA-SPAS-1 mission of DARA/NASA on Shuttle flight STS-56 (Nov. 3-14, 1994) provided the “first demonstration of real-time attitude determination” on the SPAS free-flyer platform of DASA (one day receiver operation). See also chapter J.1.2.

- The REX-II satellite of USAF (launch March 9, 1996), with a GPS experiment by the name of ADACS, can be regarded the first successful demonstration of closed-loop attitude control application using real-time GPS carrier-phase-based attitude measurement as sensor input (first time on March 29, 1996). It is also the first mission to provide orbital elements in the downlink.

- The first spaceborne flight demonstration of SIGI (Space Integrated GPS/INS) took place on Shuttle flight STS-101 (May 19-29, 2000) under the name of SOAR (SIGI Operational Attitude Readiness). A relight of SOAR occurred on STS-106 (Sept. 8-20, 2000). SIGI became fully operational on ISS in May 2002. It is now determining the attitude, position and speed of ISS on a continuous basis. Prior orbit determination of ISS required ground tracking (once per day) and other techniques. The GPS antennas,

1991) L. Kruczynski, J. Delucchi, T. Iacobacci, “Results of DC-10 Tests using GPS Attitude Determination,” Proceedings of ION GPS-95,
brought to ISS with STS-110 (Apr. 8-19, 2002), were the final piece of the system (installed on the truss). The antennas feed their information to two GPS receivers, located in the US Lab Destiny. Another unit of SIGI is planned on CRV (Crew Return Vehicle). CRV is scheduled to become an operational part of the station in 2004/5 (CRV is designed to be used as a life-boat in case of an emergency evacuation from ISS). See also H.4.3.4. - SIGI is a NASA instrument based on the Honeywell model H-764G EGI (Embedded GPS/INS); Honeywell Space Systems is also the prime contractor of SIGI on ISS. Honeywell’s COTS baseline H-764G SIGI design is a modular system which is integrated (tightly coupled) with either an embedded Collins or Trimble GPS receiver [either P(Y) and C/A code]. Over 9000 SIGI and EGI systems have been delivered worldwide as of early 2003 (widely used in military applications such as fighter jets). 1993) 1994) 1995)

At the beginning of the 21st century it is expected that lightweight spaceborne GPS receiver systems, providing the functions of: position, velocity, attitude, attitude rate and time, are going to replace a number of conventional attitude measurement devices such as horizon sensors and sun trackers. The GPS orbit/attitude receiver in combination with a control scheme (actuator) offers sound technical and economical attitude-control solutions. Previous experiments with GPS attitude determination have demonstrated a potential for coarse attitude determination in the 0.1º range. Also spaceborne GPS receivers have demonstrated a time transfer capability of <100 ns, thus making very precise, coordinated time available to spacecraft systems.

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Mission</th>
<th>GPS Receiver</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 25, 1993</td>
<td>RADCAL (USAF)</td>
<td>TANS Quadrex (Trimble)</td>
<td>2 cross-strapped receivers, attitude solutions in post-processing</td>
</tr>
<tr>
<td>Sept. 12-22, 1993</td>
<td>ORFEUS-SPAS-1 (DARA)</td>
<td>Alcatel/SEL receiver, C/A code + L1 carrier-phase</td>
<td></td>
</tr>
<tr>
<td>Aug. 3, 1994</td>
<td>APEX (USAF)</td>
<td>TANS Vector</td>
<td>Shuttle STS-51, free flyer</td>
</tr>
<tr>
<td>Nov. 3-14, 1994</td>
<td>CRISTA-SPAS-1 (DARA/NASA)</td>
<td>Alcatel/SEL Rx+ TANS Vector + IRU</td>
<td></td>
</tr>
<tr>
<td>Jan. 11-20, 1996</td>
<td>GADACS (NASA)</td>
<td>TANS Vector (2)</td>
<td>Shuttle STS-72, on SPARTAN</td>
</tr>
<tr>
<td>March 9, 1996</td>
<td>REX-II (USAF)</td>
<td>TANS Vector (2) named ADACS</td>
<td>First long-term mission with GPS orbit/attitude determination</td>
</tr>
<tr>
<td>May 19-29, 1996</td>
<td>GANE (NASA)</td>
<td>TANS Vector + IRU</td>
<td>Shuttle STS-77</td>
</tr>
<tr>
<td>Nov.19-Dec 7, 96</td>
<td>ORFEUS-SPAS-2 (DARA/NASA)</td>
<td>Alcatel/SEL Rx+ GPS Tensor (Laben)</td>
<td>Shuttle STS-80, SPAS free-flyer; also relative navigation experiment ARP of ESA/ESTEC</td>
</tr>
<tr>
<td>May 15-24, 1997</td>
<td>ARP (ESA) Shuttles/MIR</td>
<td>GPS Tensor (Laben)</td>
<td>STS-84 Shuttle - MIR rendezvous</td>
</tr>
<tr>
<td>Aug. 23, 1997</td>
<td>SSTIT-Lewis (NASA)</td>
<td>GPS Tensor (2) named GADFLY</td>
<td>Lewis could not be operated and reentered Sept. 28, 1997</td>
</tr>
<tr>
<td>Aug.7-19, 1997</td>
<td>CRISTA-SPAS-2</td>
<td>Alcatel/SEL Rx+ GPS Tensor</td>
<td>Shuttle STS-85, SPAS free-flyer</td>
</tr>
<tr>
<td>Dec. 24, 1997</td>
<td>EarlyBird-1 (Earthwatch)</td>
<td>Vector and Viceroy</td>
<td>S/C lost contact with ground</td>
</tr>
<tr>
<td>Feb. 14, 98 (1st four satellites)</td>
<td>Globalstar (constellation of 48 satellites)</td>
<td>GPS Tensor on SS/L LS-400 platform</td>
<td>Big LEO communication system of Globalstar L.P., San Jose, CA</td>
</tr>
<tr>
<td>1998</td>
<td>SSTIT-Clark (NASA)</td>
<td>TANS Vector (2) named GADFLY</td>
<td>NASA cancelled the Clark mission in Feb. 1998</td>
</tr>
<tr>
<td>Feb. 23, 1999</td>
<td>ARGOS (USAF)</td>
<td>Embedded receiver</td>
<td></td>
</tr>
<tr>
<td>Nov. 15, 2000</td>
<td>AMSAT-3D (AMSAT)</td>
<td>TANS Vector (2)</td>
<td>AMSAT OSCAR-40 Spacecraft</td>
</tr>
</tbody>
</table>

Table 105: Overview of early spaceborne GPS attitude receivers flown on various missions

The following two tables, Table 106 and Table 107, provide an (incomplete) overview and some characteristics of present and planned GPS receivers (as of 2007) for space applications for single- and dual-frequency receivers, respectively.1996

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Receiver</th>
<th>Channels</th>
<th>Antennas</th>
<th>Power, Mass</th>
<th>TID (krad)</th>
<th>Sample Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thales Alenia Space (F, I)</td>
<td>TopStar 3000</td>
<td>12–16 C/A</td>
<td>1–4</td>
<td>1.5 W 1.5 kg</td>
<td>&gt; 30</td>
<td>DEMETER, KOMP-SAT-2</td>
</tr>
<tr>
<td>EADS Astrium GmbH (Germany)</td>
<td>MosaicGNSS</td>
<td>6–8 C/A</td>
<td>1</td>
<td>10 W 1 kg</td>
<td>&gt; 30</td>
<td>SAR-Lupe, TerraSAR-X, ADM/Aeolus</td>
</tr>
<tr>
<td>General Dynamics, USA</td>
<td>Viceroy</td>
<td>12 C/A</td>
<td>1–2</td>
<td>4.7 W 1.2 kg</td>
<td>15</td>
<td>M3TI-3, SeaStar, MIR, ORBVIEW, KOMP-SAT-1</td>
</tr>
<tr>
<td>SSTL (UK)</td>
<td>SRG-05</td>
<td>12 C/A</td>
<td>1</td>
<td>0.8 W 20 g</td>
<td>&gt; 10</td>
<td>SNAP-1,</td>
</tr>
<tr>
<td>SSTL (UK)</td>
<td>SRG-20</td>
<td>4x6 C/A</td>
<td>4</td>
<td>6.3 W 1 kg</td>
<td>&gt; 10</td>
<td>UoSat-12, PROBA-1, BILSAT,</td>
</tr>
<tr>
<td>DLR (Germany)</td>
<td>Phoenix-S</td>
<td>12 C/A</td>
<td>1</td>
<td>0.9 kg 20 g</td>
<td>15</td>
<td>PROBA-2, X SAT, Flying LapTop, ARGO, PRISMA</td>
</tr>
<tr>
<td>Accord (India)</td>
<td>NAV2000HDCP</td>
<td>8 C/A</td>
<td>1</td>
<td>2.5 W 50 g</td>
<td></td>
<td>X-SAT</td>
</tr>
</tbody>
</table>

Table 106: Single-frequency GPS receivers for space applications

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Receiver</th>
<th>Channels</th>
<th>Antennas</th>
<th>Power, Mass</th>
<th>TID (krad)</th>
<th>Sample Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAAB (Sweden)</td>
<td>GRAS/GPSOS</td>
<td>12 C/A, P1/2</td>
<td>3</td>
<td>30 W 30 kg</td>
<td></td>
<td>MetOp-1, NPOESS</td>
</tr>
<tr>
<td>Labeuf (Italy)</td>
<td>Lagrange</td>
<td>16x3 C/A, P1/2</td>
<td>1</td>
<td>30 W 5.2 kg</td>
<td>20</td>
<td>SAC-C, RADARSAT-2, GOCE,</td>
</tr>
<tr>
<td>General Dynamics, USA</td>
<td>Monarch</td>
<td>6–24 C/A, P1/2</td>
<td>1–4</td>
<td>25 W 4 kg</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>JPL/Broad Reach Engineering</td>
<td>Blackjack/IGOR</td>
<td>16x3 C/A, P1/2</td>
<td>4</td>
<td>10 W 3.2/4.6 kg</td>
<td>20</td>
<td>SAC-C, CHAMP, GRACE, Jason-1, Formosat-2, COSMIC, ICESat, TerraSAR-X,</td>
</tr>
<tr>
<td>Thales Alenia Space</td>
<td>TopStar 3000G2</td>
<td>6x2 C/A, L2C</td>
<td>1</td>
<td></td>
<td></td>
<td>PROBA-2</td>
</tr>
<tr>
<td>Austrian Aerospace</td>
<td>GNSS Navigation Receiver</td>
<td>Up to 36 C/A, P1/2</td>
<td>2</td>
<td>&gt; 20</td>
<td>20</td>
<td>Under development</td>
</tr>
<tr>
<td>Broad Reach Engineering, USA</td>
<td>Pyxis Nautica</td>
<td>16–64 C/A, P1/2</td>
<td>1–4</td>
<td>20 W 2.5 kg</td>
<td></td>
<td>Under development</td>
</tr>
<tr>
<td>NovAtel (Canada)</td>
<td>OEM4-G2L</td>
<td>12x2 C/A, P2</td>
<td>1</td>
<td>1.5 W 50 g</td>
<td>6</td>
<td>CanX-2, CASSIOPE,</td>
</tr>
<tr>
<td>Septentrio (Belgium)</td>
<td>PolaRx2</td>
<td>16x3 C/A, P1/2</td>
<td>1 (3)</td>
<td>5 W 120 g</td>
<td>9</td>
<td>TET</td>
</tr>
</tbody>
</table>

Table 107: Dual-frequency GPS receivers for space applications

- Flight demonstrations of relative navigation using GPS observables. ESA, in cooperation with NASA, DARA, and RKA (now Roskosmos), conducted three flight demonstra-

tions in its ARP (ATV Rendezvous Pre-development) program with proximity navigation approaches [ATV is the future Automated Transfer Vehicle, the ESA resupply vehicle for ISS (International Space Station)].

- Deployment and retrieval maneuvers of SPAS release/approach with Shuttle. The ORFEUS-Spas-2 free-flyer on Shuttle flight STS-80 (Nov. 19 - Dec. 7, 1996) carried, in addition to its prime payload, an ARP secondary payload of ESA/ESTEC, consisting of a GPS Tensor receiver and R-GPS (Relative-GPS) navigation algorithms (developed by MMS). The Shuttle orbiter carried also a GPS receiver (TANS Quadrex), implemented on the fixed part of WSF (Wake Shield Facility) within the cargo bay, and an optical sensor TCS (Trajectory Control Sensor). TCS (of NASA, a laser based sensor) verified the R-GPS measurements by tracking a retro-reflector mounted on the x-face of ORFEUS-SPAS. (1997) 1998)

- Shuttle - MIR flight approach and departure phases. ARP proximity navigation approaches were demonstrated with an instrument package of GPS Tensor (Laben) in combination with the R-GPS algorithm, and a close-range laser sensor, referred to as RVS (Rendezvous Sensor), built by DASA Jena Optronik - on Shuttle flights STS-84 (May 15-24, 1997) and STS-86 (Sep. 25-Oct. 6, 97). The GPS receiver of the MOMSNAV payload (DARA) on MIR/Priroda provided GPS measurements from the other direction. The Shuttle RVS used three retro-reflectors installed on MIR.

- Integrated GPS+GLONASS receiver technology. (1999) The combination of GPS and GLONASS signals enhances the overall navigation solution in three ways: availability, integrity and accuracy. The GLONASS constellation has no deliberate signal degradation; hence, the GPS+GLONASS horizontal accuracy is 15-20m compared to 100m for GPS-only (with SA on).


- The private company Soft Nav Ltd. of St. Petersburg, Russia (established in early 1998; mainly of former employees of RIRT (Russian Institute of Radionavigation and Time), St. Petersburg (2001) was instrumental in developing a combined GPS/GLONASS avionics software package which was used in a number of receivers such as ASN-22 of former DASA, now EADS Astrium GmbH [which features 18 parallel signal channels (10 GPS/ 6 GLONASS/2 EGNOS]). The same experts were also key participants in the development of the world’s first GLONASS receivers: ASN-16 (developed in the early 1990s), ASN-21 and SNS-85, mainly flown on Russian military aircraft such as MIG-31, TU-160, IL-96, IL-114, and TU-204.

- Soft Nav Ltd. is also a contributor to the EADS Astrium GmbH developed receiver called MosaicGNSS. The backbone of this receiver is the software correlator developed by Soft Nav. All signal processing and navigation processing functions are being performed in software. The single board MosaicGNSS receiver is embedded in an ACOs (Attitude and Orbit Control System), providing precise autonomous orbit determination for spaceborne applications from LEO to HEO, MEO and GEO. The MosaicAODS (Attitude and Orbit

1999) Note: Prior to measurement integration of GPS and GLONASS into one receiver, proper transformations must be established between the two time scales [UTC(USNO) and UTC(SU)], and the two coordinate systems [WGS84 and PE90 respectively]
2001) http://www.softnav.ru/
Earth Observation History on Technology Introduction

Determination System) is based on the MosaicGNSS receiver and complemented by a star sensor (ASTRO-15 of Jena Optronik GmbH) and optional gyros. Thus, the MosaicAODS makes the full state information continuously available. It can be used as integral part of a spacecraft ICDS (Integrated Control and Data Handling System) or as a stand-alone unit. Extensive simulator tests of MosaicAODS were successful. MosaicGNSS (along with MosaicAODS and ASTRO-15), a radiation-hardened receiver (100 krad), will be flown on the German TerraSAR-X satellite (launch June 15, 2007); it will be an integral part of the new OBC in a redundant configuration.

- En-route navigation in civil aviation. Airborne testing against a proven flight truth source (Z-12 dual-frequency GPS + ground-based reference station). In September 1996, Ashtech Inc. and Universal Avionics made the world’s first transoceanic flight with GPS+GLONASS technology, using an Ashtech GG24 receiver for an overseas flight (from Shannon, Ireland to Teterboro, NJ, USA). During the flight the 24-channel receiver computed positions using up to 17 satellites. Horizontal positions within an accuracy of 16 m were achieved 95% of the time. The potential benefits to civil aviation (navigation and positioning operations) in general have become increasingly obvious. (2008)

- Spaceborne testing. a) A GPS+GLONASS receiver [LAGRANGE \textsuperscript{TM} (Laben GNSS Receiver for Advanced Navigation, Geodesy and Experiments) of Laben S.p.A., Vimodrone, Italy] is part of the SAC-C satellite payload with a launch Nov. 21, 2000. The design employs the AGGA-2 (Advanced GPS/GLONASS ASIC) \textsuperscript{2009} \textsuperscript{2010} chip device providing an integrated AODS (Attitude and Orbit Determination System) using a hybrid parallel multiplex scheme for attitude determination, b) an ESA GPS+GLONASS receiver by the name of GRAS (GNSS Receiver for Atmospheric Sounding) is part of the MetOp-A satellite (see G.2.2). LAGRANGE processes the received GPS and GLONASS signals in both the L1 and L2 frequency bands, allowing compensation of ionospheric delays. A special codeless adaptive tracking scheme is implemented in order to process the encrypted P(Y) signals transmitted in the GPS L2 frequency band when Anti-Spoofing is on.

Some background of AGGA (Advanced GPS/GLONASS ASIC) receiver development

AGGA was predominantly developed within the ESA-funded EOPP (Earth Observation Development Program). AGGA experienced several redesigns, functional enhancements, miniaturization, and demonstrations. AGGA-2 represents the 2nd generation version of AGGA.

- The first GPS/GLONASS receiver breadboard model was developed in the timeframe 1993-95 at ISN (Institute of Navigation) of the University of Nottingham, UK. This system featured eight dual-frequency channels with 20 FPGAs and power of 50 W.

- In the period 1994-96, IMEC (Belgium) studied miniaturization of the ISN device.

- In the period 1996-98, IMEC performed a redesign of the ISN receiver with functional enhancements into a highly integrated ASIC (also part of ARTES-5 program).


2003) Note: In MosaicAODS, the ASTRO-15 system is being used as a star tracker. All attitude algorithms, command- ing, mode logic, etc. are being performed on the common platform MosaicGNSS. MosaicAODS can operate with various star sensors, it is not tied in any way to ASTRO-15.

2004) Information provided by Michael Mittnacht of EADSAstrium GmbH


Some background of AGGA (Advanced GPS/GLONASS ASIC) receiver development

- A full validation of AGGA-0 was done by Austrian Aerospace and ESA in 1998
- Design/development of a flight-worthy AGGA-2 device within the period 1998-99, with validation by Austrian Aerospace and ESA in 1999
- P-code bug fix in AGGA-2 by Saab-Ericsson Space (Sweden) in 2000 and subsequent validation by Austrian Aerospace

**AGGA-2 functionality and features:**
- 12 single frequency channels (36 complex correlators) each capable of tracking any GNSS C/A code signals
- 4 P-code units for dual-frequency operation and semi-codeless tracking (ESA-ESN patent)
- Supports IF sampling, R2C (real-to-complex) conversion, final down conversion
- Highly configurable and programmable
- Either 8 real inputs or 4 complex inputs, each 2 bits, support of different input formats
- Signal level detector, clock and time-base generator and antenna switch controller
- 32-bit microprocessor interface with interrupt controller and basic I/O port
- Features for multipath mitigation and adequate semi-codeless tracking of GPS Y code

2004 version: AGGA-2a is available to industry as an application-specific standard product (T7905E component from ATME)

**Applications supported by AGGA:**
- Spacecraft control: onboard determination of spacecraft position, attitude and time in real-time
- POD (Precise Orbit Determination): onboard receiver, L1 and L2 carrier phase tracking, in combination with ground reference stations and with post-processing on ground (cm accuracy)
- POD (Precise Orbit Determination): onboard receiver, L1 and L2 carrier phase tracking, in combination with ground reference stations and with post-processing on ground (cm accuracy)
- Atmospheric sounding: refractive limb sounding technique, onboard receiver with on-ground post-processing, to determine temperature and humidity profiles up to 50 km
- Reference stations: ground-based receiver with real-time processing, to compensate for errors
- AGGA receivers are supporting the following navigation systems: GPS, GLONASS, EGNOS (Europe), WAAS (USA), MTSAT (Japan)

**AGGA instruments on spaceborne missions:** Several receiver designs employ the AGGA-2 chip of ATME Wireless & Microcontrollers, including GRAS on MetOp, SSTI on GOCE (E.11), Lagrange on RADARSAT-2 and COSMO/SkyMed, and GPSOS on NPOESS.

As of 2005, an AGGA-3 fully integrated receiver is under development to further reduce the cost and size of the device and to increase its functionality (also support of Galileo signals). First use of AGGA-3 is being planned in the GRAS-2 receiver. Example: The ACE+ mission in ESA's Explorer Opportunity Program (constellation planned for 2008) is using AGGA-3 for GRAS-2. AGGA-3 provides enhanced high speed digital signal processing functionality, a powerful onboard microprocessor, LEON-FT (AT697E by Atmel), and versatile interfaces for a wide range of GNSS applications.


- Starting in about 1994/5, spaceborne/airborne GPS/GLONASS receiver applications developed into two major functional directions:
  - Use of the receiver as a navigation sensor - to determine relative and absolute spacecraft attitude, orbit and time. The receiver is expected to provide an engineering environment of real-time, autonomous onboard support to the spacecraft (mission-critical functions).
  - Use of the (GPS/GLONASS) receiver as a science instrument in Earth observation - to perform atmospheric sounding measurements, gravity measurements, ionospheric sounding measurements, etc. These science applications require extensive postprocessing of the data to achieve the desired results. - Receivers are included on virtually all new Earth-observation missions. Parallel to orbit determination, the technology opened new applications in atmospheric profiling (GPS/MET on OrbView-1/Microlab-1, launch April 3, 1995) and possibly in ocean altimetry (SAC-C). NASA/JPL-provided dual-frequency GPS receivers are part of four geomagnetic missions: Ørsted (launch Feb. 23, 1999), SUNSAT (launch

February 23, 1999), CHAMP (launch July 15, 2000), and SAC-C (launch Nov. 21, 2000) - and also of such missions as: SRTM (Shuttle Radar Topography Mission, launch Feb. 11-22, 2000), Jason (launch Dec. 7, 2001), GRACE (Gravity Recovery and Climate Experiment) with a launch Mar. 17, 2002.

- Demonstration of GPS receiver measurements in satellite orbits outside of the MEO GPS constellation of 20,000 km altitudes.

- The TEAMSAT/YES (Young Engineers' Satellite) spacecraft (ESA technology demonstrator payload on Ariane-5 test flight with a launch Oct. 30, 1997) made GPS measurements in its HEO orbit at an altitude of 25,000 km. 2015

- The Motorola GPS Viceroy receiver of the Equator-S (launch Dec. 2, 1997) satellite - with a near-equatorial HEO orbit of 10 R_E distance apogee and low perigee at 500 km - was able to measure carrier phase and/or C/A code of up to three GPS satellites at altitudes of 34,000 km (Dec. 3, 1997 while in transfer orbit). The GPS receiver measurements were considered for post-event (on-ground) orbit determination at GSOC. In addition, GPS side-lobe measurements were verified.

- AMSAT-3D (launch Nov. 15, 2000, also referred to as AMSAT OSCAR-40) in a HEO (Molniya) orbit of 1000 x 58,800 km, inclination = 63.4°. 2017 The AMSAT-GPS experiment is to demonstrate real-time GPS attitude and orbit determination above the GPS constellation (two Trimble TANS Vector (6-channel, L1, C/A code) GPS receivers along with two sets of four GPS antennas, GEC Plessey front-end chipset and AMD 29200 embedded RISC processor board). An additional experiment is to map the GPS signal patterns outside the GPS constellation. GPS signals from all around the orbit were measured. SNR levels up to 48 db-Hz were measured near apogee.

- GPS measurements in GEO. 2018 In general, GPS receivers in GEO cope with unfavorable conditions which are: 1) poor visibility and geometrical distribution of GPS signals, and 2) weak GPS signal power (low SNR). In spite of these handicaps, GPS pseudorange measurements were already demonstrated in GEO for orbit determination in US military applications. Since geostationary orbit determination is a very attractive option for commercial GEO satellite operations, solutions are being introduced to a new generation of GPS receivers for any satellites in GEO. Two examples:

- EADS Astrium GmbH offers an instrument, MosaicGNSS, 2019 a GNSS receiver using a software and hardware correlation (applications in LEO, GEO, MEO, HEO) and capable of tracking up to 8 GPS satellites. The so-called MosaicAODS is a spaceborne Attitude & Orbit Determination System, extended by a star sensor and an optional INS. The system provides the full state vector information (position, velocity, attitude, and time) permitting a good degree of onboard autonomy. MosaicAODS is planned to fly on TerraSAR-X (launch June 15, 2007).

- The TOPSTAR 3000 GPS receiver of ASI (Alcatel Space Industries, ESA sponsored) 2020 employs a filter and integration techniques to analyze weak GPS signals. TOPSTAR 3000 (a 4-antenna 24-channel C/A code GPS receiver) is part of the Stentor spacecraft (Note: a launch of Stentor took place on Dec. 11, 2002; however, a launch failure of Ariane 5

2015) http://www.estec.esa.nl/teamsat/page_menu_results.html
ECA occurred, destroying the Stentor S/C to be used as a navigation tool for GEO spacecraft.

- Second frequency for civil GPS users (Block IIF series). Uninterrupted access to “carrier phase” of the L2 frequency will be provided as a second civil frequency. This agreement was announced Feb. 27, 1997, by DoT and DoD. The goal of the second civil frequency is to enhance GPS civil capabilities by: 1.) providing a redundant signal for civil use in the event that the GPS L1 were to become unavailable (due to jamming or interference), and 2.) enhancing civil GPS performance by providing a second civil frequency for ionospheric delay calculations, a critical design requirement for the FAA’s Wide Area Augmentation System (WAAS). The first Block-IIIR-M GPS satellite launch is planned for 2003, ushering into operation the new L2 civil and L1/L2 military signals, and IOC (Initial Operational Capability) for WAAS and initial operations of LAAS (Local Area Augmentation System).

- CDGPS (Carrier-phase Differential GPS), see H.4.3. CDGPS sensing techniques provide very precise measures of relative position (1-2 cm level) and attitude between vehicles in formation (CDGPS is demonstrated to be useful in relative positioning and orbit determination in indoor and outdoor experimental settings). Given GPS measurements at two nearby antennas, relative position between these antennas can be estimated to a high degree of accuracy based on tracking the relative phase. Sample implementations: 1) CDGPS is flown on the Orion microsatellite of Stanford University (planned launch at the end of 2001). The Orion CDGPS receiver (total instrument mass of 1.07 kg, including processors) consists of a single 6-antenna attitude and relative navigation receiver using carrier-differential GPS. 2) As of 2001, AeroAstro Inc. of Herndon, VA is developing “Star Ranger” (initially intended for the TechSat-21 mission of AFRL). The Star Ranger design concept utilizes Ku-band for its operation (intersatellite communication), DSSS (Direct Sequence Spread Spectrum) for precise ranging, a two-PN code technique for multiple access within the three-satellite formation, and CDGPS for the determination of relative position and attitude between the formation flying satellites. The mass of Star Ranger is expected to be <2 kg.

- Integration of GPS and INS (Inertial Navigation System) to GPS/INS. GPS and INS are two different, but very complementary, positioning systems. GPS is, essentially, a geometry-based system, with navigation determined by distances a receiver is from the different GPS satellites. It has the advantage of long-term position accuracy; errors from one observation time do not propagate to the next observation. Unlike GPS, an INS system is based on the laws of Newtonian physics and initialization errors propagate throughout the trajectory. Although the long-term accuracy of a stand-alone INS cannot compare to that of GPS, its navigation solution is still necessary during times of GPS loss.

The integration of GPS with INS devices improves the quality and integrity of each navigation system due to synergistic effects of the tight sensor combination and data fusion: use of GPS permits calibration of inertial instrument biases, and the INS can be used to improve the tracking and re-acquisition performance of the GPS receiver. Traditionally, INS devices provide positioning and attitude information for the guidance (and perhaps control) of a wide range of moving platforms in space, the air, at sea, or on the ground. A concern in INS applications is the time-dependent growth of systematic errors. It turns out

that precise GPS satellite measurements are ideally suited for the calibration of INS systematic errors. Therefore, integrated INS and GPS (and/or Glonass) systems, i.e., GPS/INS devices, have been developed, which can provide high-rate precise positioning and attitude information. Many applications have benefited from GPS/INS integration. Some advantages of integrating these very complementary navigation systems are:

- Cycle slips in GPS data can be detected and eliminated in real-time by using the high short-term accuracy of the INS velocity
- The excellent positioning accuracy of differential GPS (DGPS) can be used to provide frequent updates to the inertial system which allows in-flight calibration and thus a major reduction of INS orientation errors. In general, the fact that nine independent measurements are available for the determination of the six required trajectory parameters greatly enhances the reliability of the system. Usually, a Kalman filter is used to handle both types of signals for optimal measurement performance.
- The DGPS/INS 2026) performance permits for direct georeferencing of source data from imaging instruments. In fact, GPS/INS platform orientation systems have emerged as core components of modern imaging platforms - in particular in airborne photogrammetric mapping applications. 2027)
- GPS/INS technology can be used for over-the-horizon intelligence gathering, reconnaissance, and targeting.

Most of the early GPS/INS 2028) applications have been developed for military purposes and have focused on improved accuracy of anti-jam performance. For most civil aviation applications, accuracy is not the primary issue. The primary shortcoming of GPS for civil aviation is the availability of service with integrity (civil aviation). So far (2001), very few GPS/INS applications have been focused on enhancing the availability of GPS with integrity.

- Joint GPS/LEO navigation receiver. As of 2000/1 new dual-use tracking concepts of GPS and LEO constellation signals are being considered by the communications industry. Commercial LEO satellite systems, such as Orbcomm, Iridium, and Globalstar, provide a global coverage of their data and/or voice services. In addition to these prime services, the LEO constellations may also serve as “guide posts in space” to complement and enhance the GPS navigation performance. 2029) 2030) The combined use of positioning and two-way communication in LEOs may eventually lead to such applications ranging from emergency roadside assistance to location-based merchandising. The overall objective is to achieve precision (cm-level) navigation performance using pre-existent LEO transceiver hardware. In this concept, the LEOs provide additional ranging signals, which improves GDOP, availability of navigation solutions, and availability of RAIM (Receiver Autonomous Integrity Monitoring) geometry. The geometric diversity, achieved mainly by the motion of the LEOs, enables the GPS/LEO receiver to resolve the integer cycle ambiguities on the GPS constellation signals as well as parameters related to the cycle ambiguities on the LEO signals. First experimental tests have been conducted with the Orbcomm constellation in conjunction with GPS.

- At the start of the 21st century, well over two decades since the launch of NAVSTAR-1 (Feb. 22, 1978), GPS has exploded onto the scene, introducing itself into our society in ways

never before conceived. Essentially providing anytime, anywhere positioning and timing, GPS is now integrated into nearly all major commercial and infrastructure components, including transportation, communications, energy, and commerce. The maritime industry has largely adopted it, and the aviation industry is establishing the groundwork for its use in nearly every phase of flight.  

- Hybrid navigation concepts (i.e. digital multi-sensor systems) with considerable performance improvements are achieved with the functional integration of GPS receivers with other attitude measurement devices such as: a) GPS + star sensor, b) GPS + magnetometer, c) GPS/INS + magnetometer, d) CDGPS/INS (Carrier-phase Differential GPS/INS). Each design takes the particular instrument advantages and disadvantages into account, reaching a hybrid navigation solution that is superior in its performance (quality and integrity) to that of various a single-instrument implementations.

- PRARE and DORIS are microwave tracking systems requiring a host satellite (for the space segment instrument) and global ground-based tracking networks for precise orbit determination. Both systems (PRARE and DORIS) require an orbit determination process using conventional dynamic techniques (with physical models) whose accuracies depend on the quality of the models.

PRARE (H.7.2) was initially installed on ERS-1 (launch July 17, 1991), but could not be operated. Further PRARE uses: Meteor-3-7 (launch Jan. 25, 1994, PRARE demonstration operations until March 1995), ERS-2 (April 21, 1995). PRARE is a two-way tracking system, broadcasting dual-frequency signals (2200 and 8500 MHz) from a transmitter onboard the host satellite to receiver-transponders on the ground. The signals are modulated by pseudonoise ranging codes to permit both range and range-rate measurements. The 8500 MHz signal is coherently transponded back to the host satellite (at 7200 MHz) for onboard range and range rate extraction. The 2200 MHz signal is received and tracked on the ground to provide an ionospheric correction. As of 2004, PRARE is operational on ERS-2.

DORIS was a prototype payload on SPOT-2 (launch Jan. 22, 1990) and SPOT-3 (launch Sept. 26, 1993); then flown on: TOPEX/Poseidon (launch Aug. 10, 1992). DORIS was initially a one-way Doppler system which broadcasts continuously at two frequencies: 401 and 2036 MHz. A two-way upgrade is planned for use on Envisat (launch Mar. 1, 2002). The DORIS instrument on the host satellite observes individual ground beacons in sequence and measures the Doppler frequency of the received signals.

1.12.6 GNSS (Global Navigation Satellite System) Augmentation Systems

GNSS is a concept to circumvent the limitations of current navigation system service provision. The limitations of current/future radionavigation systems (GPS, GLONASS, Galileo) are evident in particular in the area of aviation requirements to achieve a level of performance critical for civil aviation applications. Specific requirements are in the areas of: accuracy, availability, integrity and continuity of service.

Some of these risks could be attenuated by a receiver interoperability mode (GPS, GLONASS, Galileo), providing substantial improvements in redundancy (multiple navigation systems), accuracy as well as better coverage and integrity. However, this situation does still not provide sufficiently enough performance in safety-critical transportation applications (aviation and shipping). A workable solution can only be provided by complementary regional Wide Area Augmentation Systems (WAAS) which are being developed and

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deployed in USA, Europe, and Asia (see H.2). International cooperation is required to provide system interoperability.

The first generation GNSS-1 comprises the following elements: GPS, GLONASS as prime navigation constellations and their augmentation systems [WAAS (Wide Area Augmentation System) of the US, EGNOS (European Geostationary Navigation Overlay System) of Europe, and MSAS (Multi-Transport Satellite Augmentation System) of Japan]. The three augmentation segments of GNSS-1 are expected to provide their IOC (Initial Operational Capability) in the time frame 2003/5. In fact, the formal completion of the technical qualification of EGNOS and the acceptance of the EGNOS system was delivered to ESA on June 16, 2005 by the European industry. 2034)

- Enhanced performance of GPS and GLONASS constellation service provision (of integrity, availability, accuracy, and continuity monitoring) for civil aviation applications. This type of service requires so-called augmentation systems, since neither the current GPS nor the GLONASS constellation are able to provide the needed functions. Augmentation systems are referred to by their generic name as SBAS (Satellite-Based Augmentation System) and GBAS (Ground-Based Augmentation System). An SBAS consists of a network of ground stations that monitor the navigation signals of the primary constellations (GPS and GLONASS). The ground stations send their observations to one or more master control stations, which generate the augmentation message. This in turn is sent to uplink stations for transmission to GEO satellites (Inmarsat). The GEO satellites broadcast their SBAS message to the user community, modulated onto a GPS look-alike signal at L1 (1575.42 MHz) GPS frequency (see H.2).

Starting in the 1990s with the WAAS (USA) and EGNOS (Europe) initiatives, several other countries have started their own initiatives to develop and implement regional augmentation systems in addition to the primary constellations. In 2002, these initiatives are at various stages of planning/development or initial service provision.

- WAAS (Wide Area Augmentation System) of USA (FAA)
- EGNOS (European Geostationary Navigation Overlay System) of Europe (European Tripartite Group; coverage of ECAC region)
- MSAS (Multi-Transport Satellite Augmentation System) of Japan (JCAB)
- CWAAS (Canadian WAAS) of Canada (NavCanada)
- SNAS (Satellite Navigation Augmentation System) of China
- GRAS (Ground-based Regional Augmentation System) of Australia 2035) 2036
- India also plans to implement its own augmentation system, called GAGAN (GPS And Geostationary Augmented Navigation).

The following GEO satellite service providers are involved in the regional broadcast of SBAS messages to the user community.

- Inmarsat. The service started with the Inmarsat-3 (third generation) constellation in 1996. The Inmarsat-3 navigation transponders form an integral part of two SBAS systems, WAAS and EGNOS. – Each of the new Inmarsat-4 satellite series (launch of InmarSat-4F1 on March 11, 2005, launch of Inmarsat-4F2 on Nov. 8, 2005) incorporates a navigation transponder for L1 and L5 frequency SBAS operations [service in bent-pipe mode, support of the same functions (with enhanced features) as the Inmarsat-3 navigation transponder]. Starting with the Inmarsat-4F1 service, an L5 frequency navigation signal (2nd civil GPS

\[2034\) “EGNOS system delivered to ESA by industry,” http://www.esa.int/esaNA/SEM2VV1DU8E_index_0.html
signal) is being broadcast for the first time from space, paving the way for the introduction of the second civil frequency for SBAS systems. \(^{(2037)}\) \(^{(2038)}\)

- WAAS achieved its IOC (Initial Operating Capability) in January 2003, providing a location accuracy of 2–3 m (horizontal and vertical). It was commissioned on July 10, 2003 as part of the US NAS (National Airspace System). The FOC (Full Operating Capability) is expected in the late 2007 time frame.


- BNTS-1B (launch Dec. 21, 2000). The Space Technology Research Institute, one of the five major research institutions of CASC (China Aerospace Science and Technology Corporation, built the BNTS satellites. BNTS provides navigation services for highway traffic, railway transport and ocean operations in China. Note: The final BEIDOU constellation will consist of 4 GEO satellites.

- ARTEMIS (Advanced Relay and Technology Mission Satellite) of ESA, launch July 12, 2001 (see M.4). ARTEMIS complements the required constellation of three GEO satellites (2 Inmarsats+ARTEMIS) in the ECAC (European Civil Aviation Conference) region.

- MTSAT (Multifunctional Transport Satellite) of Japan (JMA and JCAB), launch of MTSAT-1R on Feb. 26, 2005 (MTSAT-1 experienced a launch failure Nov. 15, 1999). MTSAT is the space segment to MSAS of Japan. MTSAT-2 was launched on Feb. 18, 2006.

- EGNOS operations. As of July 2005, ESSP (European Satellite Services Provider) – a consortium of AENA (Spain), DFS (Germany), DSNA (France), ENAV (Italy), NATS (United Kingdom), NAV (Portugal), and Skyguide (Switzerland) – started the “initial operations phase” of EGNOS, a joint project of ESA, EC, and Eurocontrol. \(^{(2039)}\) \(^{(2040)}\) \(^{(2041)}\)

As of the end of 2005, the EGNOS ground infrastructure consists of 4 MCC (Mission Control Centers), 6 NLES (Navigation Land Earth Stations), and 31 RIMS (Ranging and Integrity Monitoring Station). Since December 2003, when the first transmissions were made, 3 geostationary satellites (Inmarsat-3, AOR-E, Inmarsat-3 IND-W), and ESA’s ARTEMIS have been transmitting successfully EGNOS signals.

- Technology demonstration of precision GPS-assisted aircraft landings. A US government-industry team accomplished the first precision approach by a civil aircraft, using the military JPALS (Joint Precision Approach and Landing System) at Holloman AFB, NM. A Boeing 727-200F aircraft (of FedEx Express Inc.), equipped with MMR (Multi-Mode Receiver) of Rockwell-Collins (GNLU-930), successfully conducted category-I (200 foot ceiling and 0.5 visibility) approaches and autolandings using the JPALS DGPS (Differential GPS) ground station, designed and developed by Raytheon Company for the USAF. The military test flight activities took place from June to Aug. 2001 using JPALS of the USAF. Over 280 military aircraft approaches were conducted at Holloman AFB using the USAF C-12J test aircraft. The JPALS equipment was also used for the military/civil interoperabil-


\(^{(2040)}\) http://www.esa.int/esaNA/SEMFQA808BE_index_0.html

ity demonstrations of JPALS/LAAS. On Aug. 25, 2001, a series of 16 approaches were conducted with the FedEx aircraft using the civil LAAS equipment (MMR). Precision approaches were conducted using precision guidance formed from C/A and Y-code differential solutions; Y-code solutions were used in both benign and hostile EMI environments to investigate a performance of operational and next-generation techniques for the mitigation of electronic interference in the GPS frequency band. Basically, the aircraft were guided by DGPS signals, integrity information, and precision approach path points transmitted from the JPALS ground station. The JPALS demonstration system is a test platform hosting multiple antennas, antenna electronics, and GPS receiver technologies integrated to provide a differential GPS precision approach capability based primarily on the civil LAAS (Local Area Augmentation System). The demonstration system consisted of a ground segment and an airborne segment and implemented core functionality envisioned in the proposed JPALS LDGPS (Local Area Differential Global Positioning System) program. - JPALS is the military version of the civilian LAAS (Local-Area Augmentation System) of FAA; JPALS and LAAS are similar and interoperable systems (both programs started in 1999, JPALS initial DoD program approval in May 1996).

Similarly, a civilian LAAS prototype station installed at Salt Lake City International Airport [Raytheon's RAYNAV-4100 LGF (LAAS Ground Facility)] guided 16 precision landings there by the FedEx aircraft on Aug. 26, 2001 (demonstration of civil onboard GPS equipment with a civil LASS).

In the same context, on April 23, 2001, an FA-18A Hornet aircraft of the US Navy touched down on deck of the USS Theodore Roosevelt aircraft carrier performing the “first ever” fully automated landing at sea using GPS. The SRGPS (Shipboard Relative GPS), the Navy version of JPALS, achieved a touchdown dispersion of 5.6 m horizontal and a vertical accuracy of 12 cm. The aircraft carrier was equipped with SRGPS, providing 3-D coverage for up to 100 aircraft at a range of as much as 200 nautical miles.

JPALS key performance requirements call for: a) landing minima / guidance quality, b) system transportability and short set-up time, c) shipboard compatibility, d) non-vulnerability to signal disruption/spoofing, e) standardization, interoperability, and commonality to other LDGPS (compliance with RTCA messages), f) information exchange capability.

- In March 2002, plans of the US government (Federal Radionavigation Plan) call for a transition commitment from land-based to space-based radionavigation systems (GNSS-1) for civilian aircraft navigation in 2010 (originally planned for 2008). This implies primary reliance on the GPS constellation with its augmentation systems starting from 2010 onwards. (2046) (2047)
  - GNSS-2 (Global Navigation Satellite System-2). The second generation GNSS comprises all elements of GNSS-1 plus Galileo. GNSS-2 is planned to be operational by 2008/10.
  - EGNOS flight trials. In March 2007, a test plane of the Direction Générale de l’Aviation Civile (DGAC – French Civil Aviation Authority) was specially equipped to make tests using EGNOS. At Limoges airport the ATR42 aircraft made a number of approaches and landings using the new procedures, in each case aligning itself with the runway’s axis.

and then following a descent path to touchdown. Inside the aircraft, the method of analyzing the quality of the EGNOS signals was by comparing the landing phases guided by satellite with landings using traditional means such as the ILS (Instrument Landing System). The results of these trials show again that EGNOS signals allow approaches and landings that meet the safety standards that govern international air traffic.

One of the main advantages of EGNOS in this application is that it is available everywhere in Europe without the need for ground infrastructure and it provides vertical guidance procedures for every runway. Furthermore, the cockpit data display is the same as that for ILS, so there are no familiarization problems for the pilots and no additional training costs. Currently in pre-operational service, EGNOS will be certified in 2008 for safety—of—life applications such as air traffic control. 

1.12.7 Galileo

Galileo is Europe’s civilian-managed GNSS (Global Navigation Satellite System) under design and development by ESA and the EC (European Commission). The overall system architecture includes the space segment, the ground control segment, the ground mission segment and the user segment. The planned space segment architecture consists of a MEO constellation of 30 satellites placed in three orbital planes with an inclination of 56° and a mean altitude of 23616 km. The satellites are organized to give a 27/3/1 Walker constellation. One satellite per plane will act as an active spare for the other 9 MEO satellites in the same plane (quick recovery in case of failure). The orbital period is 5/3 revolutions/day. Each satellite in the constellation will broadcast precise time signals, together with clock synchronization, orbit ephemeris and other data. The Galileo system will provide eight open and twoPRS (Public Regulated Service) signals per satellite. See also chapter H.1 for a Galileo system description.

In July 2003, ESA awarded two contracts, one to SSTL (Guildford, UK) and one to Galileo Industries SA of Brussels, each one is to build a Galileo test satellite for the Galileo satellite navigation system. The purpose is to transmit test signals at the frequencies reserved for Galileo so that the project secures those frequencies with ITU. Both test satellites are regarded as forerunners of the system’s in-orbit validation phase (risk mitigation). The satellites will also test various critical technologies. Also, an initial performance demonstration capability and in-orbit system validation of two further Galileo spacecraft is planned for 2006. 

- GIOVE-A (Galileo In-Orbit Validation Element-A), built by SSTL for ESA, was launched successfully on Dec. 28, 2005 from Baikonur, Kazakhstan, on a Soyuz-Fregat launcher into MEO (Medium Earth Orbit)
- GIOVE-B, built by Galileo Industries for ESA, is scheduled for launch in 2007 from Baikonur.

Background: In early 1999 the EU proposed a strategy with the goal to design, implement and operate its own (civil) constellation of navigation satellites with the appropriate terrestrial infrastructure within a program by the name of Galileo. The space segment of the overall Galileo program is referred to as GalileoSat. Galileo is considered an element in a future GNSS-2 (Global Navigation Satellite System-2) - currently comprising GPS, GLONASS

2048) http://www.esa.int/esaNA/SEMTHVLJC0F_index_0.html
2049) Note: Galileo Industries SA is a European joint venture of the following companies (to define and build the Galileo System): Alenia Spazio of Rome, Alcatel Space of Paris, EADS Astrium Ltd. of Stevenage, UK, and EADS Astrium GmbH of Friedrichshafen, Germany.
and their future augmentation systems. The rationale for Galileo is the provision of a service with a certifiable service performance level, which neither GPS nor GLONASS can presently do. The goal is the support of safety-critical civilian applications, especially in civil aviation, marine navigation, and road transport. Formal approval and funding of the Galileo program was given by the European Council of Transport Ministers on March 26, 2002. The goal is to complete implementation of the Galileo system by 2011. Although Galileo is a civil system, it doesn’t mean it doesn’t have military applications and implications in its service provision.

Successful deployment of Galileo will more than double the number of GNSS signals in space available to the user community. This large increase in satellites will benefit not only single-point accuracy but also position reliability and the ability of GNSS user equipment to resolve integer ambiguities when using carrier-phase tracking techniques.
1.13 Services

Earth observation is a valuable information source. The rendering of any sustained or long-term service implies the provision of an operational capability. The early introduction of the NASA/NOAA broadcast service policy of free access to polar-orbit weather satellite data reception generated a totally new participative/cooperative research and application environment for a global user community (laboratories and research institutes in particular). Real-time data reception of AVHRR data became affordable to many with the installation of a simple receiving station. Eventually a network of thousands of small ground stations was realized, and the AVHRR sensor became the best known sensor in the world. The most important service aspect was probably the provision of a timely, reliable and repetitive data stream to the user community which in turn accelerated the pace of exploration and of technological development in the various fields of applications.

- TIROS-1 (launch April 1, 1960) is regarded the first true weather satellite.
- Starting with TIROS-8 (launch Dec. 21, 1963), real-time observational data were transmitted (broadcast) continuously in APT (Automatic Picture Transmission) mode to ground stations. Eventually, APT pictures could be received on fairly simple ground stations anywhere in the world.
- Introduction of APT and HRPT (High Resolution Picture Transmission) broadcast modes (VHF link for ATP and L-band link for HRPT) in parallel with TIROS-N (launch Oct. 13, 1978). Further broadcast services of ‘weather data’ followed:
  - The Terra satellite (launch Dec. 18, 1999) of NASA’s EOS (Earth Observing System) program introduced a direct broadcast in X-band for instrument data (MODIS) to the user community.
  - The Aqua (formerly EOS/PM-1) S/C of NASA (launch May 4, 2002) provides a direct broadcast in X-band for all its instrument data, including MODIS
  - MetOp-A of EUMETSAT (planned launch Oct. 19, 2006) supports a real-time broadcast of instrument data to local users by means of LRPT (72 kbit/s in VHF for selected instruments) links and HRPT (3.5 Mbit/s in L-band) links.
  - NPP (NPOESS Preparatory Project) of NASA/IPO (planned launch in 2009) provides X-band broadcasts of instrument data at 20 Mbit/s.
  - NPOESS of IPO (planned launch in 2012) features a broadcast of two data streams:
    - LRD (Low Rate Data) in L-band (1706.5 MHz) at a data rate of 3.88 Mbit/s (4 Mbit/s nominally) with full CCSDS convolutional coding, Viterbi decoding, and Reed Solomon encoding/decoding into a tracking receive antenna aperture of 1 m diameter. This data stream supports the retrieval of 23 EDRs (out of a total of 55). The LDR broadcast is a subset of the full NPOESS sensor data set and is intended for the global user community. The LRD format is compatible with the AHRPT (Advanced High Resolution Picture Transmission) format, accepted and approved by CGMS (Coordinating Group on Meteorological Satellites); it will also be used on the MetOp spacecraft.
    - HRD (High Rate Data) in X-band (7.75-785 GHz) at a rate of 20 Mbit/s (required receiver antenna diameter of 2 m with a bandwidth of 30 MHz). This data stream supports the retrieval of 51 EDRs, a complete full-resolution data set containing all sensor data and auxiliary/ancillary data necessary to generate all NPOESS EDRs (except some Earth Radiation EDRs); it is intended to support users at fixed, regional hubs.
- WEFAX (Weather Facsimile) services. The first installation of WEFAX on ATS-1 (launch Dec. 6 1996) worked well until 1972. It demonstrated that WEFAX transmissions were practical. The original transponder received on 149.22 MHz and transmitted on 135.6 MHz. Due to technological design improvements and interference with the aeronautical band, these frequencies were re-allocated to the S-band frequencies. The most pertinent one of these to date is the 1691 MHz WEFAX frequency.
- Presumably, NOAA-6 (launch June 27, 1979) is regarded as the first operational satellite of the TIROS-N series.
- The onboard store & forward data concept (with a data recorder and a data dump during a station pass) was introduced fairly early in the game (TIROS-1 with a launch in 1960 had a tape recorder). The lack of world-wide coverage (ground stations) for data downlinks dictated this strategy.
- Global coverage once per day was first provided by AVHRR on TIROS-N (launch Oct. 13, 1978)
- Introduction of search and rescue services (S&RSAT) on polar-orbiting satellites with the launch of COSPAS-1 on June 29, 1982 (Soviet Union) and with the S&RSAT payload flown on NOAA-8, March 28, 1983. The polar-orbiting satellites with the S&RSAT payload are also referred to as LEOS&R. The LEOS&R system calculates the location of distress events using Doppler processing techniques. The complementary GEOS&R (Geostationary Search and Rescue) system has been developed for GEO satellites. The GEOS&R system consists of 406 MHz repeaters carried on board various geostationary satellites (the Doppler effect technique cannot be used on a GEO system). The first GEOS&R (demonstration) system was flown on GOES-7 (launch Feb. 26, 1987). ISRO introduced the COSPAS-S&RSAT service over the Indian Ocean in 1992 with its SAS&R (Satellite Aided Search and Rescue) payload flown on the GEO INSAT-2 series, starting with INSAT-2A (launch July 9, 1992). GEOS&R is also flown on the MSG series of EUMETSAT (launch of MSG-1 Aug. 28, 2002, renamed to Meteosat-8 as of Jan. 29, 2004 when the operational service officially started).

- As of 2002 (20th anniversary of service), the COSPAS/S&RSAT system comprises six LEOS&R payloads (launch period of 2000-2004 to orbit the last in the current generation of instruments that began in 1998) and three GEO satellite payloads, dedicated for search & rescue services. In addition, there is a worldwide network of 48 ground stations for receiving and processing distress alert signals and 24 MCCs (Mission Control Centers) for relaying distress alerts. This infrastructure has moved far beyond the program's initial goals, since in 1982 none of the founding partners (USA, Canada, France, and the Soviet Union) had yet formed a clear idea of the international cooperation structures needed to operate the system successfully.

- Starting with the launch of MetOp-A satellite of EUMETSAT (launch Oct. 19, 2006), the next generation of CNES S&RSAT instruments with new digital technologies for improved receiver sensitivity (developed by Thales and Alcatel Space) will be flown on the MetOp series as well as on the NOAA-POES series.

- Current planning (2002) calls for S&RSAT systems to be deployed on the MEO Navigation Satellite Constellations of GPS (US) and Galileo (Europe). The intent is to provide a search and rescue service alongside the established COSPAS/S&RSAT service and infrastructure. The payload on the GPS constellation is referred to as DASS (Distress Alerting Satellite System), while the name of the Galileo payload is S&R/Galileo.

- Introduction of spaceborne data collection systems (DCS) in LEO. The first DCS anywhere was IRLS (Interrogation, Recording, and Location System) flown on Nimbus-3 (launch April 14, 1969, see M.26.3). DCS were also flown on the first three Landsat S/C, LS-1, LS-2, and LS-3 (LS-1 launch July 23, 1972). The first Argos DCS in LEO (polar orbit) was flown on TIROS-N (launch Oct. 13, 1978). The first DCS in GEO orbit was flown on SMS-1 (launch May 17, 1974). In the meantime all geostationary meteorological satellites series (METEOSAT, NOAA-GOES, GMS (JMA), etc. use DCS or variations thereof (see Table 213 for DCS). The following Argos upgrades are realized or planned:

2053) http://www.sarsat.noaa.gov/
Starting with NOAA-15 (launch May 13, 1998), a modified Argos data collection system is flown referred to as Argos DCS-2. The data transmission rate for DCS-2 changed from 1200 bit/s to 2560 bit/s. The PTT capacity was increased from four to eight, this means eight DRU (Data Recovery Unit) onboard. The data are formatted and stored, then dumped each time the satellites moves within visibility of one of the three ground stations (Wallops, Gilmore Creek, or CMS). VHF and S-band transmitters also perform real-time relay (broadcast) for any user station within visibility.

- The first Argos-Next instrument is being flown on ADEOS-II (launch Dec. 14, 2002) providing two-way messaging services (demonstration for Argos/ADCS).
- The first 3rd generation Argos system, also referred to as Argos/ADCS (Advanced Data Collection System), is scheduled to fly on MetOp-A (launch Oct. 19, 2006) of EU-METSAT (and of course on the POES series S/C of NOAA starting with NOAA-N ’). Argos/ADCS features two-way messaging services, data reception at 401.65 MHz, data transmission at 466 MHz, and higher data rates.

- Satellite navigation data, such as position, velocity, and time, of GPS (GPS-1 launch in 1978) and GLONASS (first GLONASS launch in 1982) systems. The GPS constellation became operationally available in 1994 (officially in 1995). The real-time global availability of navigation data has spawned numerous positioning and navigation applications that have surpassed initial expectations. They are fast becoming an indispensable part of people’s everyday lives. The navigation services on all levels (civil and military aviation, coastal and ocean ship navigation, automobile navigation, surveying, etc.) are becoming increasingly essential to the world’s infrastructure. As a consequence, a large commercial market of equipment and service providers is unfolding, responding to the new needs of society.

- GPS time is being utilized as a cost-effective standard time source by many operators. Networks like Internet and many TTPs are being synchronized by GPS time. The GPS time service is provided by USNO (US Naval Observatory). GPS provides two types of time:

  - GPS time. Defined by its ‘composite clock.’ It consists of an ensemble of more than 20 GPS space and ground-based atomic frequency standards. GPS time is referenced to UTC (Universal Time Coordinated) as maintained by USNO. Time updates are maintained to within 1 μs of UTC by the operators of the GPS Master Control Station at Falcon Air Force Base, Colorado Springs. Note: GPS time differs from UTC by the number of leap seconds accumulated since January 1980.

  - UTC. To obtain UTC from GPS, users must apply the GPS-UTC (USNO) correction, available in the navigation message, to transition from GPS time to an estimate of UTC (USNO). The estimate of UTC (USNO) is called UTC (GPS). 2056

Starting in the mid 1980s a number of commercial services have come into the Earth observation arena to complement (or replace) the institutional services.

- Spacecraft operators and data distributors like Eosat (Landsat-4, -5)
- In 1990, SSTL of Surrey (UK) started a unique microsatellite technology transfer program, providing on-the-job training of engineers and scientists of foreign national organizations in cooperative programs [KAIST (Korea), LNETI (Portugal), FACH (Chile), TMSC (Thailand), etc.]. Affordable access to space is the overall theme of the service. - The design, building and operating experience of their own microsatellites gave these organizations a means to start/continue their own involvement in national space programs. The ‘Surrey Space Centre’ of SSTL (since 1992) is a European center of excellence, a facility which accommodates the activities for the technology transfer service of academic and post-graduate research.

- Distributors of imaging data products from a particular spacecraft and sensor (SPOT Image, Eurimage, etc.)

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The RADARSAT-1 satellite of CSA, Canada, is an Earth observation mission for SAR data, operated on a commercial basis by RSI.

Real-time ERS altimetry data are distributed via Internet. The NOAA/NODC Laboratory for Satellite Altimetry (LSA) receives ERS altimetry data and generates RGDGRs (Real-time Geophysical Data Records). These RGDGRs are distributed via Internet and may be used in oceanographic analysis and model assimilation studies.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Data Availability</th>
<th>Sensor</th>
<th>Band</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-4,-5</td>
<td>1982</td>
<td>TM</td>
<td>0.45 - 2.35 μm (MS)</td>
<td>30 m</td>
</tr>
<tr>
<td>Landsat-7</td>
<td>1999</td>
<td>ETM+</td>
<td>0.50 - 0.90 μm (Pan)</td>
<td>15 m</td>
</tr>
<tr>
<td>SPOT-1, -2, -3</td>
<td>1986</td>
<td>HRV</td>
<td>0.51 - 0.73 μm (Pan)</td>
<td>10 m</td>
</tr>
<tr>
<td>Resurs-O1-1, 2, 3</td>
<td>1985</td>
<td>MSU-E</td>
<td>0.50 - 0.90 μm (MS)</td>
<td>45 m x 33 m</td>
</tr>
<tr>
<td>JERS-1</td>
<td>1992</td>
<td>OPS</td>
<td>0.52 - 2.40 μm (MS)</td>
<td>18 m x 24 m</td>
</tr>
<tr>
<td>IRS-1C, IRS-1D</td>
<td>1996, 1997</td>
<td>PAN</td>
<td>0.50 - 0.75 μm (Pan)</td>
<td>6 m</td>
</tr>
</tbody>
</table>

Table 109: Availability of long-term high-resolution imaging data of major Earth surface missions

A multitude of commercial enterprises provide their services in the airborne arena, most with a full service (aircraft, sensor(s), data recording and processing, etc.).

**Shuttle Small Payload Program (SSPP).** A flight service package offered by NASA for payload masses in the range between 23 kg to about 2270 kg. SSPP is for “small, self-contained payloads” with the objective to ensure divers user groups (educational, commercial, government, foreign experimenters, etc.) to have access to space at reasonable costs. Payloads are accommodated by providing various carrier systems [GAS, Hitchhiker, Hitchhiker Jr., and SEM (Space Experiment Module)] in the Shuttle’s unpressurized payload bay. SSPP started in 1984.

Note: In general a S/C launch from Shuttle has advantages and disadvantages. Typically the low orbit implies a relatively short lifetime for the mission. This may be of interest in itself, as the orbital decay can be studied. But the Shuttle is the only launcher that really allows a payload to be viewed being released into space. In addition the g-loads are modest compared with other launchers.

- **GAS (Get Away Special).** GAS is a carrier system concept with standards and conditions relating to GAS payloads (they must fit in a standard container of 0.14 m³ in volume with a payload mass not exceeding 90 kg, two or more experiments may be included in a single container). In addition, GAS payloads must be self-powered and be easy to handle for the payload crew. The GAS container is made of aluminum with circular end plates. It can be pressurized (or evacuated) to suit experiment requirements.

GAS payloads are mounted during flight in the Shuttle payload bay, on the sidewall, or on a cross-bay truss structure (referred to as “getaway bridge”). The aluminum bridge fits across the payload bay of the orbiter and offers a convenient and economical way of flying several GAS canisters. The getaway bridge, capable of holding up to 12 canisters, made its maiden flight on STS-61-C (Jan. 12-18, 1986).

The service was initially announced by NASA in 1976, five years prior to the first Shuttle flight in 1981. The first GAS demonstration payload, FVP (Flight Verification Payload), was flown in 1982 on STS-3 (Mar. 22-30, 1982). The first customer GAS payload, G-001 of Utah State University, flew on STS-4 (June 27 - July 4, 1982). STS-95 (Oct. 29 - Nov. 7, 1998) is the 33rd Shuttle mission with the GAS payload service. Almost 200 individual GAS canisters have been flown in these 33 missions for a very divers user community.

- **Hitchhiker carrier system.** The Hitchhiker concept is based on a modular and expandable carrier with the provision of extended functional features (standard power, data, and

2058) http://sspp.gsfc.nasa.gov/gas.html
command services for customer equipment). The structure can carry equipment mounted in canisters but also has mounting plates of various sizes for user equipment (provision of options). The carrier provides electrical power (28 VDC), command signals (1200 baud), and downlink data interfaces (various data rates: 1200 baud asynchronous low-rate, 1-1400 kbit/s medium rate). Hitchhiker customers are able to operate their payloads from the ground segment (GSFC) using their own ground support equipment (usually a PC) to send commands and display data. The ACE (Advanced Carrier Equipment) package provides such standard services devices as: power distribution unit, remote interfaces unit, Hitchhiker central unit, digital storage unit, Hitchhiker video interface unit, and lightweight avionics plate. NASA initiated the service in 1984. The first flight was on STS-61-C (Jan. 12-18, 1986) with the Hitchhiker-G1 payload [consisting of IEH-1 (International Extreme Ultraviolet Hitchhiker), CAPL-2 (Combined Pumped Loop-2), TES (Thermal Energy Storage), etc.]. The SLA-1 (Shuttle Laser Altimeter) experiment on STS-72 (Jan. 11-20, 1996) was also a Hitchhiker payload.

- **Hitchhiker Jr. carrier system.** A limited Hitchhiker version, designed for payloads which do not need the functions of command and telemetry interfaces from the experiment to the ground (GSFC). The CONCAP-IV-3 payload on STS-69 (Sept. 7-18, 1995) was the first to use the Hitchhiker Jr. service package. The experiment was activated and de-activated by the Shuttle crew via a laptop computer. This requires autonomous payload operations for the duration of the experiment. The SOLSE/LORE (Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment), a NASA instrument package flown on STS-87 (Nov. 19 - Dec. 5, 1997), used also the Hitchhiker Jr. service version.

- **SEM (Space Experiment Module) carrier system.** The SEM program is an upgrade version of the GAS program. It uses GAS canisters with the added feature of installed power provision and more. On behalf of frequent student requests, NASA funded in 1995 the SEM program and designed a standard power supply. As a result, the standard SEM consists of subsystems which function together to provide containment, structural support, power, experiment command and data storage capabilities for experiment support. This new functional capability/availability of the carrier system permitted the students to focus their energies on creating their own experiments. The very first flight of the SEM system, SEM-1, took place on STS-80 (Nov. 19 - Dec. 7, 1996) with many experiments, built by students in cooperation with their mentors of various High Schools and Universities across the USA.

- Commercial spaceborne imaging missions with high-resolution data (1 m) have been introduced in the latter nineties (1998) by several companies and/or consortia (Space Imaging EOSAT, Earthwatch, Resource 21, OrbView, etc.). The consortia provide also a full ground segment with corresponding archives and services. Their imaging products are being offered to anyone who pays for the service. The provision of commercial imaging is considered a major shift in Earth observation policies - from government-sponsored research institutes toward private enterprise.

- Underwater/spacelaunch. July 7, 1998, a Russian nuclear submarine of the Northern Fleet launched two environmental nanosatellites, TUBSAT-N and -N1 of the Technical University of Berlin, into Earth orbit (launch site of western Barents Sea). The launch represents the world’s first underwater/spacelaunch of a satellite into Earth orbit on the basis of a commercial service.

- First commercial satellite constellations in LEO (Low Earth Orbit). In 1998, the first two major satellite telephone systems, so-called “Big LEO Systems” of global handheld telephone service as well as mobile fax and data services, were launched. Iridium, a network developed by Motorola, completed its planned 66-spacecraft constellation in LEO, and started service. Globalstar, created by Loral, successfully launched its first 8 satellites. However, 12 other spacecraft were lost in a failure of Ukraine’s Zenit rocket. In all, Iridium featured 10 launches and Globalstar had three.
On the “Little LEO Systems” front of non-voice messaging and data relay (i.e. store & forward) services, ORBCOMM of Dulles VA, had the complete constellation of 35 satellites in orbit (with altitudes of 825 km) on Dec. 4, 1999. The initial launch of this constellation started on April 3, 1995. The ORBCOMM System is a wide area, packet switched, two-way data communication system. Communications to and from Subscriber Communicators (SCs) and the geographically distributed ORBCOMM Gateways are accomplished via the LEO constellation of microsatellites (43 kg).

- Cooperation contracts with on-the-job training of customer engineers for Earth observation missions. In 1999, EADS—Astrium started the practice of on-the-job training of engineers of foreign national organizations in cooperative programs. The first customer was NSPO (National Space Program Office) of Taiwan with an order for ROCSat-2, which was later renamed to FormoSat-2 (launch May 20, 2004). This was followed with KOMPSAT-2 and COMS-1 (Communication, Ocean and Meteorological Satellite-1) spacecraft contracts of Korea, with the THEOS (Thailand Earth Observation System) spacecraft for Thailand, and with the AISAT-2 program for Algeria. AISAT-2 consists of 2 high-resolution imaging minisatellites, about 25 engineers from Algeria are participating in a 32 month training program at EADS. In Feb. 2006, EADS Astrium SAS signed a contract with CNTS (Centre National des Techniques Spatiales) of Arzew (Algiers), Algeria. 2059)

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1.14 Start of International Cooperation

The space age in general and Earth observation in particular turned out to be a natural field for all types of national and international cooperations/participations - unmatched in history. Initial cooperation (with NASA) started with permissions to operate ground stations in various countries. Later on, foreign ground station operators contributed to NASA missions through tracking and data receiving services. International cooperation in the early 1960s manifested itself also in such policies of flying sensors (experiments) of non-US scientists on NASA missions or in providing launches for foreign satellites. This evolved eventually in the common design and construction of spacecraft and instruments. In January 1970, NASA had official cooperations with agencies/institutes of 35 foreign countries (agreements of ground stations, exchange of personnel, etc. brought the total cooperations to 74 countries). Some of the first cooperations involving research satellites are listed below: \(2060\)

- Ariel-1, a product of USA/UK cooperation, was launched April 26, 1962 on a Delta vehicle from Cape Canaveral (60 kg S/C, 389 km x 1214 km inclined orbit at 54º) with the objective to measure parameters of the ionosphere and of the sun.

- Alouette-1, a Canada/USA cooperative venture, was launched September 29, 1962 from VAFB, CA aboard a Thor-Agena B launch vehicle (Alouette-1 mass = 145 kg) with the objective to investigate the ionosphere.

- San Marco-1 (mass of 24 kg), an Italian satellite, was launched December 15, 1964 with a US launcher (from a floating platform off Kenya) to investigate atmospheric densities.

- Asterix-1, the first French satellite launched on November 26, 1965 on a French launch vehicle, Diamant, from Hammaguir, Algeria (Elliptical orbit, apogee of 1736 km, perigee of 530 km, inclination of 34.3º). The 41.7 kg satellite transmitted for two days. FR-1, the first operational French satellite, was launched into a 780 km orbit on Dec. 6, 1965 on a Scout launcher from Vandenberg AFB. The satellite was used to study the ionosphere.

- WRESAT (Weapons Research Establishment Satellite), an Australian/US S/C involved the development and launch from Woomera, Australia, of a small scientific satellite (mass of 50 kg) on Nov. 29, 1967 (reentry Jan. 10, 1968). The satellite was placed in a near-polar orbit (perigee = 198 km, apogee = 1252 km, inclination = 83.3º, period = 99.3 min) by a US Redstone rocket. The objective was to monitor solar radiation in the upper atmosphere and to demonstrate an Australian capability for developing a satellite.

- ESRO-1/Aurora, an ESRO (Europe)/NASA cooperative venture (86 kg S/C mass), was launched Oct. 3, 1968 from VAFB to investigate auroras and the ionosphere. Prior to this, ESRO-2 (a 75 kg S/C) was launched on May 17, 1968 on a Scout launcher from VAFB with a payload measuring cosmic rays and solar X-rays. - ESRO-1/Boreas, almost identical to ESRO-1/Aurora, was launched Oct. 1, 1969 from VAFB and performed similar measurements simultaneously with its sister spacecraft Aurora.

- Azur-1, a German satellite (71 kg), was launched Nov. 11, 1969 on a Scout vehicle from VAFB (387 km x 3150 km sun-synchronous orbit inclined at 103º), to investigate radiation belts, solar particles and polar lights.

- ANS-1, Netherlands satellite (129 kg), launched August 30, 1974 on a Scout vehicle from VAFB, CA (258 km x 1173 km inclined orbit at 98º). ANS-1 studied UV spectra of young stars, and hard and soft X-rays from cosmic sources.

- Intasat, Spain/USA satellite, was launched November 15, 1974.

- COS-B, the first ESA/NASA satellite, was launched August 9, 1975 to investigate stellar x-ray and gamma-ray radiation.

\(2060\) W. Buedeler, “Geschichte der Raumfahrt,” Sigloch Edition, Künzelsau, 1979,
India conducted the world’s largest sociological experiment, in the mid-1970s (1975–1976), using space technology through the experimental project called SITE (Satellite Instructional Television Experiment) for which NASA provided its ATS-6 (Application Technology Satellite), a communications satellite positioned over the Indian Ocean. This enabled the direct broadcast of educational programs on agriculture, family planning, health, hygiene, etc. – to TV sets in about 2400 villages across six states of rural India. This experiment was the precursor to the establishment of the multipurpose INSAT system in the 1980s. At that time, India procured all the four satellites under the INSAT-1 series from a US company (Ford Aerospace Corporation) and three of them namely INSAT-1A, INSAT-1B, INSAT-1D were also launched by US launch vehicles.

Meteosat-1, the first geostationary ESA weather satellite, was NASA-launched on November 23, 1977.

APPLE (Ariane Passenger Payload Experiment). ISRO developed the passenger payload APPLE in 1980, a indigenously a 672 kg state-of-the-art three-axis stabilized GEO communication satellite APPLE. ESA offered to ISRO a free flight on one of Ariane’s demonstration flights in June 1981. The APPLE satellite had only one communication transponder, but the entire exercise of building a large three-axis stabilized satellite to operate in the geostationary orbit resulted in ISRO acquiring the necessary expertise that was to prove invaluable to build the indigenous second generation INSAT-2 series of satellites in the 1990s.2061)

In the USSR, the program Intercosmos was created in 1967 with the objective to invite cooperation/participation of Soviet-affiliated countries in the Soviet space program with their own national contributions. An important area of participation was in remote sensing, building sensors for specific missions, dissemination and scientific interpretation of data, etc. The new policy fostered a number of collaborative science projects among its nine members as well as with other nations. The Intercosmos satellite series began with the launch of Intercosmos-1 on October 14, 1969. The payload featured, beside Soviet, also Czech and East-German instruments for the measurement of UV and x-ray radiation in the upper atmosphere. Up to 1991, there were a total of 25 Intercosmos satellites.

The first foreign-built satellites launched from a Russian launch site, were from France.

- Aureole-1 was launched from Plesetsk by an SL-8 vehicle on Dec. 27, 1971 into an orbit of 410 km x 2500 km, inclination of 74°. S/C mass of 300 kg. Objective: study of the aurora borealis and ionosphere.
- SRET-1 was launched from Plesetsk on Apr. 4, 1972 along with the Molniya-1 spacecraft. The French satellite was placed in a 460 km x 39248 km orbit and was used to study radiation effects on solar cells.
- Aureole-2 was launched from Plesetsk by an SL-8 vehicle on Dec. 26, 1973. S/C mass of 400 kg. Orbit: 400 km x 1975 km, inclination of 74°.
- April 19, 1975. Launch of the first Indian satellite, Aryabhata of ISRO, by a Cosmos launch vehicle.
- SRET-2, a technological research and study satellite, was launched piggyback on a Molniya satellite from Plesetsk on June 5, 1975. The 29.6kg satellite was used to test the passive cryogenic radiation system for Meteosat cooling, and to study of the aging of thermal casings and plastic films.

The Soviet Union (Alexei N. Kosygin) and the USA (Richard M. Nixon) signed formal agreements of cooperation on May 24, 1972 (of talks that started in 1969) in Moscow, concerning the Apollo-Soyus Test Project (ASTP), leading to a common spaceflight (docking of both spacecraft, Apollo 18 and Soyus-19) on July 17, 1975 (the flight was from July 15 - 24).

This represented the first international meeting of men in orbit. The main objects were to test the compatibility of rendezvous and docking systems for American and Soviet spacecraft, to open the way for international space rescue as well as future joint manned flights. The Apollo spacecraft was nearly identical to the one that orbited the Moon and later carried astronauts to Skylab. The Soyuz craft was the primary Soviet spacecraft used for manned flight since its introduction in 1967. A docking module was designed and constructed by NASA to serve as an airlock and transfer corridor between the two craft.

- The Spacelab program of NASA, with over 25 missions over a period of 16 years (1983–1999) has probably generated the greatest amount of cooperation in any space program so far. Over 500 PI (Principal Investigators) were involved in the program. Their investigations have included major scientific efforts in such fields as astrophysics, atmospheric science, the life sciences, space plasma physics, and Earth observations. The Spacelab program represents the longest duration, the most multi-disciplinary and the most international of any space programs conducted so far. Until 1994, in addition to the 242 students who had completed masters or Ph.D. degrees within the Spacelab program, a few hundred government and university institutions and other organizations, had been involved at the PI level, with the degree of international participation being valued higher than on any other space program. Obviously, the number of Co-Investigators, team members and contractors was up in the thousands. Also, a number of research centers were started by a role in the Spacelab program. 2062)

- First Shuttle docking at the MIR space station. A new era of international cooperation in space began on June 30, 1995 with the docking of both S/C. The event occurred on Shuttle flight STS-71 (Atlantis, June 27 - July 7, 1995).

- International partnerships have also been very successful in solar and space physics. NASA is the lead agency for the GGS (Global Geospace Science) program which includes the WIND and POLAR satellites, both of which have important international components. Conversely, ESA is the lead agency for Ulysses, SOHO (Solar and Heliospheric Observatory) and Cluster, while ISAS of Japan is the lead for Yohkoh (Solar-A), and Geotail. Within STP (Solar Terrestrial Probes) program, NASA has the lead with TIMED and STEREO while JAXA (formerly ISAS) has the lead of Solar-B.

- In the latter part of the 1990s, the cooperations between partners in the Earth observation community have reached new dimensions. They are truly global in nature - a network of interrelations - they are so numerous and on so many levels (permeating many facets of society and affecting our every-day lives) - too complex for the scope of this writing.

- Public/private partnerships are vital for the continued growth and commercialization of the space sector. 2063) 2064) Historically, spaceborne systems have become a business only after the high-risk technologies and markets have been developed, most often through government initiatives and with public funding. First government/industrial project partnerships in the area of Earth observation were being introduced as early as 1985. The overall objective is cost-sharing of ever tighter government space budgets with commercial companies in projects that require new technology introduction. The investing companies are given some incentives (commercial data rights and/or ownership of the S/C, etc.) to recover their investments and to make a profit. An effective framework in such partnerships includes benefits to all partners. Some examples in satellite development are:

- In Sept. 1985 the US company Eosat was selected by NOAA (government) to operate the Landsat system (LS-4 and LS-5), to market LS data, and to build and launch LS-6.
- SPIN-2 venture of Russia (since 1992). SPIN-2 is a joint venture (company), located in Washington DC, of Interbranch Association SOVINFORMSPUTNIK (Moscow, Russia), Aerial Images, Inc. (Raleigh, NC), and Central Trading Systems, Inc., (Huntington Bay, NY). The objective is to market high-resolution panchromatic imagery data (2 m) of past Russian missions, in particular data from the Resurs-F series.

- RADARSAT-1 (launch Apr. 11, 1995) and RADARSAT-2 (launch in 2007) are jointly-funded SAR missions of CSA (Canadian Space Agency) and MDA (MacDonald Dettwiler and Associates Ltd. of Richmond, BC). CSA is providing approximately 75% of the funding for the development of the satellites and MDA is investing the difference. MDA owns and operates the satellites. CSA's investment will be recovered through the supply of imagery to a number of Canadian government agencies during the mission lifetime.

- OrbView-1/Microlab-1 and OrbView-2/SeaStar are commercially built and operated small satellites of OSC (Dulles, VA) flying government-sponsored instruments, OTD of NASA/MSFC and GPS/MET of UCAR in the case of OrbView-1, and SeaWiFS of GSFC on OrbView-2. Data of these instruments is provided to government agencies as well as commercially sold (SeaWiFS).

- In Europe, CNES is introducing cost-sharing programs with commercial S/C builders. The SPOT-5 satellite development is such a joint venture of CNES with French industry, namely MMS (Matra Marconi Space), now EADS Astrium SAS. Earlier S/C in the SPOT series of CNES (government) started data distribution arrangements with private companies like Spot Image. [Note: the CNES contract with EADS Astrium SAS is referred to as: Public-Private Partnership (PPP) program in which EADS Astrium SAS has a share of 47%] 2065)

- The LightSAR project of NASA was conceived as a public/industry partnership. However, in July 1999, NASA cancelled the project due to lack of interest from industry. Industry officials could not see a sufficiently large commercial market for L-band imagery (a NASA requirement) to justify the required investments. 2066)

- ISRO of Bangalore, India, announced in Nov. 2000 a new policy by inviting private sector investments with corresponding customer equipment and service-sharing arrangements on its GEO program of INSAT satellites. User demand is mostly expected in the field of communications.

- TerraSAR alliance. As of 2001, Infoterra/TerraSAR is a proposed cooperative Public-Private Partnership (PPP) program between the Infoterra Company (EADS Astrium) and ESA. The fundamental objective of the Infoterra/TerraSAR initiative is to establish a self-sustaining geo-information business built on European strengths in SAR satellite technology, in SAR applications expertise and in the provision of services based on Earth observation data sources. TerraSAR is planned to be an element of the ESA Earth Watch program. The initial program calls for two satellites, featuring high-resolution X-band and L-band SAR imagery, respectively.

- The planned commercial RapidEye minisatellite constellation (launch of 5 S/C in 2007) of RapidEye AG, Munich, Germany, became a cooperative PPP on May 16, 2001 when the German government passed legislation of a new national space program. The German PPP program is managed by DLR (German Aerospace Center).

- COSMO-SkyMed (Italy) and Pleiades (France) program alliance. France and Italy signed an agreement (MOU) on Jan. 29, 2001 to jointly develop four radar satellites and two optical satellites. The first COSMO-SkyMed high-resolution radar satellite was launched on June 8, 2007. Pleiades is the SPOT successor program of CNES. The first two high-resolution optical satellites are planned for launch in 2009 and 2010. COSMO-SkyMed as well as Pleiades are also proposed PPP programs within ESA's Earth Watch and GMES initiatives.

2065) Note: In a general PPP scheme the business aspect of a mission becomes a critical element of the entire program, including the space segment, the ground segment, as well as the service sector.

At the start of the 21 century,\textsuperscript{2067} success of international cooperation among and between the world's space agencies is based on the following principles, according to William Barry of NASA (formulated at the IAF Specialists’ Symposium, Paris, France, Dec. 3-5, 2001):

- Mutual efforts to understand each other and keep an eye on the common objectives
- A willingness to invest in each other — it is not only money, it is also an investment in human capital and relationships crucial to successful cooperation
- An openness, understanding and patience that leads to higher levels of mutual trust and shared success.

NOAA weather satellite on loan to JMA (Japan Meteorological Agency).\textsuperscript{2068} In May 2002, NOAA announced that the US has agreed to lend Japan a geostationary environmental satellite to ensure weather data from the Western Pacific are available continuously should a weakening Japanese satellite fail. GOES-9 could be placed in an orbit over the Western Pacific region. The GOES-9 backup service is needed for JMA's GMS-5 which is past its expected operational life (GMS-5 was launched in 1995). GOES-9 started its backup service in April 2003. The replacement follow-on S/C, MTSAT-1R (Multifunctional Transportation Satellite-1 Replacement), was launched Feb. 26, 2005. GOES-9, also launched in 1995, does not meet US weather forecasting requirements, but does have sounding and limited imaging capabilities which supplying data comparable to that of the GMS-5. The loan of this satellite set the stage for long-term mutual backup arrangements between the United States and Japan.

The India—US Joint Working Group (JWG) on Civil Space Cooperation held its first meeting at Antariksh Bhavan, the Headquarters of ISRO at Bangalore during June 29–30, 2005. This Joint Working Group was constituted as a follow up to the India—United States Conference on Space Science, Applications and Commerce held in Bangalore during June 21–25, 2004. The JWG explored the potential and possibility of cooperation in Earth observation, satellite communication, satellite navigation and its application, space science, natural hazards research and disaster management support, and education and training in space. These topics were identified based upon the vision document on strengthening India—US cooperation issued at the end of the June 2004 Bangalore Conference.

The DMC (Disaster Monitoring Constellation) program of SSTL (Surrey Satellite Technology Ltd), UK, is a showcase of international collaboration success with a number of countries participating in the constellation: Algeria, China, Nigeria, Thailand, Turkey and the United Kingdom. The first launch of the DMC series started on Nov. 28, 2002 with Al-Sat-1. As of fall 2005, the DMC contains 5 microsatellites in one orbital plane observing the entire Earth on a daily basis with wide-swath medium-resolution imagery (32 m). The program gave several of the participating countries a chance to establish a first immediate national asset in space. The DMC satellites were developed as cooperative projects at SSTL and included technology transfer and on-the-job training. The well-trained staff of engineers of each country was able to operate their new microsatellite, to participate in a network of spacecraft, and to go on with further projects of their own. DMC represents a novel form of international collaboration — a satellite constellation where each satellite is owned by a different country. By purchasing a single satellite, the owning country has the added benefit of being part of a constellation. Not only does this provide benefits such as vastly improved data timeliness (daily revisits of medium-resolution optical imagery on a global scale), it also allows the costs of the operational and exploitation systems to be shared amongst the participating countries.

The International Charter "Space and Major Disasters" was founded in July 1999 by ESA and CNES, followed by CSA (Canadian Space Agency) in Oct. 1999. In Sept. 2001,
NOAA and ISRO (Indian Space Research Organization) also became members of the Charter. The Argentine Space Agency (CONAE) joined in July 2003. The Japan Aerospace Exploration Agency (JAXA) became a member in February 2005. The United States Geological Survey (USGS) has also joined the Charter as part of the U.S. team. BNSC/DMC became a member in November 2005.  

In April 2007, GeoEye and DigitalGlobe two American commercial satellite imagery firms, joined forces with the USGS. In May 2007, CNSA (China National Space Administration) became the newest member of the joint initiative.

The objective of the International Charter is to provide a unified system of space data acquisition and delivery to those affected by natural or man–made disasters through Authorized Users. Each member agency has committed resources to support the provisions of the Charter and thus is helping to mitigate the effects of disasters on human life and property.

The International Charter was declared formally operational on November 1, 2000. An Authorized User can now call a single number to request the mobilization of the space and associated ground resources (RADARSAT, ERS, ENVISAT, SPOT, IRS, SAC–C, NOAA satellites, LANDSAT, ALOS, DMC satellites and others) of the member agencies to obtain data and information on a disaster occurrence.

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2069) [http://www.disasterscharter.org/main_e.html](http://www.disasterscharter.org/main_e.html)
2070) [http://www.esa.int/esaEO/SEMCG59RR1F_environment_0.html](http://www.esa.int/esaEO/SEMCG59RR1F_environment_0.html)
1.15 A brief overview of the EMS (Electromagnetic Spectrum)

**Spectral regions.** The EMS (Electromagnetic Spectrum) is a continuum extending over a wide range of energies and wavelengths: from about $10^{11}$ m (ULF waves) and $10^7$ m (very long radio waves) to about $10^{15}$ m (very short gamma rays). High-energy cosmic rays are even shorter.

For convenience, the EMS is subdivided into a number of spectral regions and subregions to suit the needs of particular applications, or for use in various fields of science. In general, there are no hard boundaries to each spectral region or subregion; they just blend into a continuum of smoothly changing wavelengths. This leads to many overlapping definitions in the literature (on all levels). The best accepted boundaries for any spectral region are probably those of visible light (0.4 - 0.7 μm), a narrow interval that can be detected by the human eye. The so-called superregions are a convenient shortcut for coverage of certain phenomena and/or use of similar instrument classes. The general boundaries of the superregions are:

- The so-called "high-energy spectrum" consists of the X-ray, gamma-ray, and cosmic-ray regions, all of which are overlapping depending on application or research objective. The high-energy radiation is mostly of the non-thermal type.
- The so-called optical spectrum extends from 0.01 μm to 1000 μm in wavelength, i.e., from the UV to the FIR regions inclusively. The infrared region (0.7 - 1000 μm) itself represents by far the greatest portion of the optical spectrum and is generally divided into a number of subregions (NIR, SWIR, MWIR, FIR). The atmospheric reflected infrared (IR, 0.7 - 3 μm) subregion, in turn, consists of the subregions NIR + SWIR. A telescope generally serves as the radiation collection aperture in an optical instrument.
- The so-called microwave region extends roughly from 1 mm to 1 m in wavelength (<300 GHz frequencies < 300 MHz)
- The so-called “radio region” or “radio frequency (RF) spectrum,” as defined by ITU (International Telecommunication Union), extends from 0.1 mm to $10^4$ km in wavelength, covering the frequency range from SMMW [Submillimeter Wave: 0.1 mm to 1 mm in wavelength] over EHF [Extremely High Frequency (30 ≤ 300 GHz)] to ELF [Extremely Low Frequency (30 ≤ 300 Hz)]. An inspection of Table 110 shows that the entire microwave region, and a portion of the optical region, are actually part of the upper-most radio region (overlap). Often, the terms “microwave region” and “radio region” are being used interchangeably (see Table 111). The reason is that most emphasis, in particular in communications, is placed into the 1 mm to 1 m wavelength range (covering the bands UHF, SHF and EHF, i.e., the microwave region). The infringement into the optical region (with SMMW) from the radio and microwave sides demonstrates only the increasing technological capabilities that are being conquered by these communities. An antenna is generally the collecting aperture for microwave or RF instruments.
- The so-called ULF waves occur virtually everywhere within the magnetosphere and at any time. They are a response to changes in the magnetosphere, and are thus evidence of its dynamic behavior. The designation ULF usually refers to waves with frequencies < 1 Hz. Waves with frequencies in the mHz range have scale sizes comparable to the size of the magnetosphere and are therefore strongly affected by the magnetospheric structure.

<table>
<thead>
<tr>
<th>Super region</th>
<th>Region or Subregion</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy</td>
<td>Cosmic rays</td>
<td>Radiation of galactic origin. Energy spectrum: from about $10^{11}$ eV - $10^{12}$ eV</td>
</tr>
<tr>
<td></td>
<td>γ-rays</td>
<td>Gamma-rays: photon energy: &gt; 400 keV; spectral range: ≤ 3 pm (0.003 nm)</td>
</tr>
<tr>
<td></td>
<td>X-rays</td>
<td>Soft x-rays: photon energy: 0.1 - 10 keV; spectral range: 0.1 - 0.1 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard x-rays: photon energy: 10 - 400 keV; spectral range: 0.1 - 0.003 nm</td>
</tr>
</tbody>
</table>
### Earth Observation History on Technology Introduction

<table>
<thead>
<tr>
<th>Superregion</th>
<th>Region or Subregion</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>UV</td>
<td>Optical: 6 - 400 nm</td>
</tr>
<tr>
<td></td>
<td>NUV</td>
<td>Near Ultraviolet: 125 - 400 nm</td>
</tr>
<tr>
<td></td>
<td>FUV</td>
<td>Far Ultraviolet: 60 - 125 nm</td>
</tr>
<tr>
<td></td>
<td>EUV</td>
<td>Extreme Ultraviolet: 6 - 60 nm (EUV, also abbreviated as XUV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The term VUV (Vacuum UV) is also used for the range: 10 &lt; λ &lt; 200 nm</td>
</tr>
<tr>
<td></td>
<td>VIS</td>
<td>Visible: 0.4 - 0.7 μm</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>Near infrared: 0.7 - 1.3 μm</td>
</tr>
<tr>
<td></td>
<td>VNIR</td>
<td>Visible/Near infrared: 0.4 - 1.3 μm, - the predominant mode of energy detection is that of reflected sunlight</td>
</tr>
<tr>
<td></td>
<td>SWIR</td>
<td>Short-Wave infrared: 1.3 - 5 μm - the predominant mode of energy detection is that of reflected sunlight</td>
</tr>
<tr>
<td></td>
<td>MWIR (also referred to as MIR)</td>
<td>Mid-Wave infrared: 3 - 6 μm - the detected energy is a mixture of solar reflected and thermally emitted radiation. MWIR offers nearly 100% atmospheric transmission, with the added benefit of lower, ambient, background noise.</td>
</tr>
<tr>
<td></td>
<td>TIR</td>
<td>Thermal infrared: 6 - 14 μm [also referred to as LIR (Long wavelength infrared)] - practically all energy received (detected) is attributed to thermal emission. LIR actually spans from 8-14 μm. The atmosphere provides nearly 100% transmission on the 9-12 μm band (window).</td>
</tr>
<tr>
<td></td>
<td>VLWIR</td>
<td>Very Long-Wave Infrared (14 - 30 μm), emissive detection</td>
</tr>
<tr>
<td></td>
<td>FIR</td>
<td>Far infrared: 30 - 1000 μm (note: 1000 μm = 1 mm). FIR radiation can be measured remotely by the thermal emission technique. A problem with this technique is instrument self-emission.</td>
</tr>
<tr>
<td></td>
<td>SMMW</td>
<td>Submillimeter wave region: 0.1 mm to 1 mm (frequency range of ≲ 3000 GHz to ≥ 300 GHz – or from ≲ 3 THz to ≥ 0.3 THz). This portion of the EMS bears an amazing scientific potential in astronomy and atmospheric research. Many fundamental absorption and emission lines of astrophysical and atmospheric important molecules and atoms occur in this spectral region. resolution spectroscopy (in particular heterodyne spectroscopy) of molecular rotational lines and fine structure lines of atoms or ions is a powerful tool which allows obtaining valuable information about the observed object such as temperature and dynamical processes as well as density and distribution of particular species.</td>
</tr>
<tr>
<td></td>
<td>MW</td>
<td>Microwave region: 1 mm - 1 m (frequency range ≲ 300 GHz to ≥ 300 MHz) - the detected energy is of microwave (thermal) emissions. Since microwave sensors do not depend on solar illumination the observations are virtually independent of aerosols and also much less affected by clouds (cirrus) than sensors operating in IR or VIS.</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>Radio frequency spectrum: 10⁴ km to 0.1 mm (30 Hz to 3000 GHz)</td>
</tr>
</tbody>
</table>

#### Table 110: Overview of spectral regions of the EMS

<table>
<thead>
<tr>
<th>ITU Designation</th>
<th>Name of Frequency Band</th>
<th>Frequency Band</th>
<th>Wavelength (λ)</th>
<th>Remarks/Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF</td>
<td>Extremely Low Frequency (Megametric waves)</td>
<td>30 &lt; 300 Hz</td>
<td>10⁴ - 100 km</td>
<td>Alternating current (50 - 60 Hz)</td>
</tr>
<tr>
<td>VF</td>
<td>Voice Frequency</td>
<td>300 Hz &lt; 3 kHz</td>
<td>10³ - 100 km</td>
<td>Voice (telephony)</td>
</tr>
<tr>
<td>VLF</td>
<td>Very-low Frequency (Myriametric waves)</td>
<td>10 &lt; 30 kHz</td>
<td>30 - 10 km</td>
<td>Radiotelegraphy</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency (Kilometric waves)</td>
<td>30 &lt; 300 kHz</td>
<td>10 - 1 km</td>
<td>Radiotelegraphy, radio</td>
</tr>
<tr>
<td>ITU Designation</td>
<td>Name of Frequency Band</td>
<td>Frequency Band</td>
<td>Wavelength (λ)</td>
<td>Remarks/Use</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------------------------------</td>
<td>----------------</td>
<td>----------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>MF</td>
<td>Medium Frequency (Hectometric waves)</td>
<td>300 &lt; 3000 kHz</td>
<td>1000 - 100 m</td>
<td>Radio, (AM radio)</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency (Decametric waves)</td>
<td>3 &lt; 30 MHz</td>
<td>100 - 10 m</td>
<td>Radiotelephony, radio navigation, amateur radio</td>
</tr>
<tr>
<td>VHF</td>
<td>Very-High Frequency (Metric waves)</td>
<td>30 &lt; 300 MHz</td>
<td>10 - 1 m</td>
<td>Radio, TV, radio navigation, radiobeacon, (FM radio)</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-High Frequency (Decimetric waves)</td>
<td>300 &lt; 3000 MHz</td>
<td>1 m - 0.1 m</td>
<td>Radio, TV, radio navigation, radiobeacon, (FM radio)</td>
</tr>
<tr>
<td>SHF</td>
<td>Super-High Frequency (Centimetric waves)</td>
<td>3 &lt; 30 GHz</td>
<td>10 - 1 cm</td>
<td></td>
</tr>
<tr>
<td>EHF</td>
<td>Extremely-High Frequency (Millimetric waves)</td>
<td>30 &lt; 300 GHz</td>
<td>10 - 1 mm</td>
<td></td>
</tr>
<tr>
<td>SMMW</td>
<td>Submillimeter Waves (Decimillimetric waves)</td>
<td>300 &lt; 3000 GHz (or 0.3 &lt; 3 THz)</td>
<td>1 - 0.1 mm</td>
<td></td>
</tr>
</tbody>
</table>

Table 111: Overview of ITU radio spectrum designations

Figure 49: Illustration of the EMS 2071)

Allocation of frequency bands in the microwave region:

The frequency bands used for space radiocommunications and SAR applications are often denoted by various letters such as C-band, L-band, S-Band, etc. This practice of denoting frequency bands by letters has its origin in early radar (radio detecting and ranging) applications. Table 112 shows the standard letter designations for radar frequency bands of ASPRS (American Society for Photogrammetry and Remote Sensing) and of IEEE (Institute of Electrical and Electronic Engineers). There are many more definitions around, depending on author or institute.

The following comments pertain to Table 112:

- The official ITU designation for UHF extends from 300 to 3,000 MHz. In radar practice, however, the upper limit is usually taken as 1,000 MHz with the L- and S-band being used to describe the higher UHF region.
- The radar UHF band is sometimes called the P-band. Note: The WRC-03 (World Radio Conference 2003) provided a new allocation for P-band SAR applications in the 432-438 MHz frequency range.
- The designation “mm-band” is derived from “millimeter wave radar”, and is also used to refer to V- and W-bands, when general information relating to the region above 40 GHz is to be conveyed.
- The sub-mm band designation of 0.1 mm - 1 mm (radar) is almost identical to the FIR (Far Infrared) region of 30 μm - 1000 μm (telescope) in the optical spectrum. This is because for some people the FIR region ends at 100 μm, and the region between 100 μm and 1 mm (1000 μm) is referred to as the ‘sub-millimeter’ region.


<table>
<thead>
<tr>
<th>Radar Band</th>
<th>Wavelength Range</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-band</td>
<td>136 - 77 cm</td>
<td>220 - 390 MHz</td>
</tr>
<tr>
<td>UHF</td>
<td>100 - 30 cm</td>
<td>300 - 1 GHz</td>
</tr>
<tr>
<td>L-band</td>
<td>30 - 15 cm</td>
<td>1 - 2 GHz</td>
</tr>
<tr>
<td>S-band</td>
<td>15 - 7.5 cm</td>
<td>2 - 4 GHz</td>
</tr>
<tr>
<td>C-band</td>
<td>7.5 - 3.75 cm</td>
<td>4 - 8 GHz</td>
</tr>
<tr>
<td>X-band</td>
<td>3.75 - 2.4 cm</td>
<td>8 - 12.5 GHz</td>
</tr>
<tr>
<td>Ku-band</td>
<td>2.4 - 1.67 cm</td>
<td>12.5 - 18 GHz</td>
</tr>
<tr>
<td>K-band</td>
<td>1.67 - 1.18 cm</td>
<td>18 - 26.5 GHz</td>
</tr>
<tr>
<td>Ka-band</td>
<td>1.18 - 0.75 cm</td>
<td>26.5 - 40 GHz</td>
</tr>
<tr>
<td>V-band</td>
<td>40 - 75 GHz</td>
<td>0.75 - 0.40 cm</td>
</tr>
<tr>
<td>W-band</td>
<td>75 - 110 GHz</td>
<td>0.40 - 0.275 cm</td>
</tr>
<tr>
<td>mm-band</td>
<td>2.75 - 1.0 mm</td>
<td>110 - 300 GHz</td>
</tr>
<tr>
<td>Sub-mm-band</td>
<td>1.0 - 0.1 mm</td>
<td>300 - 3000 GHz</td>
</tr>
</tbody>
</table>

Table 112: Radar band letter designations of ASPRS and IEEE

Radio Wave Propagation: Electromagnetic waves propagate in space at the speed of light (c), approximately 300,000 km/s. The wave amplitude varies periodically in time with frequency (f) measured in periods per second (Hz). The distance from crest to crest is the wavelength (λ), measured in meters. The relationship between these three parameters is: \( f = \frac{c}{\lambda} \)

Radio waves with frequencies of the order of 1 megahertz (MHz) can be reflected by the ionized atmosphere, or refracted when entering or coming out of these ionospheric layers, or even attenuated when crossing them. These effects, which influence the ray path, depend on the wavelength (or frequency), and the angle of incidence. Thus, radio messages can be sent to considerable distances, over the horizon and to the antipodes. Yet, some frequency limitations remain; the highest frequencies are not reflected at all. This last property makes space telecommunication possible. However, at the higher frequencies, radiation is affected by the atmospheric particles and molecules encountered, such as ice, rain drops, water vapor, and oxygen.

Relevance of spaceflight:
What makes satellite observation missions so valuable and powerful is the absence of the atmosphere in orbit, and consequently the availability of the entire electromagnetic spectrum (EMS) into the observation direction toward outer space. This fact is making spaceborne spectroscopy a very powerful tool for all astronomic observations. Naturally, the entire EMS is also available into the direction toward Earth, but only to the top of the atmosphere in its entirety.

The Earth’s atmosphere plays an important filter role for all incoming radiation, selectively controlling the passage towards the Earth’s surface of the various components of solar radiation. In the course of penetration through the atmosphere, some of the incoming radiation is either absorbed or scattered in all directions by atmospheric gases, vapors, and dust particles (aerosols).

**Figure 50:** EMS, atmospheric windows and wavelengths of maximum absorption in the atmosphere

In Earth observation missions, emission/absorption lines are being used to monitor the terrestrial atmosphere. Spectral regions of high transmittance in the EMS are referred to as atmospheric transmission bands or as atmospheric windows. The visible spectrum, a very tiny portion of the EMS, is the dominant band for surface imagery. But atmospheric windows are of great importance for passive surface observations in the infrared region as well as in the microwave region.
# 1.16 Launch table of EO missions

The following table contains the “EO” missions (in alphabetical order according to mission acronym) that were launched after the 3rd edition was published in early 1996. Excepted are Shuttle launches and GPS/GLONASS launches, each of these series has its own launch table in this volume. There is no claim for completeness.

Note: gradually, EO missions were added that took place place prior to 1996 to obtain a better overview of various satellite series.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch Date</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>Aug. 25, 1997</td>
<td>Advanced Composition Explorer, NASA/GSFC</td>
</tr>
<tr>
<td>ACRIMSAT</td>
<td>Dec. 21, 1999</td>
<td>NASA minisatellite to monitor the amount of total solar energy</td>
</tr>
<tr>
<td>ACTS</td>
<td>Sept. 12, 1993</td>
<td>ACTS (Advanced Communications Technology Satellite) of NASA, launch on STS-51 mission. The objective was to demonstrate Ka-band communications. Deactivation on Apr. 28, 2004</td>
</tr>
<tr>
<td>ADEOS</td>
<td>Aug. 17, 1996</td>
<td>Advanced Earth Observing Satellite, JAXA (formerly NASA)</td>
</tr>
<tr>
<td>AGILE (ASI) AAM (Advanced Avionics Module)</td>
<td>Apr. 23, 2007</td>
<td>Launch of an Italian astronomical satellite, 352 kg S/C; (detection of gamma ray bursts) into LEO by the PSVL vehicle of ISRO (first commercial launch of ISRO)</td>
</tr>
<tr>
<td>AIM (Aeronomy of Ice in the Mesosphere)</td>
<td>Apr. 25, 2007</td>
<td>Launch of a NASA minisatellite (210 kg) on a Pegasus-XL vehicle from VAFB, CA</td>
</tr>
<tr>
<td>ALEXIS</td>
<td>Apr. 25, 1993</td>
<td>A minisatellite technology demonstration mission of LANL, USA, Pegasus air launch</td>
</tr>
<tr>
<td>ALOS (Daichi)</td>
<td>Jan. 24, 2006</td>
<td>JAXA satellite on H-IIA launcher from TNSC, Japan</td>
</tr>
<tr>
<td>AISAT-1 (SSTL/ CNTS) Mozhayets (Russia) Rubin-3-DSI (OHB Bremen)</td>
<td>Nov. 28, 2002</td>
<td>Algerian Satellite-1 (of CNTS cooperative venture SSTL, UK, first S/C of the DMC (Disaster Monitoring Constellation) series, launch from Plesetsk, Russia on a Cosmos-3M vehicle. AISat-1 is a secondary payload to Mozhaets (or Mozhayets), a geodesy microsatellite mission designed by students of the Mozhaiskiy Military Space Engineering Academy, St. Petersburg, and built by NPO-PM. The payload contains a GLONASS/GPS receiver, a particle detector, and an amateur radio payload.</td>
</tr>
<tr>
<td>AMSAT-3D</td>
<td>Nov. 15, 2000</td>
<td>AMSAT-3D is an amateur satellite (AO-40), launched aboard an Ariane vehicle from Kourou, French Guiana</td>
</tr>
<tr>
<td>Aqua (EOS/PM-1)</td>
<td>May 4, 2002</td>
<td>NASA satellite on Delta-2 launcher from VAFB</td>
</tr>
<tr>
<td>ARGOS</td>
<td>Feb. 23, 1999</td>
<td>DoD technology satellite, launch from VAFB</td>
</tr>
<tr>
<td>Arkon-2 (Kosmos 2344)</td>
<td>July 25, 2002</td>
<td>Russian military high-resolution (1 m) optoelectronic reconnaissance mission. Launch from Baikonur on a Proton launch vehicle. Mass: 2,600 kg. orbit: 1,506 km x 1,774 km, inclin. 63.5°</td>
</tr>
<tr>
<td>ARTEMIS</td>
<td>July 12, 2001</td>
<td>ESA communication/technology spacecraft, Ariane-5 launch</td>
</tr>
<tr>
<td>Astro–E</td>
<td>Feb. 10, 2000</td>
<td>ISAS astronomy X–ray mission with XRS of NASA as prime instrument, launch on M-5 vehicle from Kagoshima island, Japan (launch failure of first stage)</td>
</tr>
<tr>
<td>Astro-E2 (Suzaku) TSD</td>
<td>July 10, 2005</td>
<td>JAXA astronomy X–ray mission, launch on M-5 vehicle from Kagoshima island, Japan (launch mass of 1,680 kg) Secondary payload (Tokyo Tech Separation system Demonstration), a CubeSat deployer, of Tokyo Institute of Technology</td>
</tr>
<tr>
<td>Astro-F (Akari, meaning 'light')</td>
<td>Feb. 21, 2006</td>
<td>JAXA/ISAS infrared astronomy satellite with a cooled telescope of 67 cm aperture diameter; launch site: Uchinoura Space Center, Japan. The CUTE-1.7 CubeSat of the Tokyo Institute of Technology, Tokyo was a secondary payload on this flight. SSO (Sun-synchronous orbit) of Astro-F at 745 km altitude.</td>
</tr>
<tr>
<td>Aura</td>
<td>July 15, 2004</td>
<td>NASA mission (EOS-Chem) on Delta-2 7920 vehicle from VAFB</td>
</tr>
<tr>
<td>BNTS-1B</td>
<td>Dec. 21, 2000</td>
<td>Launch of 2nd spacecraft with a Long March 3A from Xichang</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
<tr>
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</tr>
<tr>
<td>CALIPSO CloudSat</td>
<td>Apr. 28, 2006</td>
<td>NASA/CNES mission. Launch on a Delta-2 vehicle from VAFB, CA. The co-passenger payload was CloudSat.</td>
</tr>
<tr>
<td>CartoSat-1 (IRS-P5)</td>
<td>May 5, 2005</td>
<td>ISRO, PSLV launcher from SHAR, along with HamSat (VU-Sat) of AmSat India as secondary payload</td>
</tr>
<tr>
<td>CartoSat-2</td>
<td>Jan. 10, 2007</td>
<td>ISRO high-resolution imaging mission, Launch on PSLV-7 vehicle from SDSC Srichirikota Range, India, along with LAPAN-TUBSAT, and PehuenSat-1 (Argentina).</td>
</tr>
<tr>
<td>CBERS (ZY-1)</td>
<td>Oct. 14, 1999</td>
<td>Chinese/Brazil imaging mission</td>
</tr>
<tr>
<td>CBERS-2 (ZY-1B)</td>
<td>Oct. 21, 2003</td>
<td>China (CAST)/Brazil (INPE) mission, ZY-1B (Resource), also called CBERS-2, launch from Tyuanyun on a CZ-4B vehicle, along with CX-1 (Chuang Xing-1)</td>
</tr>
<tr>
<td>CHAMP</td>
<td>July 15, 2000</td>
<td>Challenging Minisatellite Payload (GFZ/DLR)</td>
</tr>
<tr>
<td>China DMC+4</td>
<td>Oct. 27, 2005</td>
<td>Multiple launch of micro- and picosatellites on a Cosmos-3M vehicle from Plesetsk, Russia</td>
</tr>
<tr>
<td>TopSat</td>
<td></td>
<td>Referred to a Beijing-1, 140 kg EO satellite for DMC of SSTL, EO satellite (108 kg) of QinetiQ, UK</td>
</tr>
<tr>
<td>SSATI</td>
<td></td>
<td>European student satellite (80 kg, coordinated at ESA)</td>
</tr>
<tr>
<td>Mozahayets-5</td>
<td></td>
<td>Russian Geodesy, Education, Amateur Radio S/C (64 kg)</td>
</tr>
<tr>
<td>Sinah-1</td>
<td></td>
<td>Iranian Research Organisation for Science &amp; Technology (20 kg)</td>
</tr>
<tr>
<td>UWE-1</td>
<td></td>
<td>CubeSat of U. of Würzburg, released from SSATI (1 kg)</td>
</tr>
<tr>
<td>NCube-2</td>
<td></td>
<td>CubeSat of Norsk Romsenter, Norway, released from SSATI</td>
</tr>
<tr>
<td>Xi = V</td>
<td></td>
<td>CubeSat of U. of Tokyo, Japan, released from SSATI</td>
</tr>
<tr>
<td>Rubin-5</td>
<td></td>
<td>Messaging and Science S/C of OHB, Bremen, Germany</td>
</tr>
<tr>
<td>CloudSat</td>
<td>Apr. 28, 2006</td>
<td>A NASA/CSA mission. Launch on a Delta-2 from VAFB, CA; The co-passenger payload was CALIPSO.</td>
</tr>
<tr>
<td>Clementine</td>
<td>Apr. 25, 1994</td>
<td>DoD/NASA joint lunar mission. Launch on a Titan-2G from VAFB, CA</td>
</tr>
<tr>
<td>Cluster-1</td>
<td>June 4, 1996</td>
<td>ESA, launch failure (4 spacecraft)</td>
</tr>
<tr>
<td>Cluster-2</td>
<td>July 16, 2000</td>
<td>ESA, two S/C were launched at a time</td>
</tr>
<tr>
<td>Compass-1</td>
<td>Dec. 10, 2001</td>
<td>Compass-1 experienced uncontrolled behavior</td>
</tr>
<tr>
<td>Compass-2</td>
<td>May 26, 2006</td>
<td>Compass-1 microsatellite of IZMIRAN, Russia; Secondary payload to Meteor-3M-1; COMPASS-1 experienced uncontrolled behavior</td>
</tr>
<tr>
<td>Contour</td>
<td>July 3, 2002</td>
<td>IZMIRAN microsatellite, Russia, launch on a nuclear-powered submarine in the Barents Sea</td>
</tr>
<tr>
<td>CoRiolar (P98-2)</td>
<td>Jan. 6, 2003</td>
<td>NRL-IPO satellite (with WindSat payload), launch with Titan-2 from VAFB</td>
</tr>
<tr>
<td>Coronas-F</td>
<td>July 31, 2001</td>
<td>Russian and KNAU (Ukraine) solar physics mission</td>
</tr>
<tr>
<td>CoRoT</td>
<td>Dec. 27, 2006</td>
<td>CNES-led astronomy mission, launch on a Soyuz-Fregat vehicle from Baikonur, Kazakhstan (detection of exoplanets)</td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>June 8, 2007</td>
<td>Italian SAR mission of ASI and the Italian Ministry of Defense. Launch from VAFB, CA, on a Delta-2 vehicle. This represents the launch of the first S/C of a four S/C constellation.</td>
</tr>
<tr>
<td>CRISTA-SPAS-2</td>
<td>Aug. 7-19, 1997</td>
<td>STS-85</td>
</tr>
<tr>
<td>CryoSat</td>
<td>Oct. 8, 2005</td>
<td>ESA Earth Explorer Opportunity Mission-1 from Plesetsk, Russia, launch failure of Rockot-KM due separation problems between 2nd and 3rd stages</td>
</tr>
<tr>
<td>CubeSats (14)</td>
<td>July 26, 2006</td>
<td>Launch of smallsats on a Dnepr-1 launch vehicle from Baikonur, Kazakhstan, launch failure after 2 minutes of flight. The following CubeSats were flown: ION (U. of Illinois), Sacred (U. of Arizona), KUTESat (Kansas U.), ICEnet-1, -2 (Cornell U.), Rincon (U. of Arizona), SEEDS (Nihon U.), HAUSat-1 (Han- kuk Av. U.), nCube-1 (Norsk Romsenter), Merope (Montana St. U.), AeroCube-1 (Aerospace Corp.), PolySat-1, -2 (CalPoly), and Voyager (U. of Hawaii); additional smallsats on the flight were: Belka (IKK Energia), Baumanets (NPO Mash), UniSat-4 (U. of Rome), and PicoPot (U. of Torino)</td>
</tr>
<tr>
<td>CubeSats (7)</td>
<td>April 17, 2007</td>
<td>Launch of 14 smallsats on a Dnepr-1 launch vehicle from Baikonur, Kazakhstan. Seven CubeSats were flown: PolySat-3 and PolySat-4 of CalPoly; AeroCube-2 of The Aerospace Corporation; CSTB-1 of the Boeing Company; CAPE-1 of the University of Louisiana; MAST of Stanford and TUI; and Libertad-1 of the University of Sergio Arboleda, Columbia</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
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<tr>
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</tr>
<tr>
<td>CUTE-1.7</td>
<td>Feb. 21, 2006</td>
<td>CUTE-1.7 is a secondary payload (CubeSat) of the Tokyo Institute of Technology, Tokyo, Japan; launched on an M-5 vehicle from the Uchinoura Space Center, Japan. The prime payload on this flight was Astro-F (960 kg) of JAXA/ISAS</td>
</tr>
<tr>
<td>DMC microsatellite constellation, STSAT-1, Mozhayets-4, Rubin-4-DSI, Larets (Russia)</td>
<td>Sept. 27, 2003</td>
<td>Multi-satellite launch on a Cosmos-3M vehicle from Plesetsk, Russia; Three S/C of STSAT's DMC constellation, consisting of BilSat-1 (Turkey), NigeriaSat-1 and UK-DMC; STSat-1 (formerly KAISTsat-4) of KAIST, Korea; Mozhayets-4 of Russia, Rubin-4-DSI of OHB-System, Germany, and Larets of Russia</td>
</tr>
<tr>
<td>Deep Space 1 (DS1)</td>
<td>Oct. 24, 1998</td>
<td>DS1 is the first mission with ion propulsion, NASA/JPL</td>
</tr>
<tr>
<td>DEMETER, Saudisat-2, AMSat OE (Echo), Latin Sat-C, Latin Sat-D, Saudiscosat1, Saudiscosat2, Umsat-3</td>
<td>June. 29, 2004</td>
<td>Multiple launch of micro- and nanosatellites on Dnepr-LV vehicle from Baikonur</td>
</tr>
<tr>
<td>DMSP, 5D-2 F-12</td>
<td>Aug. 29, 1994</td>
<td>DoD/USAF meteorology satellite, launch from VAFB</td>
</tr>
<tr>
<td>DMSP, 5D-2 F-13</td>
<td>Mar. 24, 1995</td>
<td>DoD/USAF meteorology satellite, launch from VAFB</td>
</tr>
<tr>
<td>DMSP, 5D-2 F-14</td>
<td>Apr. 4, 1997</td>
<td>DoD/USAF meteorology satellite, launch from VAFB</td>
</tr>
<tr>
<td>DMSP, 5D-3 F-15</td>
<td>Dec. 12, 1999</td>
<td>launch aboard a Titan 2 rocket from VAFB,</td>
</tr>
<tr>
<td>DMSP, 5D-3, F-16</td>
<td>Oct. 18, 2003</td>
<td>DoD/USAF meteorology satellite, launch aboard a Titan 2 rocket from VAFB (launch mass of 1154 kg)</td>
</tr>
<tr>
<td>DMSP, 5D-3, F-17</td>
<td>Nov. 4, 2006</td>
<td>DoD/USAF meteorology satellite, launch aboard a Delta-4 (EELV) rocket from VAFB (launch mass of 1154 kg)</td>
</tr>
<tr>
<td>DRTS</td>
<td>Sept. 10, 2002</td>
<td>JAXA Data Relay Test Satellite-(90ºE) from Tanegashima with H-IIB-F3 vehicle. The secondary payload was USERS (Unmanned Space Experiment Recovery System), a separate S/C</td>
</tr>
<tr>
<td>DSI (Deep Sapce1)</td>
<td>Oct. 24, 1998</td>
<td>NASA technology demonstration mission, launch from Cape Canaveral on a Delta launcher. SEDSAT-1 as secondary payload</td>
</tr>
<tr>
<td>DSP-1 (TC-1)</td>
<td>Dec. 29, 2003</td>
<td>Launch of Double Star Project-1 of CNSA/ESA from Xichang</td>
</tr>
<tr>
<td>DSP-2 (TC-2)</td>
<td>July 26, 2004</td>
<td>Launch of Double Star Project-2 of CNSA/ESA from Taiyuan, China</td>
</tr>
<tr>
<td>EarlyBird</td>
<td>Dec. 24, 1997</td>
<td>EarthWatch controllers lost contact with the S/C on Dec. 28, 97</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Mar. 1, 2002</td>
<td>ESA, Ariane-5 launch from Kourou (direct SSO launch)</td>
</tr>
<tr>
<td>EO-1</td>
<td>Nov. 21, 2000</td>
<td>Earth Observing-1 of NASA</td>
</tr>
<tr>
<td>Equator-S</td>
<td>Dec. 2, 1997</td>
<td>MPI Garching, DLR</td>
</tr>
<tr>
<td>EROS-A</td>
<td>Jan. 22, 1998</td>
<td>West Indian Space Ltd., Cayman Islands, Shavit launcher failure from Palmachim, Israel</td>
</tr>
<tr>
<td>EROS-A</td>
<td>Dec. 5, 2000</td>
<td>Commercial imagery of ImageSat International</td>
</tr>
<tr>
<td>EROS-B</td>
<td>Apr. 25, 2006</td>
<td>Launch of commercial imaging satellite of ImageSat International on Start-1 launcher (350 kg) from Svobodny, Russia</td>
</tr>
<tr>
<td>ERS-1</td>
<td>July 17, 1991</td>
<td>ESA mission (launch mass of 2300 kg), Ariane-4, Kourou</td>
</tr>
<tr>
<td>ERS-2</td>
<td>Apr. 21, 1995</td>
<td>ESA mission (launch mass of 2300 kg), Ariane-4, Kourou</td>
</tr>
<tr>
<td>ETS-VII</td>
<td>Nov. 27, 1997</td>
<td>Technology mission of JAXA (formerly NASA), along with TRMM of NASA from Tanegashima, Japan</td>
</tr>
<tr>
<td>ETS-VIII</td>
<td>Dec. 18, 2006</td>
<td>Technology mission of JAXA. Launch on a H-2A vehicle from Tanegashima, Japan</td>
</tr>
<tr>
<td>FAISAT-2V</td>
<td>Sept. 24, 1997</td>
<td>Data collection, communication</td>
</tr>
<tr>
<td>FalconSat-1</td>
<td>Jan. 27, 2000</td>
<td>Microsatellite of US Air Force Academy. Launch on a Pegasus vehicle from VAFB, CA. FalconSat-1 experienced a power failure shortly after deployment</td>
</tr>
<tr>
<td>FalconSat-2</td>
<td>Mar. 24, 2006</td>
<td>Microsatellite of US Air Force Academy. Launch on Falcon-1 launch vehicle of SpaceX. Launch failure on maiden flight of Falcon-1 from the Kwajalein Atoll (Marshall Islands, Pacific)</td>
</tr>
<tr>
<td>FASat-Bravo</td>
<td>July 10, 1998</td>
<td>Microsatellite of Chile built by SSTL (secondary payload to RESURS-O-4)</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
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</tr>
<tr>
<td>FAST</td>
<td>Aug. 21, 1996</td>
<td>NASA/GSFC mission within SMEX</td>
</tr>
<tr>
<td>FedSat</td>
<td>Dec. 14, 2002</td>
<td>Australian satellite of CSIRO, secondary payload to ADEOS-II</td>
</tr>
<tr>
<td>FORTE</td>
<td>Aug. 29, 1997</td>
<td>Fast On-Orbit Recording of Transient Events, LANL, SNL</td>
</tr>
<tr>
<td>FY-1C</td>
<td>May 10, 1999</td>
<td>Feng-Yun-1C, China (along with SJ-5)</td>
</tr>
<tr>
<td>FY-1D, HY-1A</td>
<td>May 15, 2002</td>
<td>CAST (China), both S/C were launched from Taiyuan. FY-1 is a meteorological S/C in LEO. HY-1A (Haiyang-1/Ocean-1) is an ocean observation satellite.</td>
</tr>
<tr>
<td>FY-2B</td>
<td>June 10, 1997</td>
<td>Launch of GEO weather satellite of China (CASC)</td>
</tr>
<tr>
<td>FY-2 (Fen Yun-2)</td>
<td>June 26, 2000</td>
<td>Launch of GEO weather satellite of China (CASC)</td>
</tr>
<tr>
<td>FY-2C</td>
<td>Oct. 19, 2004</td>
<td>Launch of GEO weather satellite of China on a CZ-3A vehicle from Xichang Launch Site, China</td>
</tr>
<tr>
<td>FY-2D</td>
<td>Dec. 8, 2006</td>
<td>Launch of GEO weather satellite of China on a CZ-3A vehicle from Xichang Launch Site, China</td>
</tr>
<tr>
<td>Genesis–1</td>
<td>July 12,2006</td>
<td>Technology demonstration flight of an inflatable S/C of Bigelow Aerospace. Launch on a Dnepr–1 vehicle from Yasny, Russia</td>
</tr>
<tr>
<td>Genesis–2</td>
<td>June 28, 2007</td>
<td>Technology demonstration flight of an inflatable S/C of Bigelow Aerospace. Launch on a Dnepr–1 vehicle from Yasny, Russia</td>
</tr>
<tr>
<td>GeneSat-1</td>
<td>Dec. 16, 2006</td>
<td>A CubeSat of NASA/ARC and various universities (a secondary payload to TaceSat-2). Minotaur launch from Wallops Island, VA</td>
</tr>
<tr>
<td>Genesis</td>
<td>Aug. 8, 2001</td>
<td>NASA, Solar wind sample return mission</td>
</tr>
<tr>
<td>Genesis PFD-1</td>
<td>July 12, 2006</td>
<td>A privately built and financed habitable structure of Bigelow Aerospace (entrepreneur Robert Bigelow). It is intended to be available for research, manufacturing and other uses, including lodging for future space tourists. Launch on a Dnepr–1 vehicle from Dombarovskiy Missile Site, Yasny (Siberia), Russia.</td>
</tr>
<tr>
<td>GeoLITE</td>
<td>May 18, 2001</td>
<td>NRO technology demonstration mission (LaserCom, UHF communication payload), launch from Cape Canaveral on Delta–2</td>
</tr>
<tr>
<td>GEOS–1, Explorer 29</td>
<td>Nov. 6, 1965</td>
<td>NASA Geodetic S/C, launch from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>GEOS–2, Explorer 36</td>
<td>Jan. 11, 1968</td>
<td>NASA Geodetic S/C, launch from VAFB, CA</td>
</tr>
<tr>
<td>GEOS–3</td>
<td>April 9, 1975</td>
<td>NASA Geodynamics Experimental Ocean Satellite, VAFB, CA</td>
</tr>
<tr>
<td>GEOS–1</td>
<td>April 20, 1977</td>
<td>ESA Geostationary Scientific Satellite, launch from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>GEOS–2</td>
<td>July 14, 1978</td>
<td>ESA Geostationary Scientific Satellite, launch from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>GIOVE-A</td>
<td>Dec. 28, 2005</td>
<td>Successful launch of the first European navigation satellite (Galileo In-Orbit Validation Element-A) from Baikonur, Kazakhstan, into MEO (Medium Earth Orbit), built by SSTL for ESA</td>
</tr>
<tr>
<td>GOES-8 (I)</td>
<td>Apr. 13, 1994</td>
<td>GOES-8 was at 75º W, working nearly 9 years; as of Jan. 2004, GOES-8 is on standby in an inclined orbit, still potentially useful. GOES-8 was deactivated in May 2004 and placed into a disposal orbit 350 km above its GEO position</td>
</tr>
<tr>
<td>GOES-9 (J)</td>
<td>May 23, 1995</td>
<td>GOES-I to -M S/C were built by SS/L; Deactivated in Aug. 1998, due to failing bearings in the momentum wheels. Since Apr. 2003, GOES-9 is providing backup service for GMS-5 of Japan</td>
</tr>
<tr>
<td>GOES-10 (K)</td>
<td>Apr. 25, 1997</td>
<td>NASA launch on Atlas-1 vehicle from Cape Canaveral</td>
</tr>
<tr>
<td>GOES-11 (-L)</td>
<td>May 3, 2000</td>
<td>NASA launch of NOAA weather satellite</td>
</tr>
<tr>
<td>GOES-12 (M)</td>
<td>July 23, 2001</td>
<td>NASA launch of NOAA weather satellite on Atlas-II vehicle from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>GOES-13 (N)</td>
<td>May 24, 2006</td>
<td>NASA launch of NOAA weather satellite on a Delta–4 vehicle from Cape Canaveral Air Force Station, FLA</td>
</tr>
<tr>
<td>GOMS</td>
<td>Oct. 31, 1994</td>
<td>Geostationary weather satellite of Russia. Launch on a Proton vehicle from Baikonur, Kazakhstan, launch mass of 2400 kg</td>
</tr>
<tr>
<td>GRACE</td>
<td>Mar. 17, 2002</td>
<td>US-German dual-minisatellite mission (launch from Plesetsk)</td>
</tr>
<tr>
<td>Gravity Probe-A (GP-A)</td>
<td>June 18, 1976</td>
<td>Scout-D launch vehicle from Wallops Island, VA. The probe attained a ballistic (sub-orbital) flight path with an apogee of 10,000 km (measurement time of 1 hour 55 minutes).</td>
</tr>
<tr>
<td>Gravity Probe-B (GP-B)</td>
<td>April 20, 2004</td>
<td>GP-B is a NASA and Stanford University fundamental science mission, launch on a Delta-2 vehicle from VAFB, CA</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
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</tr>
<tr>
<td>Helios-1A</td>
<td>July 7, 1995</td>
<td>Military reconnaissance S/C of France, Italy and Spain</td>
</tr>
<tr>
<td>Helios-1B</td>
<td>Dec. 3, 1999</td>
<td>Military reconnaissance S/C of France, Italy and Spain, Ariane-4 launch, Clementine (built by SSTL) was a secondary S/C</td>
</tr>
<tr>
<td>HESSI (RHESSI)</td>
<td>Feb. 5, 2002</td>
<td>NASA solar physics mission, Pegasus XL launch</td>
</tr>
<tr>
<td>HST (Hubble Space Telescope)</td>
<td>April 24, 1990</td>
<td>NASA/ESA astronomy mission, launch on Space Shuttle Discovery (STS-31). Deployed into LEO, average altitude of 600 km, inclination of 28.5º</td>
</tr>
<tr>
<td>Inaugural flight of heavy lift launcher. HLVOLSDP 3CSat-1 (Sparkie) 3CSat-2 (Ralphie)</td>
<td>Dec. 21, 2004</td>
<td>Multiple launch of microsatellites on a Delta 4H/4050H vehicle (maiden flight) of Boeing from Cape Canaveral, FLA Demosat (dummy payload) of US Air Force (5993 kg) Technology demonstration of New Mexico State University Technology demonstration of University of Colorado, Boulder The 3CSat microsatellites did not reach the orbit. Demosat did not reach its intended geostationary orbit.</td>
</tr>
<tr>
<td>HY-1A</td>
<td>May 15, 2002</td>
<td>China, HY-1A (Haiyang-1/Ocean-1) is an ocean observation S/C, launch from Taiyuan launch site in China</td>
</tr>
<tr>
<td>HY-1B</td>
<td>April 11, 2007</td>
<td>China, HY-1B was developed by DFH of CAST, launch from Taiyuan on an LM-2C vehicle</td>
</tr>
<tr>
<td>ICESat/CHIPSat</td>
<td>Jan. 13, 2003</td>
<td>NASA launch on Delta-2 from VAFB, CHIPSat is a secondary microsatellite of UCB/SSL, built by SpaceDev Inc., Poway, CA</td>
</tr>
<tr>
<td>IGS-1a (optical) IGS-1b (radar)</td>
<td>March 28, 2003</td>
<td>JAXA launch of first Japanese military reconnaissance mission (optical and SAR), H2A vehicle from Tanegashima, Japan, both S/C have an orbit of about 492 km in altitude</td>
</tr>
<tr>
<td>IGS-2a (optical) IGS-2b (radar)</td>
<td>Nov. 29, 2003</td>
<td>Japanese military reconnaissance missions (optical and SAR), H2A vehicle from Tanegashima (launch failure)</td>
</tr>
<tr>
<td>IGS – 2a(?) (optical) IGS – 2b(?) (radar)</td>
<td>Feb. 24, 2007</td>
<td>Japanese military reconnaissance missions (optical and SAR), H2A vehicle from Tanegashima (to make up for the launch failure on Nov. 23, 2003)</td>
</tr>
<tr>
<td>Ikonos-1</td>
<td>Apr. 27, 1999</td>
<td>Space Imaging, launch failure</td>
</tr>
<tr>
<td>Ikonos-2</td>
<td>Sept. 24, 1999</td>
<td>A remote sensing mission of Space Imaging, Thornton, CO; launch on an Athena vehicle from VAFB, CA</td>
</tr>
<tr>
<td>IMAGE</td>
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<td>JERS-1</td>
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<td>KOMPSAT-1</td>
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<td>KOMPSAT-2</td>
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<td>Landsat-2</td>
<td>Jan. 22, 1975</td>
<td>NASA S/C, launch from VAFB, CA on a Delta 2914 vehicle</td>
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<td>Landsat-3</td>
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<td>NASA S/C, launch from VAFB, CA on a Delta 2914 vehicle</td>
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<td>Landsat-4</td>
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<td>Landsat-5</td>
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<td>Landsat-6</td>
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<td>Landsat-7</td>
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<td>Mars Express</td>
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<td>MDS-1 (Tsubasa)</td>
<td>Feb. 4, 2002</td>
<td>NASA H-2A vehicle test launch with two payloads: NASA's MDS-1 technology mission in GTO; and an ISAS vehicle</td>
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<td>MegSat-0</td>
<td>April 28, 1999</td>
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<td>ESA, launch on a Thor-Delta vehicle from Cape Canaveral</td>
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<td>Meteosat-2</td>
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<td>Meteosat-3</td>
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<td>ESA/EUMETSAT, launch on Ariane from Kourou</td>
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<td>ESA/EUMETSAT, launch on Ariane from Kourou</td>
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<td>Meteosat-5</td>
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<td>In 1998 repositioning to 65º East for INDOEX campaign support. As of 2002, Meteosat-5 continues the Indian Ocean Data Coverage Service at 63º E.</td>
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<td>Meteosat-6</td>
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<td>Meteosat-7</td>
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<td>ESA/EUMETSAT, operational as of 2004</td>
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<td>Meteosat-8 (MSG-1)</td>
<td>Aug. 28, 2002</td>
<td>Launched as MSG-1; it became Meteosat-1 in Jan. 2004 when declared to be operational (after the commissioning phase)</td>
</tr>
<tr>
<td>MetOp-A</td>
<td>Oct. 19, 2006</td>
<td>Launch of the first polar orbiting meteorological S/C of EU-METSAT from Baikonur, Kazakhstan on a Soyuz-2 – 1A</td>
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<tr>
<td>MetSat-1</td>
<td>Sept. 12, 2002</td>
<td>ISRO (India) from SHAR (replacement of INSAT-2E), PSLV launch into GTO</td>
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<tr>
<td>MightySat II.1</td>
<td>July 19, 2000</td>
<td>AFRL technology S/C with ten technologies and FTHSI</td>
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<td>Mission</td>
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<tr>
<td>MIMOSA, MOST, CubeSats (6)</td>
<td>June 30, 2003</td>
<td>MIMOSA (Czech Republic), MOST of CSA; all S/C have been launched on Rockot KS of Eurockot from Plesetsk, Russia; the CubeSats are: -XI (Univ. of Tokyo), CUTE-1 (Tokyo Institute of Technology), CanX-1 (U. of Toronto), AAUSat (Aalborg U. Denmark), DTUSat (Technical U. of Denmark), QuakeSat (Stanford U.), Monitor E mock-up (GKNPT Khrunichev)</td>
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<td>MINISAT-01</td>
<td>April 21, 1997</td>
<td>INTA of Spain,</td>
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<td>MITA</td>
<td>July 15, 2000</td>
<td>MITA (Minisatellite Italiano di Technologia Avanzata)</td>
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<td>Monitor–E</td>
<td>June 30, 2003</td>
<td>Launch on a Rocket KS vehicle of Eurockot from Plesetsk, Russia (along with MIMOSA, MOST, and 6 CubeSats). Monitor–E was a mock-up spacecraft of GKNPT Khrunichev Space Center, Moscow, Russia with a mass of 700 kg. The payload Monitor–E remained on the upper stage of the launch vehicle.</td>
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<tr>
<td>Monitor–E1</td>
<td>Aug. 26, 2005</td>
<td>An Earth observation mission of Roskosmos, built by GKNPT of Moscow. Launch from Plesetsk, Russia on a Rockot–KM vehicle</td>
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<tr>
<td>MSG-1, Meteosat Second Generation</td>
<td>Aug. 28, 2002</td>
<td>EUMETSAT mission, Ariane-5 launch from Kourou along with the Eutelsat communications satellite Atlantic Bird 1</td>
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<tr>
<td>MSG-2</td>
<td>Dec. 22, 2005</td>
<td>EUMETSAT mission (2034 kg), Ariane-5 ECA launch from Kourou along with INSat-4A (3081 kg) of ISRO</td>
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<td>MSX</td>
<td>April 24, 1996</td>
<td>DoD satellite launch from VAFB</td>
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<td>MRI</td>
<td>Mar. 12, 2000</td>
<td>DOE satellite launch from VAFB (Taurus vehicle of OSC)</td>
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<td>MTSAT</td>
<td>Nov. 15, 1999</td>
<td>NASA, launch failure</td>
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<td>MTSAT-1R</td>
<td>Feb. 26, 2005</td>
<td>Japanese Meteorology and Transport satellite (in GEO), launch on H-2A vehicle from Tanegashima, Japan (into GTO)</td>
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<tr>
<td>MTSAT-2</td>
<td>Feb. 18, 2006</td>
<td>Japanese Meteorology and Transport satellite (in GEO), launch on H-2A vehicle from Tanegashima, Japan (into GTO)</td>
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<td>Nov. 21, 2000</td>
<td>IRF (Sweden) nanosatellite, secondary payload to EO-1 and SAC-C</td>
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<tr>
<td>MUSES-B/HALCA</td>
<td>Feb. 12, 1997</td>
<td>ISAS (Japan) SVLBI satellite launch on M-V rocket of ISAS from the Kagoshima Space Center, Japan. After launch MUSES-B was renamed to HALCA. HALCA is a 1st generation SVLBI mission (deployable mesh antenna of 8 m aperture)</td>
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<td>MUSES-C (Hayabusa)</td>
<td>May 9, 2003</td>
<td>JAXA (formerly ISAS) asteroid sample return mission (to asteroid 1998 SF36), launch with M-5 vehicle from Kagoshima, Japan</td>
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<td>Nadezhda-7</td>
<td>Sep. 26, 2002</td>
<td>Launch from Plesetsk launch site, COSPAS-S&amp;R SAT series</td>
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<tr>
<td>Nadezhda-6, Tsinghua-1, SNAP-1,</td>
<td>June 28, 2000</td>
<td>Launch from Plesetsk launch site, with Nadezhda-6 as prime payload (S&amp;R Sat, COSPAS), SSTL technology S/C,</td>
</tr>
<tr>
<td>Nadezhda-5</td>
<td>Dec. 10, 1998</td>
<td>Launch from Plesetsk, Russian search and rescue satellite in COSPAS-S&amp;R SAT series</td>
</tr>
<tr>
<td>Nimbus-1</td>
<td>Aug. 28, 1964</td>
<td>NASA, launch on a Thor-Agena-B vehicle from VAFB, CA</td>
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<td>Nimbus-2</td>
<td>May 15, 1966</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA</td>
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<td>Nimbus-3</td>
<td>Apr. 14, 1969</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA</td>
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<tr>
<td>Nimbus-4</td>
<td>Apr. 8, 1970</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA</td>
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<td>Nimbus-5</td>
<td>Dec. 11, 1972</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA</td>
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<td>Nimbus-6</td>
<td>June 12, 1975</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA</td>
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<td>Nimbus-7</td>
<td>Oct. 24, 1978</td>
<td>NASA, launch on a Thor-Agena-D vehicle from VAFB, CA; payload: CZCS, ERB, SBUV/TOMS, SAM-II, SAMS, SMMR, etc.</td>
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<td>NOAA-14 (-J)</td>
<td>Dec. 30, 1994</td>
<td>NOAA weather satellite (POES series), last S/C 4th generation</td>
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<td>NOAA-15 (-K)</td>
<td>May 13, 1998</td>
<td>NOAA weather satellite (POES), 1st S/C of 5th generation</td>
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<td>NOAA-16 (-L)</td>
<td>Sept. 21, 2000</td>
<td>NOAA weather satellite</td>
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<td>NOAA-17 (-M)</td>
<td>June 24, 2002</td>
<td>NASA/NOAA POES series S/C, launch with Titan-2 from VAFB</td>
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<tr>
<td>NOAA-18 (-N)</td>
<td>May 20, 2005</td>
<td>NASA/NOAA POES series S/C, launch with Delta-2-7320-10C vehicle from VAFB (launch mass of 1420 kg)</td>
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<td>Odin</td>
<td>Feb. 20, 2001</td>
<td>Swedish satellite for astronomical and atmospheric research</td>
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<td>Oersted</td>
<td>Feb. 23, 1999</td>
<td>DTU of Denmark S/C, Earth’s magnetic field measurements</td>
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<td>Ofeq-3 (Horizon-3)</td>
<td>April 15, 1995</td>
<td>Israel military optical imaging satellite of IAI (launch in westward direction). Ofeq-3 operated until 2001. Orbit: 370-750 km</td>
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<tr>
<td>Mission</td>
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<td>Comment</td>
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<tr>
<td>Ofeq-4</td>
<td>Jan. 22, 1998</td>
<td>Israel military optical imaging satellite of IAI, launch failure</td>
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<tr>
<td>Ofeq-5</td>
<td>May 28, 2002</td>
<td>Israel military optical imaging satellite of IAI (reconnaissance). Ofeq-5 was launched on a Shavit vehicle from the Palmachim air force base (launch in westward direction)</td>
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<tr>
<td>OICETS</td>
<td>Aug. 23, 2005</td>
<td>A JAXA technology S/C to test laser communications. Launch on a Dnepr-1 vehicle from Baikonur. Launch mass of 530 kg</td>
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<tr>
<td>Okean-E, (Cosmos-1076)</td>
<td>Feb. 12, 1979</td>
<td>USSR remote sensing satellite, launch from Plesetsk on Tsyon-3 launch vehicle</td>
</tr>
<tr>
<td>Okean-A, (Cosmos-1151)</td>
<td>Jan. 23, 1980</td>
<td>USSR remote sensing satellite, launch from Plesetsk on Tsyon-3 launch vehicle</td>
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<tr>
<td>Okean-EO-N1</td>
<td>Oct. 28, 1983</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-EO-N2</td>
<td>Oct. 28, 1984</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N1</td>
<td>July 29, 1986</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N2</td>
<td>July 16, 1987</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N3</td>
<td>July 5, 1988</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N4</td>
<td>June 9, 1989</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N5</td>
<td>Feb. 28, 1990</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N6</td>
<td>June 4, 1991</td>
<td>USSR remote sensing satellite, launch from Plesetsk</td>
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<td>Okean-O1-N7</td>
<td>Oct. 11, 1994</td>
<td>USSR remote sensing satellite, launch from Plesetsk, Russia</td>
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<td>Okean-O1-N8 (renamed Sich-1)</td>
<td>Aug. 31, 1995</td>
<td>Ukrainian/Russian remote sensing satellite, launch on a Tsyon-3 vehicle from Plesetsk, Russia</td>
</tr>
<tr>
<td>Okean-O1</td>
<td>July 17, 1999</td>
<td>Ukrainian/Russian remote sensing satellite, launch from Baikonur on a Zenit-2 vehicle</td>
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<tr>
<td>Orbview-1 (Microlab-1)</td>
<td>April 1, 1995</td>
<td>Orbimage of OSC, Dulles, VA with a NASA payload; launch on a Pegasus vehicle from VAFB, CA (launched as Microlab-1)</td>
</tr>
<tr>
<td>Orbview-2 (SeaStar)</td>
<td>Aug. 1, 1997</td>
<td>Orbimage of OSC, Dulles, VA; SeaWiFS sensor for ocean color data</td>
</tr>
<tr>
<td>Orbview-3</td>
<td>June 26, 2003</td>
<td>ORBIMAGE commercial imaging satellite (launch mass of 304 kg); launch on a Pegasus-XL vehicle from VAFB, CA</td>
</tr>
<tr>
<td>Orbview-4/ QuikTOMS</td>
<td>Sept. 21, 2001</td>
<td>Orbimage and NASA S/C on Taurus launch vehicle from VAFB. launch failure</td>
</tr>
<tr>
<td>PANSAT</td>
<td>Oct. 29, 1998</td>
<td>launch on STS-95, PANSAT was built by NPS (Naval Postgraduate School) in Monterey, CA (see N.19)</td>
</tr>
<tr>
<td>PARASOL (1) Helios-IIA Essaim (4, &quot;swarm&quot;) NanoSat-1</td>
<td>Dec. 18, 2004</td>
<td>Launch of PARASOL of CNES as secondary payload to Helios-IIA (DGA) optical reconnaissance S/C as primary payload on Ariane-5 G+ from Kourou. Other payloads are 4 microsatellites Essaim eavesdropping S/C of DGA, +NanoSat-1 of INTA</td>
</tr>
<tr>
<td>PICOSat/Starshine-3, etc.</td>
<td>Sept. 30, 2001</td>
<td>PICOSat of US AFRL (Technology S/C). Launch on Athena-1 vehicle from Kodiak Island, AK - including Sapphire of Stanford University and PCSat of USNA</td>
</tr>
<tr>
<td>POLAR</td>
<td>Feb. 24, 1996</td>
<td>NASA/GSFC solar-terrestrial mission</td>
</tr>
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<td>Priroda</td>
<td>April 23, 1996</td>
<td>Russia, module of MIR station</td>
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<td>PROBA</td>
<td>Oct. 21, 2001</td>
<td>ESA technology minisatellite, launch on PSLV from SHAR, India, secondary payload to TES of ISRO and BIRD of DLR</td>
</tr>
<tr>
<td>QuickBird-1</td>
<td>Nov. 20, 2000</td>
<td>Earthwatch, commercial imaging. launch failure</td>
</tr>
<tr>
<td>QuickBird-2</td>
<td>Oct. 18, 2001</td>
<td>DigitalGlobe of Longmont, CO (former EarthWatch Inc.) commercial imaging satellite, Delta-2 launch from VAFB</td>
</tr>
<tr>
<td>QuickSCAT</td>
<td>June 19, 1999</td>
<td>NASA/JPL, wind measurements</td>
</tr>
<tr>
<td>RADARSAT-N1</td>
<td>Nov. 24, 1995</td>
<td>CSA, Canada, NASA launch on a Delta II vehicle from Vandenberg AFB, CA</td>
</tr>
<tr>
<td>Resurs-DK1</td>
<td>June 15, 2006</td>
<td>A commercial EO imaging satellite (6650 kg) of TsSKB Progress, Samara, Russia. Launch on a Soyuz–FG rocket from Baikonur</td>
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<tr>
<td>Resurs-F</td>
<td>Nov. 18, 1997</td>
<td>launch from Plesetsk</td>
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<tr>
<td>Resurs-F-1M</td>
<td>Sept. 28, 1999</td>
<td>RKA</td>
</tr>
<tr>
<td>Resurs-O1-1</td>
<td>Oct. 3, 1985</td>
<td>USSR remote sensing satellite from Baikonur on Zenit-2 vehicle</td>
</tr>
<tr>
<td>Resurs-O1-2</td>
<td>April 20, 1988</td>
<td>USSR remote sensing satellite from Baikonur on Zenit-2 vehicle</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Resurs-O1-3</td>
<td>Nov. 4, 1994</td>
<td>RKA remote sensing satellite launched from Baikonur on Zenit-2 vehicle</td>
</tr>
<tr>
<td>Resurs-O1-4</td>
<td>July 10, 1998</td>
<td>RKA RS satellite launched on a Zenit-2 vehicle Secondary payloads: LLMS/IRIS, TMSat (Thailand), TechSat/Gurwin-II (Israel), FaSat-Bravo (Chile), SAFIR-2 (OHB), WESTPAC (Australia)</td>
</tr>
<tr>
<td>REX-2</td>
<td>March 9, 1996</td>
<td>DoD S/C launch on a Pegasus vehicle from VAFB</td>
</tr>
<tr>
<td>RHESSI (HESSI)</td>
<td>Feb. 5, 2002</td>
<td>NASA solar physics mission, Pegasus XL launch</td>
</tr>
<tr>
<td>ROCSat-1</td>
<td>Jan. 27, 1999</td>
<td>First S/C of Taiwan with an ocean color sensor</td>
</tr>
<tr>
<td>ROCSat-2 (re-named Formosat-2)</td>
<td>May 20, 2004</td>
<td>NSPO (Taiwan) remote sensing mission. Launch on Taurus XL vehicle of OSC from VAFB, CA</td>
</tr>
<tr>
<td>ROCSat-3 (re-named Formosat-2)</td>
<td>April 14, 2006</td>
<td>NSPO (Taiwan) remote sensing constellation of 6 S/C. Launch on Minotaur vehicle of OSC from VAFB, CA</td>
</tr>
<tr>
<td>Rosetta</td>
<td>March 2, 2004</td>
<td>ESA science/astronomy mission (study of the origins of comets), Launch on Ariane-5G launcher (with Comet Lander “Roland”)</td>
</tr>
<tr>
<td>SAC-A</td>
<td>Dec. 4, 1998</td>
<td>CONAE, Argentina, launched as HH payload on STS-88</td>
</tr>
<tr>
<td>SAC-C</td>
<td>Nov. 21, 2000</td>
<td>CONAE, NASA, launched as secondary payload to EO-1</td>
</tr>
<tr>
<td>SACI-1</td>
<td>Oct. 14, 1999</td>
<td>INPE, secondary payload to ZY-1 of CASC</td>
</tr>
<tr>
<td>SAR-Lupe-1</td>
<td>Dec. 19, 2006</td>
<td>German military S/C. Launch of the 1st S/C in a 5 S/C constellation from Plesetsk, Russia, on a Cosmos-3M vehicle</td>
</tr>
<tr>
<td>SAR-Lupe-2</td>
<td>July 2, 2007</td>
<td>German military S/C. Launch from Plesetsk, Russia, on a Cosmos-3M vehicle</td>
</tr>
<tr>
<td>SCD-2</td>
<td>Oct. 23, 1998</td>
<td>Data collection satellite of INPE</td>
</tr>
<tr>
<td>SCD-2A</td>
<td>Nov. 2, 1997</td>
<td>INPE, VLS launch vehicle failure from Alcantara</td>
</tr>
<tr>
<td>SciSat-1</td>
<td>Aug. 13, 2003</td>
<td>A CSA (Canada) S/C to study atmospheric ozone depletion, Pegasus-XL launch provided by NASA, from VAFB, CA</td>
</tr>
<tr>
<td>SEDSAT-1</td>
<td>Oct. 24, 1998</td>
<td>Secondary payload to DS-I, S/C of Univ. of Alabama</td>
</tr>
<tr>
<td>SERVIS-1</td>
<td>Oct. 30, 2003</td>
<td>Technology mission of USEF, Japan; launch on a Rocket-KM of Eurocet from Plesetsk, Russia, launch mass of 840 kg</td>
</tr>
<tr>
<td>Shenzhou-5 (SZ-5)</td>
<td>Oct. 15, 2003</td>
<td>First Chinese manned flight on a CZ-2F launcher from the Jiuquan Satellite Launch Center in China (14 orbits prior to reentry on Oct. 16). Shenzhou means “magic vessel or divine vessel” Yang Liwei became the first Chinese “Taikonaut”</td>
</tr>
<tr>
<td>Shiyian-1 (Tansuo-1)</td>
<td>April 18, 2004</td>
<td>Minisatellite (stereo imager) technology mission of Harbin Institute of Technology (China) with a CZ-2C vehicle from Xichang, China, S/C mass of 204 kg, orbit of 600 km, inclination 97.7°</td>
</tr>
<tr>
<td>Naxing-1</td>
<td>Aug. 31, 1995</td>
<td>Ukrainian/Russian Earth and ocean monitoring mission, launch on a Tyklot-3 vehicle from Plesetsk, Russia</td>
</tr>
<tr>
<td>Sich-1 (Okean-O1-N8)</td>
<td>Aug. 31, 1995</td>
<td>Ukrainian/Russian Earth and ocean monitoring mission, launch on a Tyklot-3 vehicle from Plesetsk, Russia (2263 kg mass of Sich-1M). Microsatellite (65 kg) of NKAU, technology demonstration</td>
</tr>
<tr>
<td>Sich-1M (Modified)</td>
<td>Dec. 24, 2004</td>
<td>Ukrainian/Russian (NKAU) Earth and ocean monitoring mission in the optical, infrared and the SHF bands. Launch on a Tyklon-3 vehicle from Plesetsk, Russia (2263 kg mass of Sich-1M). Microsatellite (65 kg) of NKAU, technology demonstration</td>
</tr>
<tr>
<td>MS-1TK (Mikron)</td>
<td>Aug. 25, 2003</td>
<td>A NASA astronomy observatory, launch on a Delta-2 from Cape Canaveral, FLA; SIRTF (Space Infrared Telescope Facility)</td>
</tr>
<tr>
<td>SIRTF (renamed to “Spitzer Space Telescope”)</td>
<td>Aug. 25, 2003</td>
<td>A CAST technology demonstration mission, launch on LM-4B vehicle from the Taiyuan launch site. SJ-5 was a secondary payload to FY-1C (meteorological payload of China)</td>
</tr>
<tr>
<td>SJ-5, China</td>
<td>May 10, 1999</td>
<td>NASA station was launched by a Saturn V booster (unmanned)</td>
</tr>
<tr>
<td>Skylab-1 (SL-1)</td>
<td>May 14, 1973</td>
<td>First manned Skylab mission. The crew conducted solar astronomy and Earth resources experiments, medical studies, and five student experiments</td>
</tr>
<tr>
<td>Skylab-2 (SL-2)</td>
<td>May 25, 1973</td>
<td>Second manned Skylab mission. Continued maintenance of the space station and extensive scientific and medical experiments</td>
</tr>
<tr>
<td>SloshSat-FLEVO</td>
<td>Feb. 12, 2005</td>
<td>A technology payload of ESA and NIVR. Launch on Ariane-5 ECA qualification flight from Kourou. Primary payloads of XTAR-EUR and MaqSat-B2 into GTO</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
<tr>
<td>--------------------</td>
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<td>-----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>SMART-1 (ESA)</td>
<td>Sept. 27, 2003</td>
<td>ESA microsatellite technology mission to the moon; launch on Ariane 5G along with INSAT-3E (ISRO) and e-Bird-1 (communication satellite of Eutelsat)</td>
</tr>
<tr>
<td>INSAT-3E</td>
<td></td>
<td>NASA/GSFC, (Fast Auroral Snapshot Explorer)</td>
</tr>
<tr>
<td>e-Bird-1</td>
<td></td>
<td>NASA/GSFC, (Transition Region and Coronal Explorer)</td>
</tr>
<tr>
<td>SNOE</td>
<td>Feb. 25, 1998</td>
<td>University of Colorado at Boulder (LASP); SNOE reentered the atmosphere on Dec. 13, 2003</td>
</tr>
<tr>
<td>Solar-A (Yohkoh)</td>
<td>Aug. 30, 1991</td>
<td>JAXA physics mission (formerly ISAS). Launch by an M-3SII-6 launch vehicle from the Kagoshima Space Center, Japan</td>
</tr>
<tr>
<td>Solar-B HIT-SAT</td>
<td>Sept. 23, 2006</td>
<td>JAXA spacecraft, on a JAXA M-V-7 launch vehicle from USC (Uchinoura Space Center), Japan Secondary payload (3 kg) of Hokkaido Institute of Technology</td>
</tr>
<tr>
<td>SORCE</td>
<td>Jan. 25, 2003</td>
<td>NASA satellite on a Pegasus XL launcher from KSC</td>
</tr>
<tr>
<td>SPOT-1</td>
<td>Feb. 22, 1986</td>
<td>CNES, launch on Ariane from Kourou</td>
</tr>
<tr>
<td>SPOT-2</td>
<td>Jan. 22, 1990</td>
<td>CNES, launch on Ariane from Kourou</td>
</tr>
<tr>
<td>ST5</td>
<td>Mar. 22, 2006</td>
<td>NASA microsatellite constellation (launch from VAFB)</td>
</tr>
<tr>
<td>STEDI/SNOE</td>
<td>Feb. 26, 1998</td>
<td>(Student Nitric Oxide Explorer), NASA, Univ. of Colorado on a Pegasus XL vehicle from VAFB, CA</td>
</tr>
<tr>
<td>STentor</td>
<td>Dec. 11, 2002</td>
<td>CNES communication technology S/C (2210 kg) on Ariane 5 vehicle (launch failure). HotBird-7 was co-passenger on launch</td>
</tr>
<tr>
<td>STEREO</td>
<td>Oct. 26, 2006 (UTC)</td>
<td>NASA Sun–Earth mission of twin S/C in heliocentric orbits, launch on Delta–2 vehicle from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>STEX/ALEX</td>
<td>Oct. 3, 1998</td>
<td>NRO technology mission launched from VAFB with tether experiment (of NRL) and many enabling technologies</td>
</tr>
<tr>
<td>STARSHINE-1</td>
<td>May 27, 1999</td>
<td>Student satellite on STS-96 (reentry of S/C Feb. 18, 2000)</td>
</tr>
<tr>
<td>STP-1 Payloads: (6 S/C) OÉ</td>
<td>March 9, 2007</td>
<td>First DoD technology demonstration mission with ESPA on an Atlas–V launch vehicle from Cape Canaveral, FLA. Orbital Express (primary) consisting of ASTRO and NextSat MidStar-1 of USNA STPSat-1 of AFRL CFESat of LANL FalconSat-3 of USNPS</td>
</tr>
<tr>
<td>STRV-1c/d</td>
<td>Nov. 16, 2000</td>
<td>DERA satellites – Note: Only the first two weeks of both missions were successful. Then, telemetry from both spacecraft (STRV-1c and -1d) indicated a serious problem. The unrecoverable problem with the spacecraft receivers caused the end of the mission.</td>
</tr>
<tr>
<td>STSat-1</td>
<td>Sept. 27, 2003</td>
<td>Science and Technology Satellite-1 of KAIST (formerly known as KAISTSat-4) was launched on a Cosmos-3M from Plesetsk</td>
</tr>
<tr>
<td>SUNSAT</td>
<td>Feb. 23, 1999</td>
<td>Student-built satellite of Stellenbosch University, SA</td>
</tr>
<tr>
<td>SWIFT</td>
<td>Nov. 20, 2004</td>
<td>NASA astrophysics mission to observe gamma rays. Launch on a Delta-2 vehicle from Cape Canaveral, FLA</td>
</tr>
<tr>
<td>SZ-1 (Shenzhen-1)</td>
<td>Nov. 20, 1999</td>
<td>First Chinese test launch for manned space flight (but without Taikonauts). After 14 orbits, the recovery capsule touched down in the Inner-Mongolia region of north China on Nov. 21, 1999</td>
</tr>
<tr>
<td>SZ-3 (China)</td>
<td>March 25, 2002</td>
<td>The SZ-3 spacecraft flew CMODIS (Chinese Medium Resolution Spectral Imager), among other EO sensors. Reentry of SZ-3 on Nov. 12, 2002 over the southern hemisphere: impact at 22° S, 109° E (first long-duration unmanned flight; the orbital module disintegrated on reentry after nearly 232 days in orbit).</td>
</tr>
<tr>
<td>Mission</td>
<td>Launch Date</td>
<td>Comment</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>SZ-5 (China)</td>
<td>Oct. 15, 2003</td>
<td>SZ-5 carried the first Chinese Taikonaut into space. After 14 orbits the SZ-5 capsule launched successfully on Oct. 16, 2003</td>
</tr>
<tr>
<td>TacSat-2</td>
<td>Dec. 16, 2006</td>
<td>Technology demonstration S/C of AFRL. Launch on a Minotaur vehicle from NASA's Wallops Flight Facility, Wallops Island, VA. A CubeSat of NASA/ARC and various universities (secondary payload to TacSat-2)</td>
</tr>
<tr>
<td>GeneSat-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDRS-H</td>
<td>June 30, 2000</td>
<td>NASA Data Relay satellite</td>
</tr>
<tr>
<td>TDRS-1 (TDRS-9)</td>
<td>Mar. 8, 2002</td>
<td>NASA Tracking and Data Relay Satellite</td>
</tr>
<tr>
<td>TEAMSAT, YES</td>
<td>Oct. 30, 1997</td>
<td>ESA technology demonstrator payload on Ariane-5 test flight</td>
</tr>
<tr>
<td>TechSat/Gurwin-II</td>
<td>July 10, 1998</td>
<td>Technion Israel Institute of Technology, Haifa, Israel</td>
</tr>
<tr>
<td>Terra (EOS/AM1)</td>
<td>Dec. 19, 1999</td>
<td>NASA S/C with MODIS, ASTER, etc.</td>
</tr>
<tr>
<td>TERRIERS</td>
<td>May 18, 1999</td>
<td>Boston University/NASA. Note: the S/C got lost and could not be operated</td>
</tr>
<tr>
<td>TES, PROBA, BIRD</td>
<td>Oct. 22, 2001</td>
<td>ISRO prime payload TES (Technology Experiment Satellite), a classified S/C of ISRO (military surveillance); secondary payloads are: PROBA of ESA and BIRD of DLR; Launch from SHAR on a PSLV-C3 vehicle, orbit of 560 km, inclination of 98.7º</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>June 8, 2007</td>
<td>German SAR mission (DLR). Launch on a Dnepr-1 vehicle from Baikonur, Kazakhstan</td>
</tr>
<tr>
<td>TIMED</td>
<td>Dec. 7, 2001</td>
<td>NASA launch (Delta-2-7925) from VAFB</td>
</tr>
<tr>
<td>TiungSat-1</td>
<td>Sept. 26, 2000</td>
<td>Microsatellite of ATSB, Kuala Lumpur, Malaysia (built by SSTL)</td>
</tr>
<tr>
<td>TMSat/Thai-Paht-1</td>
<td>July 10, 1998</td>
<td>Microsatellite of Thailand built at SSTL by a Thai engineering team, the new name of the spacecraft is Thai-Paht-1. Launch as secondary payload on a Zenit-2 vehicle from Baikonur.</td>
</tr>
<tr>
<td>TRACE</td>
<td>April 2, 1998</td>
<td>NASA/GSFC mission in the SMEX (Small Explorer) program</td>
</tr>
<tr>
<td>TRMM</td>
<td>Nov. 27, 1997</td>
<td>NASA/NOAA (Tropical Rainfall Measuring Mission) on H-II launcher from Tanegashima, Japan (along with ETS-VII)</td>
</tr>
<tr>
<td>Tsinghua-1</td>
<td>June 28, 2000</td>
<td>Tsinghua University, Beijing - Imaging Demonstrator Mission Three S/C in Cosmos launch from Plesetsk (SNAP-1, Nadezhda-6 (Hope) and Tsinghua-1</td>
</tr>
<tr>
<td>TSX-5</td>
<td>June 6, 2000</td>
<td>DoD with STRV-2 payload package and CEASE</td>
</tr>
<tr>
<td>TUBSAT-A</td>
<td>July 17, 1991</td>
<td>Technical University Berlin (TUB); launch from Kourou on Ariane-4 (secondary payload to ERS-1 of ESA)</td>
</tr>
<tr>
<td>TUBSAT-B</td>
<td>Jan. 25, 1994</td>
<td>TUB S/C, launch on a Tyklon vehicle from Plesetsk, Russia, as a secondary payload to Meteor-3-7</td>
</tr>
<tr>
<td>TUBSAT-N+N-1</td>
<td>July 7, 1998</td>
<td>Data collection satellites of TU Berlin, Russian submarine tandem launch from the western Barents Sea</td>
</tr>
<tr>
<td>DLR-TUBSAT</td>
<td>May 26, 1999</td>
<td>Earth observation, TU Berlin (TUB)</td>
</tr>
<tr>
<td>Maroc-TUBSAT</td>
<td>Dec. 10, 2001</td>
<td>TUB and CTS (Morocco) S/C, launch on a Zenit-2 vehicle from Baikonur as secondary payload to Meteor-3M-1</td>
</tr>
<tr>
<td>LAPAN-TUBSAT</td>
<td>Jan. 10, 2007</td>
<td>LAPAN (Indonesia). Launch on PSLV-7 vehicle from SHAR, India. CartoSat-2 was the primary payload.</td>
</tr>
<tr>
<td>UoSat-1</td>
<td>Oct. 6, 1981</td>
<td>First microsatellite of SSTL, Surrey, UK; launch as secondary payload on a Thor Delta from VAFB. Reentry on Oct. 13, 1989</td>
</tr>
<tr>
<td>UoSat-3 also known as HealthSat-1</td>
<td>Jan. 22, 1990</td>
<td>Launch as secondary payload to SPOT-2 from Kourou. The mission ended in May 1997 due to OBC failure. First use of ASAP ring on an Ariane launch vehicle.</td>
</tr>
<tr>
<td>UoSat-4</td>
<td>Jan. 22, 1990</td>
<td>Launch alongside UoSat-3 as secondary payload to SPOT-2. Communications were lost shortly after launch.</td>
</tr>
<tr>
<td>UniSat-1</td>
<td>Sept. 26, 2000</td>
<td>Dnepr launch from Baikonur with SaudiSat-1A/B (SISR), UniSat (University of Rome, Italy), MegSat-1 (MegSat SPA, Italy), and TiungSat 1 of ATSB, Malaysia</td>
</tr>
</tbody>
</table>
Table 113: EO satellite launches since submission of 3rd edition to the publisher (Feb. 1996)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch Date</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>UniSat-2, LatinSat-1/2, Rubin-2, SaudiSat-2, Trailblazer</td>
<td>Dec. 20, 2002</td>
<td>Launch of nanosatellites (Dnepr 1 launch from Baikonur) into 650 km circular orbit at 65° inclination. UniSat-2 of the University of Rome, Italy. LatinSat-1,2 of Aprize Satellite Inc., Argentina (S&amp;F communication, S/C built by SpaceQuest Ltd., Fairfax, VA, each S/C of 11 kg), Rubin-2 of OHB-System, Germany (technology), SaudiSat-2 (15) of KACST, Saudi Arabia (technology), and Trailblazer (dummy) of TransOrbital Inc., Alexandria, VA, USA.</td>
</tr>
<tr>
<td>UniSat-3</td>
<td>June 29, 2004</td>
<td>Multisatellite launch on a Dnepr launch vehicle from Baikonur.</td>
</tr>
<tr>
<td>WMAP</td>
<td>June 30, 2001</td>
<td>Launch of NASA astronomy probe on a Delta-II vehicle into L2 orbit.</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>Dec. 10, 1999</td>
<td>ESA astronomy mission, launch on Ariane-5 from Kourou into HEO (113.083 km x 8.062 km, inclination = 36.86°).</td>
</tr>
<tr>
<td>XSS-10</td>
<td>Jan. 29, 2003</td>
<td>Experimental Spacecraft System-11 of AFRL (USA), launch as a secondary payload to a GPS spacecraft (2R-8) on a Delta-2 vehicle from KSC, FLA.</td>
</tr>
<tr>
<td>XSS-11</td>
<td>April 11, 2005</td>
<td>Experimental Spacecraft System-11 of AFRL (USA), launch on a Minotaur vehicle from VAFB, CA; Demonstration of autonomous rendezvous technology.</td>
</tr>
<tr>
<td>ZY-1A (Zi Yuan-1) see also CBERS</td>
<td>Oct. 14, 1999</td>
<td>ZY-1A (Resource) was launched on a Long March 4B vehicle from the Taiyuan Satellite Launch Center.</td>
</tr>
<tr>
<td>ZY-1B (Zi Yuan-1) CBERS-2</td>
<td>Oct. 21, 2003</td>
<td>China/Brazil mission, ZY-1B (Resource), also called CBERS-2, launch from Taiyuan on a CZ-4B vehicle, along with CX-1 (Chuang Xin-1).</td>
</tr>
<tr>
<td>ZY-2A (Zi Yuan-2A)</td>
<td>Sept. 1, 2000</td>
<td>Chinese CZ-4B launch vehicle with the Zi Yuan 2 remote sensing satellite from the Taiyuan launch facility (altitude of 492 km, inclination of 97.4°). ZY-2 is a classified mission also code-named Jianbing-3 and is considered China’s first high-resolution military optical reconnaissance satellite (&lt; 5 m resolution).</td>
</tr>
<tr>
<td>ZY-2B (Zi Yuan-2B)</td>
<td>Oct. 27, 2002</td>
<td>Launch of the Chinese reconnaissance mission ZY-2B from the Taiyuan launch facility. SSO of 477.5 km x 505.4 km, inclination of 97.4°, period of 94.4 min. ZY-2B operates in tandem with ZY-2A. Image resolution of 3 m Pan.</td>
</tr>
<tr>
<td>ZY-2C (Zi Yuan-2C)</td>
<td>Nov. 6, 2004</td>
<td>Launch of the remote sensing satellite ZY-2C of CAST, China, from the Taiyuan launch facility.</td>
</tr>
</tbody>
</table>

1.17 Coordinates of satellite launch sites around the world

<table>
<thead>
<tr>
<th>Name of Launch Site</th>
<th>Resp. Organization (Country)</th>
<th>Location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baikonur Cosmodrome (Tyuratam Leninsk)</td>
<td>CIS (Kazakhstan)</td>
<td>45.6° N, 63.4° E</td>
<td>since 1957, launch of manned S/C, interplanetary S/C and geostationary S/C</td>
</tr>
<tr>
<td>Plesetsk (northern Cosmodrome)</td>
<td>Russia/CIS</td>
<td>62.8° N, 40.1° E</td>
<td>since 1966, launch of polar orbiting satellites</td>
</tr>
<tr>
<td>Kapustin Yar (Volgograd Cosmodrome)</td>
<td>Russia/CIS</td>
<td>48.4° N, 45.8° E</td>
<td>since 1962, launch of small satellites and interplanetary space probes</td>
</tr>
<tr>
<td>Cape Canaveral Air Force Station (CCAFS), FL</td>
<td>USAF/NASA (USA)</td>
<td>28.5° N, 80.0° W</td>
<td>since 1958, launch of manned S/C, interplanetary S/C, GEO satellites, etc.</td>
</tr>
<tr>
<td>Kennedy Space Center, FL</td>
<td>NASA (USA)</td>
<td>28.5° N, 80.0° W</td>
<td>since 1967, Complex 39 (launch of Saturn V vehicle, adapted to launch the Shuttle)</td>
</tr>
<tr>
<td>Vandenberg AFB, CA</td>
<td>USAF/NASA (USA)</td>
<td>34.4° N, 120.35° W</td>
<td>since 1959, launches of S/C into polar orbit</td>
</tr>
<tr>
<td>Vandenberg AFB, CA Commercial spaceport</td>
<td>Spaceport Systems International L.P.</td>
<td>34.4° N, 120.35° W</td>
<td>since 1998 (a joint venture of ITT Industries and CA Commercial Spaceport Inc.) launches of S/C into polar orbit</td>
</tr>
<tr>
<td>Wallops Island, VA</td>
<td>NASA/GSFC WFF (USA)</td>
<td>37.8° N, 75.5° W</td>
<td>since 1961, launch of sounding rockets and Scout launcher for small satellites, commercial launches since 1997</td>
</tr>
<tr>
<td>Name of Launch Site</td>
<td>Resp. Organization (Country)</td>
<td>Location</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------------------------------</td>
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</tr>
<tr>
<td>Edwards AFB, CA</td>
<td>USAF (USA)</td>
<td>35.0° N 118.0° W</td>
<td>Space Shuttle returns since 1981</td>
</tr>
<tr>
<td>Tanegashima Kagoshima Space Center</td>
<td>ISAS, U. of Tokyo, (Japan)</td>
<td>31.2° N, 131.1° E</td>
<td>since 1970, launch of scientific satellites</td>
</tr>
<tr>
<td>Tanegashima Space Center (TNSC)</td>
<td>JAXA (Japan)</td>
<td>30.4° N, 131.0° E</td>
<td>since 1975, launch site for scientific and commercial satellites</td>
</tr>
<tr>
<td>SHAR Sriharikota (Satish Dhawan Space Center)</td>
<td>ISRO (India)</td>
<td>13.9° N, 80.4° E</td>
<td>since 1980, launch of ISRO satellites</td>
</tr>
<tr>
<td>San Marco Platform (off the coast of Kenya)</td>
<td>CRA, U. of Rome (Italy)</td>
<td>2.9° S, 40.3° E</td>
<td>since 1967, launch of Scout rockets for NASA/ASI</td>
</tr>
<tr>
<td>Guiana Space Centre Kourou (Fr. Guiana)</td>
<td>CNES/ESA</td>
<td>5.2° N, 52.8° W</td>
<td>since 1970, launch of scientific and commercial satellites</td>
</tr>
<tr>
<td>Woomera Range</td>
<td>WRE (Australia)</td>
<td>31.1° S, 136.8° E</td>
<td>since 1967, launch of sounding rockets since 1999, launch of LEO S/C (Kistler)</td>
</tr>
<tr>
<td>Jiuquan Satellite Launch Center (JSLC)</td>
<td>China</td>
<td>40.6° N, 99.9° E</td>
<td>since 1970, launch of experimental satellites</td>
</tr>
<tr>
<td>Xichang Satellite Launch Center (XSLC)</td>
<td>China</td>
<td>28.25° N, 102.0° E</td>
<td>since 1984, launch of satellites into geost. and polar orbits</td>
</tr>
<tr>
<td>Taiyuan Satellite Launch Center (TSLC)</td>
<td>China</td>
<td>37.5° N, 112.6° E</td>
<td>since 1988, launches of CZ-4A and -4B into polar orbits for remote sensing</td>
</tr>
<tr>
<td>Esrange, Kiruna</td>
<td>SSC (Sweden)</td>
<td>67.9° N, 21.0° E</td>
<td>launch of sounding rockets and balloons</td>
</tr>
<tr>
<td>Alcántara Launch Center</td>
<td>CTA/INPE (Brazil)</td>
<td>2.3° S, 44.4° W</td>
<td>in preparation for satellite launches</td>
</tr>
<tr>
<td>Palmachim/Yavne</td>
<td>Israel</td>
<td>31.5° N, 34.5° E</td>
<td>since 1989, launch of LEO satellites into westward direction (Ofeq series of IAI)</td>
</tr>
<tr>
<td>Svobodny Cosmodrome</td>
<td>Russia</td>
<td>51.4° N, 128.3° E</td>
<td>since 1996, Start-1 launcher (Zeya, etc. EarlyBird)</td>
</tr>
<tr>
<td>Sea Launch</td>
<td>Partnership of Boeing Co., USA, Yuzhnoye, Ukraine RKK Energia, Russia, and Kvaerner Maritima A.S. Oslo, Norway</td>
<td>Pacific Ocean</td>
<td>since March 27, 1999, inaugural launch of two-stage Zenit (Zenit-3SL and Zenit-2) rockets of the Yuzhnoye Design Bureau. The first commercial launch was on Oct. 9, 1999, The Sea Launch home port is Long Beach, CA for the command ship and launch platform</td>
</tr>
<tr>
<td>Poker Flat Research Range (PFRR), AK</td>
<td>University of Alaska (USA)</td>
<td>65.117° N, 147.60 W</td>
<td>since 1968 rocket launch facility (auroral and meteorological research), located about 50 km north of Fairbanks</td>
</tr>
<tr>
<td>Kodiak Launch Complex on Kodiak Island, AK</td>
<td>Alaska Aerospace Development Corporation</td>
<td>57.445° N, 152.34°W</td>
<td>The first satellite launch took place on Sept. 30, 2001, with Picosat of AFRL, Athena-1 vehicle (along with Starshine-3 and PCSat).</td>
</tr>
<tr>
<td>“Reagan Test Site” on the Kwajalein Atoll, part of the Republic of the Marshall Islands</td>
<td>US Military Range run by the Army</td>
<td>9.99° N, 167.6° E</td>
<td>Launch site (since World War II) for missiles and, occasionally, Pegasus and Falcon-1 launched small satellites</td>
</tr>
<tr>
<td>Yasnaya Launch Base (a Russian strategic missile facility) Alternate name: Dombrovsky</td>
<td>ISC Kosmotras, Russia</td>
<td>51.0° N, 58.0° E</td>
<td>Yasnaya Launch Base is a new Russian space launch base dedicated to Dnepr launch vehicles. First launch of a Dnepr occurred on April 21, 1999 (launch of UoSat–12 of SSTL, UK. Also launch of Genesis–1 and –2 of Bigelow Aerospace</td>
</tr>
</tbody>
</table>