4

GNSS Antennas and Front Ends

4.1 Background

Although the focus of this text is on the algorithms for software signal processing of the Global Navigation Satellite System (GNSS) signals, it is important to consider the source of that data stream to be processed. Since “software” signal processing is stated, it implies an input digital data stream. Thus, the purpose of this chapter is to provide some insight into how the satellite signals propagating through space result in this digital data stream. This is done, of course, via a GNSS antenna/front end. There are numerous books completely devoted to the topics of antenna and others to front-end design; see Balanis (1996) and Tsui (2000). The purpose of this chapter is to illustrate functional designs for GNSS, discuss the tradeoffs associated with different designs, and provide a basic understanding of the source of the digital data to be processed. The focus is on the narrowband GNSS L1 signals, primarily the Global Positioning System (GPS) Coarse/Acquisition (C/A) code, but references are made to the Galileo BOC(1,1) code where appropriate. At the end of the chapter, multiple-band GNSS front ends are introduced.

The process begins with the GNSS signal, propagating through space, which is incident on a user’s GNSS antenna. This, in turn, induces a voltage within the element. That voltage is extremely weak, corresponding to a guaranteed signal power of $-160\,\text{dBW}$ in the case of the Global Positioning System (GPS) [see ICD-GPS-200 (1991)] and has a carrier frequency of 1575.42 MHz. Considering a bandwidth of 2 MHz (the approximate null-to-null bandwidth the GPS C/A code signal), the received GPS signal power is actually below that of the thermal noise floor, as defined by Equation (4.1) with a simplified illustration in Figure 4.1.
Let the Boltzmann’s constant be denoted by \( k = 1.38 \cdot 10^{-23} \text{ J/°K} \), the absolute temperature by \( t \) in °K, and the equivalent noise bandwidth by \( B \) in Hz, then

\[
P_{\text{Thermal Noise}} = k t B. \tag{4.1}
\]

For the GPS C/A code signal \( P_{\text{Thermal Noise}} \) can be approximated by 1.38 \( \cdot \) 10\(^{-23} \) \( \times \) 290 \( \times \) 2 \( \cdot \) 10\(^6 \) = 8.004 \( \cdot \) 10\(^{-15} \) or more conveniently expressed in dB as 10 \( \times \) \( \log_{10} \) (8.004 \( \cdot \) 10\(^{-15} \)) = −140.97 dBW = −110.97 dBm.

This is quite unique in the field of radio transmission. For example, if you connected a traditional GPS antenna to a spectrum analyzer and searched for the presence of the GPS signal, then any such characteristics of the signal would be hidden as the observation would be dominated by the thermal noise. This is a feature of the code division multiple access (CDMA) spread spectrum signal and requires the appropriate signal processing to acquire and process the signal. This also implies that the design of the front end is based more on the level of the thermal noise rather than the received L1 band navigation signal. Thus, the voltage induced within the GNSS antenna element results from the thermal noise, which dominates, as well as the GNSS signals from the satellites in view. Given that that L1 GNSS band is a designated Aeronautical Radio Navigation Service frequency band, no other signals should be present within the frequency span.

The analog voltage that results from the incident GPS signal and thermal noise remains much too weak and at too high a frequency for most analog-to-digital converters (ADCs) to operate. In order to overcome this, the front end will utilize a combination of amplifier(s), mixer(s), filter(s), and its own oscillator to condition the incident voltage on the antenna to the resulting digital samples.

A fully functional GNSS L1 front end is depicted in Figure 4.2. In the coming sections, the function of each of the elements within the figure will be discussed using this implementation as a case study, Gromov et al. (2000), pages 447–457.
4.2 GNSS L1 Front-End Components

4.2.1 GNSS Antenna

The antenna is typically not considered part of the front-end design, but since it is the first component in the signal path and dictates elements that follow, it is important to summarize when describing the GNSS front end. There are numerous texts on antenna theory and design, e.g., Balanis (1996), Straw (2003). Also the trade publication GPS World, over the past four years, has published a GPS Antenna Survey that lists all GPS antennas and their features. All of these are excellent references for additional information on GNSS antennas.

As is the case with most of the components associated with analog signal conditioning, there is an extensive set of parameters associated with an antenna that describe its performance. Three fundamental parameters to be discussed here are the frequency/bandwidth, polarization, and gain pattern.

The antenna will be designed to induce a voltage from radio waves propagating at the GNSS L1 frequency or 1575.42 MHz. In addition, the design should accommodate the appropriate bandwidth of the desired signal. This is usually specified using two additional antenna parameters: the Voltage Standing Wave Ratio (VSWR) and impedance. Practically all GNSS front-end components utilize an impedance of 50 Ω, which is typical for a majority of radio frequency design. VSWR is a measure of impedance mismatch or the measure of how much of the incident power will be absorbed and how much will be reflected. And, of course, this is a function of frequency. The VSWR is typically on the order of 2.0:1, which equates to 90% power absorption across the bandwidth of desired frequencies.

Polarization refers to the orientation of the electric field from the radio frequency transmission. Received GNSS signals are right-hand circularly polarized (RHCP), and the antenna should be designed as such. The decision to employ RHCP for GNSS was definitely not arbitrary. One of the most difficult error
sources to mitigate for GNSS is multipath. When the GNSS signal is reflected off an object, an undesirable situation for a system attempting to measure time-of-flight, the polarization will flip to left-hand circular polarization (LHCP). An RHCP antenna is quite effective in suppressing the LHCP reflection and minimizing this error source. Of course, a second reflection will reestablish the RHCP polarization, but the signal power is also likely diminished as a result of the multiple reflections. Thus, the polarization of the GNSS antenna provides a significant level of suppression from erroneous multipath reflection.

The antenna pattern describes the directivity of the antenna. The most basic idea for the antenna pattern would be one that receives signals equally from all directions—this is known as an isotropic antenna. However, such a uniform gain pattern does not make sense for GNSS. Since the signal source, GNSS satellites, are overhead for most applications the preferred antenna pattern would be hemispherical, designed to receive signal from only positive elevation angles from all azimuth directions. Given the problem of multipath and that most multipath rays arrive from low elevation angles, the antenna pattern could be crafted such that it was designed to receive signals only above 10°–20° elevation. Such an approach is definitely bound to further reduce multipath reflections, but as a consequence, the low elevation satellite signals would also be neglected, decreasing the availability of satellite measurements. A promising research area within GNSS antennas is that of antenna arrays, or a combination of individual antenna elements combined in such a way to shape distinct antenna pattern beams and nulls. Such an implementation should provide significant performance enhancement for GNSS.

Probably two of the most popular GNSS L1 antenna implementations are the patch and helix approaches but others also exist. These refer to the actual construction of the antenna element itself. Yet the parameters above should provide a measure of comparable performance between antennas.

The last topic in regard to antennas refers to the choice of an active or passive antenna. An antenna will often be integrated with other front-end components that improve their performance or are necessitated by the environment in which the antennas will operate.

One important parameter in front-end design is the overall noise figure $F_n$ of the system. This parameter quantifies the noise added as a result of the analog signal conditioning. Of course, any additive noise or decrease in signal-to-noise ratio (SNR) is undesirable and should be minimized.

Denoting the resulting system noise figure by $F_{\text{system}}$, the noise figure $F_n$ of the $n$th element in cascade, and the gain of the $n$th element in cascade $G_n$ the formula for noise figure is

$$F_{\text{system}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \frac{F_4 - 1}{G_1G_2G_3} + \cdots + \frac{F_n - 1}{G_1G_2G_3 \cdots G_{n-1}}. \quad (4.2)$$

What this equation indicates is that the first element in the RF cascade dominates the resulting noise figure for the system. This indicates that all passive components (cables and filters) prior to the first amplifier will have a negative impact
on the noise figure. Likewise, components that follow a high gain amplifier in the cascade will have a minimal effect on the overall noise figure.

For example, consider working with a GNSS receiver in a laboratory environment. The optimal position for the GNSS antenna will be on the rooftop, clear of any obstructions. In most cases, this will require a lengthy cable run to the GNSS receiver with its self-contained front end. This RF cable from the antenna to the front end will be the first component within the cascade of components. Since all RF cables have some degree of attenuation, or noise figure, and no gain, the system noise figure will be severely degraded. This can be improved if an amplifier can be incorporated within the antenna itself prior to the long cable. This implementation is the norm in many GNSS antennas, and such a design is known as an active antenna and is characterized by the gain of the amplifier.

This active antenna approach complicates things slightly as the antenna itself is now considered an active element and requires power for the internal amplifier. This is accomplished in most cases using a bias-tee. The bias-tee component has three ports: RF, RF+DC, and DC. This component injects DC power onto the antenna cable from the front end to power the amplifier within the antenna. Thus, the antenna cable is utilized to pass the GNSS signal from the antenna to the bulk of the analog signal conditioning and then also to provide a DC voltage from the analog signal conditioning to the amplifier within the antenna. This is the approach outlined in Figure 4.2.

A passive antenna is practical in those designs that have the antenna in close proximity to the analog signal conditioning and, in particular, the first amplifier. This is commonly the case in the handheld GNSS receivers or for configurations employing expensive low-loss RF cables.

### 4.2.2 Filter

The first component within the RF path is a filter. A filter is a frequency selective device that allows only certain frequencies to pass and attenuates others.

The treatment of the filter as well as the following individual components will be kept terse. It is expected the reader has a basic background in signal processing; this will allow the focus to be on the overall GNSS front-end design.

This first filter in Figure 4.2 is a bandpass filter, as opposed to a lowpass or highpass filter, and its purpose is to provide additional frequency selectivity. Ideally, the antenna would only induce voltages for precisely the frequency band of interest. However, the antenna, like practical filters, is not ideal. The ideal component would pass a range of frequencies and completely eliminate those frequency components outside that range. Unfortunately, such a filter does not exist, and the transition between those frequencies that are passed and removed is a gradual transition. Further, even signals at frequencies within the passband typically experience some level of attenuation.

Typical antennas have fairly poor frequency selectivity. When this is considered, along with the received signal power levels (and the amplification that will be required), it is important to try to eliminate any high-power, out-of-band signal
sources that could enter the front end and saturate later-stage components. For this reason, a bandpass filter typically is the first component following the antenna. The other filters within Figure 4.2 serve specific roles, as will be discussed in the following sections, but all are used to perform the primary role of a filter: pass selective frequencies and attenuate others.

Filters can be characterized by their insertion loss, or the attenuation of the desired frequency components. Ideally, there would be no insertion loss, but alas that is not the case for practical components, and the lower this value the better. Note that this filter insertion loss will result in a system noise figure penalty when it is placed prior to the first amplifier. Yet this is still very often the case to minimize any issues from adjacent frequency bands given the limited selectivity of the antenna itself. If the receiver will be operated in an environment that will not have high-power adjacent frequency band transmitters in close proximity, then this filter may not be necessary and the position of the first amplifier and filter can be switched. Or the impact to the noise figure can be minimized by selecting a filter with a low insertion loss.

The second filter parameter is the bandwidth. Again, since no filter is ideal, typically a 3 dB bandwidth is specified. This indicates at which frequency(s) the attenuation will be 3 dB (or 50% of the signal power). However, these two parameters cannot completely describe most filters but only provide some insight into their performance, as shown in Figure 4.3.

A goal in filter design is to provide sharp transitions between the desired (passband) and undesired (cutoff) frequencies while maintaining a minimal insertion loss. Depending on the practical implementation of the filters [options include cavity, surface acoustic wave (SAW), ceramic, or lumped elements (resistors, capacitors, and filters)], this can be done by increasing the number of sections/elements within the design.
4.2.3 Amplifier

Amplification is the process that increases the signal magnitude. Thus, an amplifier is a component that does just that. Unlike most filters, an amplifier is an active component and requires power to accomplish its function. Note that the ideal amplifier would only increase the amplitude of the signal. However, any commercial amplifier will not only increase the amplitude but also add noise to the resulting signal. The goal, of course, is to have a component that amplifies the signal and adds minimal noise.

The fundamental parameters used to describe an amplifier are

1. gain, usually expressed in dB, and often assumed constant over a specified frequency range; and a
2. noise figure, again usually expressed in dB, and indicative of the amount of noise that will be added to the signal being amplified.

Note that this discussion simplifies the practical amplifier. We are assuming the amplifier is a packaged device, ignoring the actual fabrication. Further, parameters such as the third-order intercept point, power requirements, and maximum power handling are all additional factors that could be considered but are neglected to simplify the discussion.

Also the amplification shown in Figure 4.2 shows a single amplifier capable of 50 dB gain. It would be unusual to have a single amplifier capable of such gain. What is represented as a single amplifier in Figure 4.2 can be constructed of cascaded multistage amplifiers.

The goal of the amplifier is to raise the extremely weak incident signal to a level practical for analog-to-digital conversion. Thus, the amount of amplification is based on the specific ADC and will be discussed in that section. Further, there is typically a distribution of amplification or gain across different frequencies for reasons that will become obvious in the next subsection.

4.2.4 Mixer/Local Oscillator

The basic function of the mixer/local oscillator combination is to translate the input 1575.42 MHz RF carrier to a lower intermediate frequency (IF) and preserve the modulated signal structure. The most obvious reason for this is to bring the frequency to usable ranges in which to operate on the signal, in particular perform the analog-to-digital conversion. However, there are fewer obvious reasons for the frequency translation, as is discussed within this subsection.

The design illustrated in Figure 4.2 utilizes a single stage of analog frequency translation. However, it is possible to utilize multiple stages of analog frequency translation in a single front-end design. The choice is a design trade-off based on the components available and their individual specifications. The focus of this section is to illustrate the functionality of the single-stage approach shown in Figure 4.2.
First, it is important to discuss the individual components. The local oscillator for GNSS front-end designs is typically a combination of components. Most crystal oscillators, either standalone or temperature compensated/ovenized for greater stability, are not capable of generating the desired local oscillator frequency for the L1 GNSS signal. Thus, a phase lock loop (PLL) is combined with the crystal to achieve the desired higher frequency of the local oscillator. In addition, it is common practice that the local oscillator be divided down to serve as the sampling clock, as shown in Figure 4.2. This is an important aspect as a single frequency source, and any associated frequency error/drift, will serve as the basis for the receiver.

The mixer operates through the trigonometric identity expressed as

$$\cos(\omega_1 t) \cos(\omega_2 t) = \frac{1}{2} \cos((\omega_1 - \omega_2)t) + \frac{1}{2} \cos((\omega_1 + \omega_2)t). \quad (4.3)$$

It is possible to use the front-end design in Figure 4.2 as an example of the mixing process. In this case $\omega_1$ equals the GNSS L1 center frequency 1575.42 MHz and the desired IF is 47.74 MHz, then the desired local oscillator frequency $\omega_2$ would be $(1575.42 - 47.74) \text{ MHz} = 1527.68 \text{ MHz}$. Any modulation, such as the GNSS spreading codes and navigation data, can be simply expressed as a time-varying multiplier:

$$d(t) \cos(\omega_1 t) \cos(\omega_2 t) = \frac{d(t)}{2} \cos((\omega_1 - \omega_2)t) + \frac{d(t)}{2} \cos((\omega_1 + \omega_2)t). \quad (4.4)$$

In this case it is obvious that the output of the mixer will be the sum and difference frequencies. Of interest here is the difference frequency, which is at the desired IF. The sum frequency is simply a consequence in this case, and the second filter depicted in the cascade of Figure 4.2, which follows the mixer, is used to select only the desired difference frequency.

Note that in Figure 4.2 a bandpass filter is used for this process. However, given the fact that the goal is to simply remove the sum component, a lowpass filter should be more than sufficient. In many cases this is true; however, Equations (4.3) and (4.4) present a simplified model of a mixer, which in reality is more complicated. Mixer parameters include conversion loss, isolation, dynamic range, and intermodulation. In this case the bandpass filter is selected to minimize any complications from intermodulation products that result from the mixing. For this simplified discussion, only the straightforward model of the mixer is presented.

With the combination local oscillator/mixer it is now possible to translate the RF carrier to a lower IF. It has been eluded to above that this is required for the analog-to-digital conversion process, but is that the only reason? Are there other reasons as to why frequency translation is important in GNSS receivers? The answer is “yes” with two immediate additional justifications for the frequency translation.

The first is the quality and cost of the component. The goal of this text is to develop software GNSS receivers for the narrowband L1 signals, with the definition of narrowband being 2–8 MHz (see Problem 7). It is important to recognize that it can be quite difficult to fabricate narrowband filters at high frequency.
Denote the quality factor of the filter by $Q$, the center frequency of the filter (1575.42 MHz for GNSS L1) by $f_{\text{center}}$, and the bandwidth of that filter by $BW$. Then the quality of a filter is defined by

$$Q = \frac{f_{\text{center}}}{BW}.$$  

(4.5)

If we assume a 3 dB bandwidth and desire a filter to capture the main lobe of the GPS spectrum (2.046 MHz wide), the $Q$ factor for such a filter comes out to be 770—an extremely high value. To put things in perspective, fabrication of most commercial filters (although it does depend on the technology) sets a minimal bandwidth of 2% of the center frequency. This corresponds to a $Q$ value of 50, significantly less than the 770 computed above.

However, perform the same computation at the resulting 47.74 MHz IF from the design in Figure 4.2. That $Q$ factor is $47.74/2.046$ or 23.33, which is a much more realizable filter. Thus, the frequency translation to IF allows higher frequency selectivity with less costly/complex components.

The second additional factor motivating frequency translation is feedback. The amount of amplification in the RF chain is tremendous; over 100 dB of gain is applied. If this is all attempted at a single frequency, then it is highly likely that feedback will become an issue unless meticulous shielding and spatial separation across the RF chain is implemented. Otherwise, if the 100+ dB of gain were applied all within the 1575.42 MHz band even with quality RF cabling between components, it is unlikely to prevent feedback within the amplification stages in the RF chain. Utilizing multiple stages within a front-end design allows the gain to be distributed across frequency. For example, in the single-stage downconversion depicted in Figure 4.2 the gain within the RF chain is split between the RF and IF paths. Thus the level of shielding and potential for feedback are reduced as the output of the lower-frequency amplifiers cannot feedback into the input of the higher-frequency amplifiers.

### 4.2.5 Analog-to-Digital Converter

The final component in the front-end path is the analog-to-digital converter. This device is responsible for the conversion of the analog signal to digital samples. There is a wide variety of ADCs available on the market, with a dizzying set of parameters for each. Consider, for example, the Texas Instruments ADS830 ADC, see focus.ti.com/lit/ds/symlink/ads830.pdf. Such an ADC has an overwhelming number of parameters, the majority of which are not discussed here. An application note can help users sort out the various parameters associated with ADCs; see Anonymous (2000).

The key parameters to consider for this discussion are the number of bits, the maximum sampling frequency, the analog input bandwidth, and the analog input range.

The CDMA nature of the GNSS signal requires very little dynamic range from the sampled signal. It has been shown that if single bit sampling is used, then
degradation in the resulting processing is less than 2 dB; see Bastide et al. (2003). Further, if conservative 2- or more bit sampling is utilized with proper quantization, the degradation is less than 1 dB. The minimum number of bits on most commercial ADCs is 8 as is the case for the ADS830. Thus, in designing a GNSS front end, it is most convenient to either utilize a hard limiter to obtain a single bit or use a commercial ADC taking all or just a subset of the resulting bits of each sample. It is also important to recognize that if multibit sampling is employed, then some form of gain control must be implemented to provide proper quantization.

One might ask if the penalty for using single bit sampling is less than 2 dB, why any front end would utilize multibit sampling and then incorporate the overhead associated with automatic gain control? The key point to remember is that the less-than 2 dB penalty is for the ideal case. If, for example, there exists narrowband interference within the GNSS L1, then single bit sampling will be captured by the interference source and prevent GNSS processing. Thus, although the theoretical penalty for single-bit sampling is less than 2 dB, the nature of the operating environment may dictate the need for multibit sampling.

The maximum sampling frequency is an interesting parameter. This frequency needs to accommodate the bandwidth of the desired signal. Continuing to use the ADS830 part as an example, the maximum sampling frequency is 60 MHz and thus can provide a resulting sampling bandwidth of 30 MHz, more than sufficient for the narrowband L1 navigation signals. However, recognize that the IF in Figure 4.2 is at 47.74 MHz, which is greater than the resulting [0–30] MHz sampled information bandwidth. In this case, the sampling process acts as a second frequency translation stage.

Although the ADC has a sampling frequency that provides an upper limit of 30 MHz on the resulting sampling bandwidth, then analog input bandwidth of this ADC really determines what signals will be captured. For the ADS830, this value is an impressive 300 MHz. What this means is that any frequency component input to the ADC up to 300 MHz will be aliased according the sampling theorem. Should the analog input bandwidth have been as high as 1.6 GHz, which is not impossible (see pdbserv.maxim-ic.com/en/ds/MAX104.pdf), then it would be possible to directly sample and alias the original RF signal. Such an implementation has been demonstrated [Akos (1997) and Akos et al. (1999)] yet there remain many technical hurdles to overcome with such an approach. The approach outlined does provide the means to compute an appropriate sampling frequency and the resulting sampling IF.

Based on the preceding discussion, the role of the final filter in the RF chain becomes clear. It must be a bandpass filter and limit the band to only those frequencies to be preserved through the sampling process. Recognize that the aliasing does not only occur for the desired IF, but all frequencies within the analog input bandwidth of the ADC. Thus, it is critical for minimal noise that the last filter prior to the ADC allows only those frequencies of interest and attenuates all others within the analog input bandwidth.
Referring to the design in Figure 4.2, a sampling frequency of 38.192 MHz is used for the 47.74 MHz IF, and this provides a final digital frequency translation to an IF of 9.548 MHz. The resulting sampled information bandwidth of [0–38.192/2] MHz provides more.

The final ADC parameter to be discussed is the analog input range. This range defines the voltage range for which the quantization will be distributed across. In the case of the ADS830 part, the minimum analog input range is 1 V peak-to-peak. Assuming a 50 Ω load, which is traditional in radio frequency design, a 1 V signal corresponds to −17 dBW. Thus, it should now be clear why the amplification within the RF chain is needed. It had been mentioned that it was to provide suitable signal levels. The combination of thermal noise and received signal will be simply too weak to exercise the bits in this or any ADC. So a goal of the amplifiers is to increase the received signal level, which again is dominated by the thermal noise, to exercise the full range of the ADC.

Although not depicted in Figure 4.2, the final amplifier in many GNSS front-end designs will be a variable gain with a feedback signal resulting from processing implemented after the ADC. This is implemented and known within most GNSS receivers as automatic gain control (AGC). The goal of the front end is to exercise all available bits with the ADC. Thus, if the gain is insufficient to do so and this is determined by monitoring the sampled data stream, the gain can be increased. Alternatively, if the gain is too high such that the outer ADC bins have an overwhelming number of samples, then the gain can be decreased. Lastly, as will be discussed when the sampled data are presented, the AGC can be steered by the expected distribution of the sample bins. In this way, the front end can attempt to minimize the impact of narrowband interference.

In summary, the object of the bulk of the components within the front end is to condition the voltage incident on the antenna for sampling by the ADC. In order to
accomplish this for most ADCs there are three basis functions which must be accomplished. These are amplification, frequency translation/downconversion, and filtering. These prepare the signal for analog-to-digital conversion, which results in the samples to be processed within the software receiver.

4.3 Resulting Sampled Data

Now that the operation/functionality of the GNSS front end has been described, it is worthwhile to highlight the resulting data that have been collected from the front-end design depicted in Figure 4.2 and have been included on the media with the book.

Again, the important parameters for the signal processing are

- Sampling frequency: 38.192 MHz
- Intermediate frequency: 9.548 MHz, and
- Four-bit samples.

The above parameters provide all the necessary information for the operation of the signal processing algorithms. Some other items, such as the time and date and approximate location of the data collection, can speed the acquisition as will be discussed, but are not required.

What can be done is to show the resulting digital samples in typical representations. Thus, in Figures 4.4, 4.5, and 4.6, a time domain, histogram, and frequency domain depiction of the collected data are illustrated, respectively.

In the time domain depiction, no discernable structure is visible despite the 9.548 MHz IF for the collected GPS data. In the histogram, it is obvious that all four bits of the ADC are being triggered based on the 16 levels present within
the histogram. Also the histogram bears a strong resemblance to the probability density function for a Gaussian random variable, which would be expected for white thermal noise. These plots follow what would be expected based on the frequency domain depiction in Figure 4.1 where the thermal noise would dominate the resulting samples.

However, the frequency domain depiction does not resemble Figure 4.1; rather some obvious structure is present. This structure is best explained by building on Figure 4.1, as shown in Figure 4.7.

In this figure, obvious changes have been made to better correspond to the frequency domain depiction of the collected data file.

First, the “noise level” is not white, or flat and uniform as a function of frequency, but has some definite structure. This is a result of the final bandpass filter prior to sampling. This 6 MHz-wide bandpass filter shapes the spectrum of the analog signal to be sampled. Thus, the filter shape has been added within Figure 4.7.

Second, there is an obvious “bulge” within the center of the passband right at the resulting IF of the GPS translated signal. This actually appears to be the main 2.046 MHz lobe of the sinc spectrum of the signal itself. With the specified received signal power level so much lower than the expected thermal noise, how can there be any discernable structure from the satellite signal from a data set collected with a traditional hemispherical antenna? The explanation has two components:

- the individual received satellite signal power is currently higher than the minimum specified (as shown in Figure 4.7); and
- the CDMA nature of the GPS system has all the satellite signal power overlaid at the resulting IF; thus, the spectrum shows the summation of all the visible satellite signal power.
These two factors bring about some, although minimal, structure from the satellite signal spectrum into the frequency domain representation of the collected data.

For the most part, the data indeed resemble thermal noise, and all the traditional GNSS signal processing is required to acquire, track, and utilize the navigation transmission.

### 4.4 GNSS Front-End ASIC

The final section of this chapter presents the current state of the art for GNSS front-end designs. The implementation in Figure 4.2 has been built from expensive discrete components. Although this provides a high-quality front-end suitable for a lab instrument or environment, the cost for such an implementation can approach $5000. With the cost of handheld GPS receivers now well below $100, an alternative to such a design must exist.

The solution comes in the form of an integrated circuit. The bulk of the functionality of Figure 4.2 has been incorporated by multiple vendors into an ASIC that is typically smaller than 5 × 5 mm packages and utilizes less than 50 mW; see SiGe SE4110L, Nemerix NJ1006, and Texas Instruments TRF5101 data sheets. Such components strive to be as completely self-contained as possible, requiring only a minimal number of external components.

For example, consider the block diagram for the SiGe SE4110L component shown in Figure 4.8. This is an excellent example of a GPS front-end ASIC component. The complete data sheet for the SE4110L is included on the bundled DVD.
Based on the discussion within the chapter, the underlying design of the component should be somewhat familiar. A single-frequency translation stage is utilized along automatic gain control functionality to support multiple bit sampling.

It is quite impressive to see the level of integration within such a component. It utilizes a traditional antenna input (although a passive antenna can be used with an internal LNA with noise figure of less than 2.5 dB) and provides 2-bit digital samples supporting a number of different clock frequencies for a variety of applications. This particular part is only 4 × 4 mm and draws less than 10 mA from a nominal 2.7–3.3 V supply. Such integration is even more impressive when one considers the gain required for processing the received signal power of the GPS and potential feedback issues.

Such development even further facilitates the wide scale deployment of satellite navigation technology at a relatively low cost.

The ASIC-based front end is just one of multiple options for converting the signal in space to a digital format suitable for the software based signal processing. The goal of this chapter is to provide some insight into the source of that data.