Understanding Synthetic Aperture Radar Images

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To Betty and Sue, who understand
Foreword

Over the past few years, the development of spaceborne and airborne SAR systems for the observation of the Earth's surface has experienced a rapid growth. The ERS-1, JERS-1, ERS-2, and RADARSAT satellite systems have provided and continue to provide us with long time-series of high quality SAR data. At the same time, advanced airborne SAR systems exist in many countries of the world and provide multiple frequency and polarization observations for both civilian and military use. The SIR-C/X-SAR shuttle missions have widely demonstrated the advantages of having such multiple parameter systems in space.

Despite the enormous amount of available data, little effort has been expended in making use of the data in applications and scientific disciplines. To achieve this, both the physical content of the data and the information content of the SAR images, as well as the bridge between the two sources of information, must be understood by the users of Earth observation data.

While several early volumes in radar remote sensing covered either the physical content of SAR data, or the basics of SAR image formation and SAR image statistical properties, there is a strong need for an integrated book that brings together both the basic properties of SAR images related to image formation and those related to scene properties.

In this context, this book appears very timely to fill the above mentioned gap. It provides the readers with a synoptic understanding of SAR image fundamental properties; these are a prerequisite for the development of models and methods used in the interpretation and exploitation of SAR data for various applications.
This book deals with most aspects of SAR images on land surfaces and contains the most up-to-date coverage of the subject, including the underlying principles, recent developments, and future directions for research activities in this area. The subject is treated with the breadth and depth required for use as a reference text for graduate students, engineers, and application scientists. At the same time, the many illustrations of the underlying theoretical principles, contained in the different chapters, will certainly inspire the development of new tools and stimulate new practical applications of SAR images.

The authors have been leading authorities in the field for many years. Thus, the clear, thorough, and objective writing of the volume is a reflection of the authors' extensive experience as scientists and teachers. In addition, the authors have demonstrated that scientific texts can also be written in beautiful English language.

I am confident that this book will quickly become a well-read text for those interested in SAR images, and thus will contribute significantly to expand the effective use of SAR data in the observation and monitoring of the Earth's environment.

Thuy Le Toan
Toulouse, September 1997
Preface

The authors have been collaborating on SAR research since 1982, when Shaun Quegan joined Marconi Research Centre, Great Baddow, and Chris Oliver was at the Royal Signals and Radar Establishment, Malvern (later to become part of the Defence Research Agency (DRA), which is now the Defence Evaluation and Research Agency (DERA)). At that time the status of SAR as a means of producing images of the Earth's surface was very different from the present. Only the short-lived Seasat mission had provided spaceborne data, and few airborne systems were in operation. Images were not widely available (although the DRA X-band SAR provided us with a data source) and in most cases suffered from various types of defect. Image quality issues often overshadowed the task of information extraction so that, in common with many other researchers, we invested considerable time and effort on methods of data correction. The success of this work (such as the signal-based motion compensation schemes described in Chapter 3) in combination with significant progress in system engineering and calibration has ensured that close to ideal quality SAR data is now to be expected from modern systems. We have also seen the development of new techniques, such as polarimetric and interferometric SAR, and the advent of a diversity of SAR data providers, including spaceborne systems (ERS-1 and 2, JERS, and Radarsat) and flexible multifrequency polarimetric systems carried on aircraft or the Space Shuttle.

As the accent has changed from data correction, the information contained in SAR images has come to occupy its rightful place as the purpose of data acquisition. The investigation of methods for information extraction has formed the second and continuing strand in our long collaboration. In this we have been much helped by the complementarity of our interests. Chris Oliver
has primarily been concerned with the development of image-interpretation tools (usually for high resolution SAR in a military context), while Shaun Quegan has concentrated more on their impact on remote sensing applications. Necessarily, there has been significant overlap in our work. This combination of interests means that we can go some way towards crossing the cultural divides that hamper SAR development, in particular those that separate military from civil applications and applications from algorithm development.

Military applications are primarily concerned with detecting and recognizing targets, which usually demands imagery of the highest resolution. Civil applications, on the other hand, may require information about many diverse aspects of the environment, normally at lower resolution. The two have common ground in the need to understand the properties of distributed scatterers: in the military case because this constitutes the background clutter against which target detection takes place; in the civil case because this clutter is often the primary object of interest. More generally, both types of application have an interest in scene understanding. However, military needs, where cost may not have been a dominating issue, have given rise to sophisticated techniques that are potentially of considerable value to the civil field. These have become accessible due to the reduction in the cost of computing. Such is true of many of the developments described in this book.

The divide between remote sensing applications and algorithm development is symptomatic of the fact that SAR imaging presents many opportunities for formulating mathematical problems that can be pursued in an almost abstract way. Linking the problem and its solution to what is really needed by an application may be much harder; not enough attention has been paid to this issue. This does not mean that a rigorous approach should be avoided in the development of image-interpretation tools. On the contrary, such tools must be well grounded in the principles of optimization or conservation if they are to be of any general value. Ad hoc methods rarely prove robust. We tried to adopt such a rigorous approach throughout this book, but always with concern for validation of a technique and its relevance to applications.

In our attempt to bridge these cultural divides, the process of information extraction is viewed as a whole, from sensor parameters and their impact on image properties, through data models describing image statistics and the characteristics of the terrain, to the output information required by the application. This approach is tempered by our knowledge of the scattering process, based on physical understanding, models, and experimental findings. Such a complete view of what makes up the image is essential in identifying which properties of the scene affect the data. From this we can recognize those features (if any) that carry the information required by the application. The role of image analysis is to provide an optimum representation of these features. To achieve this, we
formulate a series of models that represent our best attempt to encapsulate the properties of the imaging process and those of the scene. Optimality can then often be defined in a framework such as that provided by a Bayesian analysis, although other criteria are possible. Always, the effectiveness of these optimal solutions must be judged by the user, whose requirements should impinge on every stage in the design of image-interpretation tools. Put briefly, we believe that these tools should be firmly based in an understanding of the nature of the SAR image; that their performance must be quantified and the best tools recognized; and that these best tools should be made available to the image interpreter, who is the final arbiter of their efficacy.

Although this sets out our philosophy, the reader may be helped by a more specific guide to the main structural components of the book. Fundamental aspects of how SAR images are formed, their basic characteristics arising from the imaging process, and their statistical properties are covered in Chapters 2, 4, and 5. These chapters underlie much of the later material. Chapter 3 is concerned with the recovery of nearly ideal images from imperfect systems; since its emphasis is on the SAR processing, it can be omitted by those readers interested only in working from the given data. Its purpose is to illustrate that current techniques should ensure that the data are of the highest quality. Image analysis tools for scene understanding in single-channel data form a central core of the book and are developed in Chapters 6 to 9. Chapter 10 deals with target detection in an overtly military context. The purpose of Chapters 11 and 12 is to cast much of the content of Chapters 5 to 9 into the forms required to handle multitemporal, multifrequency, polarimetric, and interferometric data and to explore the much enhanced range of information available when such multichannel data are available. Real examples and contact with applications are a recurrent theme throughout, but Chapter 13 becomes more closely oriented with applications because it considers image classification. This is a central concern in remote sensing. It provides a focal point where image analysis, physical understanding, scene properties, and user requirements all interact.

Finally, in Chapter 14 we present our view of the current status and prospects for further development. This ultimately depends on the extent to which the material of this book finds its way into applications. It will be obvious that currently available techniques show considerable promise and that in many cases preferred approaches can be identified. We hope that readers are persuaded to exploit the most powerful image analysis tools available, leading to more effective use of the data and thus allowing the analyst to concentrate more time on the real task of image interpretation. By the ensuing interplay of algorithms and applications, the shortcomings of our current understanding and methods will be exposed. This is the engine that will drive further development of techniques for extracting information from SAR images.
Acknowledgments

This book reflects many years of SAR research during which the authors have had the good fortune to work with, learn from, and disagree with each other and numerous associates at our own and other research establishments. It has been an exciting time. On many occasions we seem to have been forced back to re-examine our fundamental assumptions, often in heated discussion. One of the first questions we asked each other before this undertaking was, “Can you take criticism?” The give and take involved in being joint authors has only been possible because we thought (correctly) that the answer was “Yes.” This book represents the fruits of this often painful but ultimately rewarding interaction. We hope our efforts are better for it.

Chris would like to extend his grateful thanks to a large number of friends and colleagues in the DRA who have contributed to the research program. Chris Baker, Dave Belcher, Dave Blacknell, Alan Blake, Ian Finley, Andrew Horne, Richard White, and Jim Wood shared in the research into autofocus and signal-based motion compensation for SAR imaging. Dave Blacknell, Alan Blake, Eric Jakeman, Robert Tough, Keith Ward, and Richard White all contributed to the understanding of data models. Steve Luttrell provided exciting collaboration on super-resolution. Dave Blacknell, Alan Blake, and Richard White are all involved in despeckling filters and segmentation methods. Pierfrancesco Lombardo enjoyed a productive year at the DRA working on texture analysis before returning to the University of Rome, La Sapienza.
InfoSAR has been engaged in the development of real-time SAR autofocus processing and image-understanding techniques for the DRA. Chris would like to acknowledge the contributions of Mike Delves and Rod Cook, who are involved with the entire program; Keith Beckett and Gordon Pryde, who developed the real-time SAR processor and autofocus software; and Ian McConnell and Dave Stewart, who made significant progress in implementing and developing the image-understanding algorithms. Indeed, many of the algorithms described in this book, with subsequent development, are available in the InfoPACK software package from InfoSAR.¹

Chris would like to acknowledge the considerable investment made by the DRA and the Ministry of Defence, in terms of staff, equipment, and funding for the SAR research team. He is also grateful for the encouragement to undertake a review of the whole topic over the last two years that was initially reported in DRA Technical Reports Nos. DRA/LS2/TR96016 to 96021. Many illuminating discussions with Dave Blacknell and Richard White assisted in their preparation. Chapters 3 and 5 to 10 in this book are largely based on this material and are British Crown Copyright 1997/DERA (with the exception of Figures 6.12(a) and 8.1 and Table 10.2). So also are Figures 1.1, 4.1, 4.9, 12.11(d–j), and 12.12. These are published with the permission of the controller of Her British Majesty's Stationary Office.

Past and present members of Shaun Quegan's SAR Research Group within the Sheffield Centre for Earth Observation Science (SCEOS) contributed enormously to the overall research program and in putting this book together. Kevin Grover not only did most of the work on change detection in Amazonia but was willing to visit SCEOS long after his Ph.D. was completed in order to put the images in good order for Chapter 12. Jiong Jiong Yu is helping to extend the theoretical treatment of change detection and its applications. Ron Caves played a central role in developing algorithms for segmenting multidimensional SAR data and in producing quantitative measures of segmentation performance. Mike Preston moved this work forward on both fronts. Ian Rhodes, Coomaren Vencatasawmy, and Fraser Hatfield carried out much of the analysis of the MacEurope data; I am grateful to Coomaren for supplying Figure 11.6, which is taken from his M.Sc. dissertation. Mark Williams did much to improve our understanding of the relationship between backscattering models and image texture.

As far as the preparation of this book itself is concerned, we are grateful for many important contributions. From DRA, Alan Blake provided the image simulation and analysis software used throughout Chapters 5 to 9, Tony Currie

¹ Many images from this book, as well as other examples, can be found at the InfoSAR website: http://www.infosar.co.uk/.
the interferometric image shown in Figure 4.9, and Mark Williams the simulation in Figure 5.8. Les Novak, of MIT Lincoln Laboratories, provided Table 10.2, which is taken from one of his many informative papers on target detection and recognition. A crucial input was that of Ian McConnell and Dave Stewart of N A Software who processed all the examples of reconstruction filters and segmentation algorithms illustrated in Chapters 6 to 8 as well as Figures 12.11 and 12.12. This involved a great deal of effort and was essential to the value of those chapters.

Special thanks must go to Mike Preston and Jiong Jiong Yu of SCEOS for producing many of the figures and displaying remarkable patience when Shaun realized he had asked for the wrong thing. Mike, in particular, devoted much time to solving the numerous problems that arose in getting images to Chris in the right form. Members of SCEOS were also willing to liaise with colleagues elsewhere who were kind enough to allow access to data and images. Geoff Cook-martin took care of the data provided by ESA-ESTEC that forms Figures 13.1 and 13.2. Jiong Jiong Yu did most of the hard work involved in transferring data from CESBIO and DCRS, while Mike Preston took the lead with ESA-ESRIN.

Shaun's unreserved thanks must go to Mari Bullock, who, as SCEOS secretary, not only typed his parts of the manuscript but also took care of so many of the detailed tasks involved in putting all the material together. Her initiative, care, and sheer devotion to getting the job done played a large part in making it possible. She also managed to run SCEOS very effectively while Shaun made himself incommunicado in order to write (which tells you something about how the organization really works).

A symptom of the coherence and sustained nature of the research program from which this book springs is the sharing of staff between SCEOS, DRA, and N A Software. DRA provided support for Dave Blacknell and Mark Williams while they worked in Sheffield; both are now at DRA, as is Kevin Grover. Ron Caves spent two years with N A Software before returning to Sheffield, and Ian McConnell joined N A Software from Sheffield.

The extent of the SAR research program within SCEOS would have been impossible without the continuing support of the UK Science and Engineering Research Council and later the National Environmental Research Council, when they took over responsibility for Earth Observation.

In preparing this manuscript we had tremendous help from colleagues in other research groups who have been willing to give data, advice, and time when we sought it, providing an excellent and refreshing example of the sense of community within the field.

From CESBIO, Toulouse, we must particularly thank Thuy Le Toan for advice that vastly improved Chapter 13 (though any blemishes are our responsibility) and for providing data. Florence Ribbes and Oscar Casamian did an excellent and difficult job in rendering color images into informative black-and-
white forms for our purposes. Their efforts became Figures 13.6 and 13.8. At a deeper level, Thuy's insistence on understanding what we see in SAR images was a continual spur to the spirit; she knows measurement is easier than knowing what we have measured.

The Danish Center for Remote Sensing (DCRS), Department for Electromagnetic Systems (EMI) of the Technical University of Denmark (DTU) provided help in two very substantial ways. First, they provided the EMISAR images; our thanks go to Soren Madsen for permission to use them and Erik Lintz for comments on the text while providing that permission. Second, much of the analysis of the EMISAR images was carried out by Jesper Schou of DCRS during a four-month individual course at Sheffield. Thanks must go to his supervisor, Henning Skriver, for instigating what turned out to be a very fruitful visit and to Jesper, for the quality of his work at Sheffield and his willingness to help in preparing material after his return to Denmark.

Colleagues from DLR who helped us include Richard Bamler and Manfred Zink. Richard supplied material on SAR processing and copies of unpublished work done with Keith Raney (now of Applied Physics Laboratory, Johns Hopkins University) on the linear system model for SAR imaging. Manfred gave advice on SAR calibration.

We have several reasons to thank the European Space Agency. First and foremost they supplied data. All the ERS images shown were provided by ESA. Those from the Tapajos site in Amazonia were given to us under the auspices of the TREES program organized by the Joint Research Centre of the European Union, Ispra, whose support we would like to acknowledge. All other ERS images were provided in the framework of the First ERS Announcement of Opportunity. In addition, ESA provided access to data from two airborne campaigns. The SAREX images used in Chapter 8 were collected in the framework of the ESA South American Radar Experiment, while the NASA/JPL AirSAR data informing Chapters 11 to 13 were acquired during the 1992 MacEurope campaign. In the latter case, ESA was a formal partner of NASA and we would like to thank both organizations. Other contributions to this book include Figures 13.1, 13.2, and 13.7, which are reproduced from ESA publications.

Individual ESA scientists also helped us greatly. Maurice Borgeaud of ESA-ESTEC made available the figures and data that form Figures 13.1 and 13.2. Henri Laur, Giorgio Emiliani, and Jose Sanchez of ESA-ESRIN provided the imagery and the calibration target analysis shown in Figure 2.9. In both cases, this was not straightforward and we gratefully acknowledge the time and effort expended on our behalf.

Most of the work we describe using data from the Tapajos site would not have been possible without the support of colleagues in the Instituto Nacional Pesquisas Espaciais (INPE), Sao Jose dos Campos, Brazil. Special thanks must go
to Corina Yanasse for many years of advice, discussion, and help. We are indebted to Sidnei Sant'Anna, Alejandro Frery, and Corina for permission to use Figure 13.7. This opportunity to display information on forest types using texture measured from the Radarsat satellite arose only a week before completion of the manuscript during a visit to Sheffield by Corina and Sidnei, and we were delighted by it. More generally, effective collaboration with INPE was greatly aided by discussion and material help from Luciano Dutra and Thelma Krug.

Shaun must give particular thanks to Rob Brooks, Ralph Cordey, and Paul Saich of Marconi Research Centre, Great Baddow. Rob introduced me to the fascinating field of SAR research. Ralph has been a continual source of critical appraisal, encouragement, and financial support and he and Paul have been welcome collaborators on several projects. MRC must also be thanked for seconding Dave Blacknell to Sheffield for the duration of his doctoral studies.

This book would never have been completed (almost) on schedule without the continual involvement of Susanna Taggart at Artech House in London. She managed to make her demands in such a pleasant manner that it was impossible to take offense.

When he started writing this book Chris had no conception of the demands it would make on his time and energy. He especially wishes to thank his wife Betty for her understanding and patience over the whole period, but particularly the last few hectic weeks. In contrast, Shaun knew perfectly well what was involved and went like a lamb to the slaughter. He has no words that can do justice to the forbearance of his wife Sue.
About the Authors

After earning a degree in physics from Worcester College, Oxford, Chris Oliver conducted his doctoral research into low-energy nuclear structure at Liverpool University. In 1967, he joined the photon statistics group at the Royal Signals and Radar Establishment (RSRE), Malvern [later the Defence Research Agency (DRA) and now the Defence Evaluation and Research Agency (DERA)]. He was one of the joint inventors of the technique of single-clipped photon-correlation spectroscopy exploited in the Malvern Correlator, for which he won the MacRobert Award for Engineering Achievement in 1977.

Chris Oliver led a section at the DERA (Malvern) undertaking long-term research on the extraction and processing of information from SAR images since 1981; from 1991 until 2000, he took on a consultancy role to free him from management responsibilities. He was appointed Visiting Professor of Physics at King's College London in 1987. In 1996, he was invited to become a Visiting Professor in Electronic Engineering at University College, London. He has also been a Visiting Professor at “La Sapiensa,” the University of Rome, in 1999 and 2001.

Chris Oliver has published in excess of 100 papers and holds 7 patents, many in both Europe and the United States in addition to the United Kingdom. His academy status was recognized within the DERA, where he was an Individual Merit Deputy Chief Scientific Officer. In 2000, he was appointed a Commander of the British Empire (CBE) in Her Britannic Majesty the Queen’s Birthday Honors as recognition of his contribution to radar. Since his retirement, Chris has set up InfoSAR Ltd. (www.infosar.co.uk), which offers consultancy and training in SAR exploitation. The company has produced a SAR image interpretation software suite, InfoPACK, which exploits and extends the principles described in this book and offers significantly greater sensitivity than any others.
Shaun Quegan received his BA in mathematics in 1970 and M.Sc. in mathematical statistics in 1972, both from the University of Warwick. After teaching for several years (and running a large mathematics department) an ever-growing interest in physics led him to undertake research into large-scale modeling of the ionosphere and upper atmosphere at the University of Sheffield, leading to a Ph.D. in 1982. He then joined Marconi Research Centre as a research scientist, becoming Remote Sensing Applications Group Chief in 1984. This was a fortunate opportunity to work with an excellent team involved in SAR research, from which many fruitful long-term collaborations sprung, including that with Chris Oliver. The offer of a post at the University of Sheffield in 1986 provided an chance to build an academic SAR research group, whose activities have flourished. In 1993 he was awarded a professorship, in the same year helping to instigate the Sheffield Centre for Earth Observation Science and becoming its first director. In this role he plays a central part in coordinating and developing the wide range of remote sensing skills in the University and in bringing them to bear on environmental science and application problems.