Signals, Targets, and Advanced Ultrawideband Radar Systems

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3.1 Introduction to the Advanced Ultrawideband Radar Concept

Imagine a radar that can identify targets by their reflected signal spectra and adjusting its transmitted signal to match a specific class of targets. The advanced ultrawideband (UWB) radar evolves the technology from a passive detector of reflected electromagnetic signals to an active sensor for finding special targets. This chapter introduces the concepts and technology needed to build this system.

The advanced UWB radar will transmit a virtual-impulse signal. The receiver will first detect the return and then it will convert the received signal to a digital format. The signal processor will analyze the return to determine the time–frequency characteristics of each target. It can then use the time–frequency profile to identify the target. The operator can then adjust the transmitted signal spectrum to match the target and enhance detection of a particular target class.

Classical communications system theory says we can determine the transfer function of a system (object/target) by exciting it with a Dirac-delta impulse of an infinite band-width and for an infinitesimally short duration. A radar target will respond with signals determined by its resonating elements that depend on the geometry and material properties. Thus we can say targets have resonance characteristics that produce a unique time-frequency signature when excited.

Such formal studies have been done for narrowband and wideband time-domain radar systems to exploit target-specific unique signal signatures produced by natural resonances and use them for target identification. The singularity expansion method (SEM) was formally developed by C.E. Baum in the 1970s for transient electromagnetic scattering from targets illuminated by pulsed electromagnetic (EM) radiation (Baum, C.E., 1976). SEM is based on some observations that the transient responses of complex electromagnetic scatterers are dominated by a small number of damped sinusoids. From a formal mathematical perspective, it is backed by the analytic properties of the electromagnetic responses that are expressed as a function of the two-sided Laplace transform complex frequency, variable s. Singularities of the Laplace transform are used to characterize the electromagnetic response of a structure to incident radiation or a driving source, in both the time and complex frequency domains (Baum, C.E et al. 1991).

A wave of new interest in the SEM emerged a decade ago and was correlated with interests in UWB applications including subsurface characterization of targets like landmines and similar obscured objects (Baum, C.E., 1997). Such SEM representations have been developed for both induced currents and scattered fields including their aspect-independent forms. Processing signal SEM signatures would give some indications on the general shape and the constitution of the illuminated targets. It was successfully demonstrated in simulations and with less success for measured data because of sensitivity of SEM techniques to noise level. For example, in the case of landmine detection, the strong soil attenuation lowers the Q factor of the observable resonances and, thus, reduces...
the detectability and signal-to-noise ratio (SNR). Other close approaches are associated with E-pulse and K-pulse (excitation pulse) techniques (Kennaugh, E., 1981; Martin, S. 1989; Rothwell, E.J et al. 1987). For example, the K-pulse technique exploits a different approach. Instead of illuminating a target with a pulse that excites all inherent target resonances, the target is illuminated by a matched pulse that produces a short possible detected response and so on.

The advanced UWB radar system will transmit a wide spectrum virtual-impulse signal that simulates a Dirac-delta impulse signal. The virtual-impulse spectrum bandwidth will cover the probable resonances in a class of targets. Distinct resonant elements of the target will appear in the return signal. Demonstrations have shown how the different objects uniquely modify the waveform (and spectrum) of UWB signals. Note that the advanced UWB radar can operate at any place in the microwave spectrum. The designer must assure that the UWB modulation bandwidth covers the likely resonances of a target class. (Barrett, T.W. 1996; Barrett, T.W. 2012; VanBlairicum, M.L. 1995)

The advanced UWB radar can carry the process one step further by changing the transmitted waveform to match a specific target class. When using correlation detection, this waveform tailoring will enhance the response of specific classes of targets. Targets outside of the selected class will have weaker returns because their signature does not match the correlation reference signal.

The advanced UWB radar will require a receiver capable of converting short duration impulse signal returns to a digital form for storage and time–frequency analysis. For special applications, it may require a transmitter, that can change signal waveforms to match the target. Knowledge of the target characteristics means the radar can modify its signal waveform to enhance the returns from specific classes of objects through correlation detection. This target probing and signal matching concept has broad applications for medical, security, nondestructive testing, and other radar applications.


This chapter will present a conceptual guide to the UWB impulse signal and target interaction phenomenon. It will show how to use the signal spectrum change to identify and enhance detection and tracking of certain target classes. After developing the performance objectives, it will present an advanced UWB radar architecture and concept of operation. The final sections present UWB radar digital receivers and transmitters implementations.

### 3.2 Advanced UWB Radar Applications

#### 3.2.1 Benefits of UWB Radar Return Signal Analysis

Capturing UWB radar return signals can provide a way to examine the spectrum change between the transmitted and the returned signal. The reflected return signal waveform (spectrum) depends on the band of the transmitted signal frequencies and physical characteristics of the target geometry and materials. If the radar target contains resonances in the spectrum of the UWB impulse signal, then analysis of the return signals into time and frequency components opens possibilities for the following:
• Target identification: Comparing the return signal spectrum against a database of known returns could provide a way to identify the target. The identification process could determine if the target belongs to a specific class of objects.

• Target return enhancement: The time–frequency signal-processing techniques described in Chapter 4 can determine the target resonance characteristics. This can let the radar modify the transmitted signal to match the target and enhance the detector correlation output from the specific target class return signal. Providing the target class signal spectrum as the reference signal for a correlation filter will enhance tracking of that target class and reduce the correlated detection signal from other targets. Barrett developed and demonstrated this technique in Resonance and Aspect Matched Adaptive Radar (Barrett, T.W. 2012).

• Intelligent remote sensing: Suppose the advanced radar operator could select a signal spectrum based on either a priori knowledge, or from immediate measurements and signal analysis. This can help to continually modify the transmitted spectrum to search for specific classes of objects. For example, a GPR could search for specific classes of buried objects, for example, land mines, low contrast objects (plastic mines), and structures. A medical radar could search for low contrast tumors or tissue pathology with harmless, low power EM radiation. Chapter 2 described detecting pavement layers using return signal analysis methods.

3.2.2 Advanced UWB Radar Technology Requirements

Building an advanced UWB radar system will require several major components including:

• Time-domain receiver: This means an antenna and a wideband receiver that can record the received signal waveform in a digital format for time–frequency analysis. Barrett described such a receiver used in the Resonance and Aspect Matched Adaptive Radar (RAMAR) demonstrations (Barrett, T.W. 2012). Pochanin et al. described a time-domain receiver based on a stationary signal and stroboscopic digitization methods in Chapter 2. This requires capturing the received waveform with enough resolution for signal processing to accurately analyze the time frequency components using the techniques of Chapter 4.

• Signal sampling and digitization: The sampling methods will depend on the capabilities of analog-to-digital converters (ADC) and the bandwidth of the needed signal spectrum as determined by the target resonance characteristics. The short received signal duration and low power levels may require techniques for increasing the amplitude for accurate digitization and time–frequency analysis.

• Time–frequency signal processing: The signal-processing system can apply one of the several methods described in Chapter 4 to determine the time–frequency profile of the signal. The resulting profile can provide the basis for target identification and transmitted signal waveform synthesis.

• Variable waveform transmitter: The system must transmit a wide variety of waveforms for target probing and/or return signal enhancement. This will require a digitally controlled transmitter that can synthesize a signal from the target time–frequency profile.

• Specialized system architecture: All advanced systems will share a common architecture, but operate in different frequency ranges depending on the type of targets.
of interest. Artificial intelligence signal processing will play important roles in locating and tracking specific type of targets if the time–frequency characteristics change due to movement.

3.3 UWB Radar Signals and Targets

Past UWB radar designs have found better ways to find objects by transmitting a fixed waveform signal and detecting the reflected energy from a given class of objects. Generally these approaches used receivers with matched filter detection based on the transmitted signal and assuming no return signal spectrum changes. Signal processing stored the received energy from multiple returns for integration to higher SNR levels. The target RCS for that particular signal spectrum set the system performance limits. These simple and effective designs work well in many applications.

Researchers have demonstrated the distinct UWB radar signatures of targets and suggested their application for passive identification. Astanin, Barrett and others have proposed matching signals to target characteristics. Immoreev et al. have shown how the waveform of a reflected UWB signal varies depending on the bistatic angle from the target. This section will give an intuitive explanation of how to exploit target resonance effects with a virtual impulse signal (Astanin, L.Y. and Kostylev, A.A. 1997; Astanin, L.Y. et al. 1994; Immoreev, I. 2000; Immoreev, I. 2012).

3.3.1 UWB Signal and Target Interactions

Most radar books include an illustration similar to Figure 3.1(a) that shows the normalized reflected energy from a perfectly conducting metallic sphere of radius \( a \) plotted against the wavelength \( \lambda \) divided by the sphere circumference \( 2\pi a/\lambda \). The reflected energy falls into three regions as follows:

![Figure 3.1](image.png)

**FIGURE 3.1**
Signal reflection from a perfectly conducting sphere. (a) The classic Mie resonance response results when the incident wavefront diffracts around the sphere and falls in phase with the directly reflected signal to produces an enhanced RCS and (b) the reflected energy response for a UWB impulse signal of duration \( \tau \) produces this response. (From Astanin, L.Y. et al., Radar Target Characteristics: Measurements and Applications, CRC Press, Boca Raton, FL, 1994).
1. The Rayleigh region with long wavelengths so that \((2\pi a/\lambda) < 1.0\). The wavefront passes around the sphere with no significant bending or diffraction. The sphere has a low effective reflecting area, or radar cross section (RCS) compared to its physical size.

2. The Mie resonance region reflection occurs when the wavelength approaches the same size as the sphere circumference, that is, \((1 < (2\pi a/\lambda) < 10)\). The resonance model assumes a single continuous frequency signal acting according to wave mechanics. This assumes that the wave front travels around the sphere and directly back to the source. This delayed diffracted wave front produces reinforcements and cancellations when it combines with the directly reflected wave. The largest reflection enhancement (+3 dB) occurs when \((2\pi a/\lambda) = 1\). The maximum RCS enhancement happens when the wavelength matches the path length around the sphere. In this condition the diffracted wavefront reinforces a directly reflected wavefront reflected by the front half of the sphere. Any deviations from this condition produce less RCS enhancement depending on the ratio of \(2\pi a/\lambda\). (Knott, E.F. 2008)

3. The optical region occurs when the wavelength is much smaller than the sphere circumference so \(( (2\pi a/\lambda) > 10)\). This provides a convenient narrowband RCS model based on the target size (cross section area) and shape. Note that most radar systems operate in the optical region for practical considerations of antenna size or frequency allocations.

Astanin et al. examined the impulse signal response spherical target. His analysis used an UWB impulse signal of duration \(\tau\) and plotted the response against the range resolution \(\Delta r = c\tau/2\) divided by the sphere of radius \(a\) or \(ca\tau/2\). The impulse response plot shown in Figure 3.1(b) implies an optimal physical size of an impulse signal for detecting targets with some characteristic dimension close to signal spatial resolution (Astanin, L.Y. et al. 1994). Note that the model does not cover the case where the impulse signal bandwidth covers natural target resonances.

Immoreev developed the idea that objects have unique responses depending on the physical length of the UWB signal \(c\tau_o\), where \(\tau_o\) indicates the signal autocorrelation time. For signal lengths about the same size as some target dimension, that is, \(d \approx c\tau_o\), the resulting target return signal will change waveform. His analysis assumed the transmitted signal induced currents in the target, which then radiated a new signal in all directions. He further showed how a reflected signal waveform will change depending on the bistatic angle from the target, or with the aspect angle of the target with respect to the arriving wavefront (Immoreev, I. 2000; Immoreev, I. 2012).

For the opposite case of \(d < c\tau_o\), the overresolved target case, the target becomes a series of returns from each reflecting part with different, but close time delays between them (Immoreev, I. 2000; Immoreev, I. 2012). Figure 3.2 shows the practical effects of under-and overresolved targets in UWB radar design. For applications such as radar imaging, the system needs the overresolved target return of Figure 3.2(b) for a fine grain target picture. For other applications the system can work with the under-resolved signal of Figure 3.2(c) Table 3.1 summarizes the continuous wave and impulse conditions.

Sachs et al. pointed out how UWB radar detection resembles determining the impulse response of an electrical system (Sachs, J. 2012). Although the analytical Dirac-delta impulse has a theoretically infinite spectrum, a signal with a spectrum covering the resonances of the object could achieve the same effect. Examining the radar return signal permits
modeling the target as a set of multiple resonating points. Figure 3.3(a) shows the concept of impulse response measurement using a signal spectrum covering the major resonances of the object. With appropriate signal processing, a UWB radar could determine the presence and electrical characteristics of an object as shown in Figure 3.3(b). In this case, the return nonsinusoidal signal is made up of sum of waveforms from the characteristic object resonances as shown in Figure 3.3(c). Time frequency analysis could find a distinct target time frequency profile. Astanin and Immoreev have established the basic theory for understanding UWB signals waveform shifting. Relating the waveform shift to the target

**TABLE 3.1**
Spherical Radar Target Resonance and Spatial Resolution Conditions

<table>
<thead>
<tr>
<th>Continuous Wave</th>
<th>Impulse Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere circumference/wavelength</td>
<td>Range resolution/sphere radius</td>
</tr>
<tr>
<td>$2\pi a/\lambda$</td>
<td>$\Delta r/a$</td>
</tr>
<tr>
<td>$2\pi a/\lambda &lt; 1$</td>
<td>Rayleigh scattering</td>
</tr>
<tr>
<td>$1 &lt; 2\pi a/\lambda &lt; 10$</td>
<td>Mie resonance</td>
</tr>
<tr>
<td>$2\pi a/\lambda &gt; 10$</td>
<td>Optical scattering</td>
</tr>
</tbody>
</table>

**FIGURE 3.2**
UWB radar reflections depend on the spatial resolution for impulse waveform matched filter detection. (a) The ratio of UWB signal-range resolution to the target size will determine the type of target response, (b) a spatial resolution much smaller than the target will result in returns from the target at each down-range increment. The overresolved target case works well for UWB imaging, and (c) the underresolved target cases detects large object, the same general size as the target, and produces single response.
characteristics will take the first step to a new field of radar spectroscopy and tomography. Barrett demonstrated this in Chapter 4 (Barrett, T.W. 2008; Barrett, T.W. 2012).

Each target will have multiple resonating components that will remain the same. Barrett observed that changing the target aspect will change the return signal waveform by shifting the time sequence of each arriving signal component. Depending on the aspect angle with respect to the virtual-impulse wavefront, some resonating elements will have a stronger response while others diminish. To understand the concept, visualize the radiation pattern of a half-wave dipole. Some resonant responses will arrive at different times with respect to others. Although these aspect angle related delays will change the composite waveform, they will not change the overall frequency content in the reflected signal (Barrett, T.W. 2012).

3.3.2 Virtual-Impulse Signal

Suppose we want to build an advanced UWB radar for the purpose of detecting a specific class of aircraft targets such as modern fighters. Assume we know the maximum target size $d$ as shown in Figure 3.4(a). This means the target will have several resonating...
parts with frequencies \( f_1, f_2, \ldots, f_n \). The lowest resonance frequency of interest will have a frequency \( f_{\text{low}} < c/2d \). The advanced UWB radar will use a virtual-impulse signal as shown in Figure 3.4(b) that will excite the resonating elements of the target, for example, wings, tail, and fuselage.

For practical purposes radar targets such as mines, trucks, aircraft, artillery shells, and missiles have distinct resonance signatures depending on the materials, physical size, and aspect angle with respect to the radar line of sight. The work of Baum, VanBlairicum, Astanin, and Immoreev predicted this interaction of UWB signals and targets, and suggested the potential applications to radar target identification.

Barrett’s RAMAR experiments demonstrated the target resonance concept on real world objects. The RAMAR used a broad spectrum signal modulation on a carrier signal to determine target resonances. After return signal time–frequency analysis, the demonstration RAMAR synthesized a signal modulation tailored to the target. In Chapter 4, Barrett presents methods for the time–frequency analysis of UWB signals. The resulting time–frequency profiles can identify targets and provide information for signal resonance modeling. He demonstrated methods for analyzing the returns from a UWB signal to provide an optimal signal tuned to a particular target class. As expected from the theoretical studies, field test results showed how the target resonances depended on the wavefront aspect angle with the object. RAMAR demonstrations showed how matching signals to the target resonances can substantially increase the return signal amplitude (Barrett, T.W. 2012).

The advanced UWB radar will operate as shown in Figure 3.5. The radar transmits an impulse signal covering the time–frequency characteristics of multiple target configurations. For example, this impulse signal could use broadband modulation of a carrier signal, such as linear frequency, step frequency, random noise, and pseudorandom noise modulations with a 3 GHz bandwidth on a 30 GHz radar signal. In this figure, the radar receives and digitizes returns from two different target geometries. The signal-processing system performs a time–frequency analysis that breaks the return into several distinct frequencies of a specific time duration. Each target class has distinct target characteristics shown in Figure 3.5(b). Comparing target signatures with a database of radar signatures from previous observations, or predicted responses, could provide the
operator with a target identification. For example, the star reflectors could indicate a specific class of mines, aircraft, rocket, vehicles, and material defect. The pentagonal symbols represent a benign object.

To illustrate the advanced UWB radar possibilities, imagine a security surveillance radar network for detecting and locating pickup trucks with machine guns. The operator could first search the field of view and determine the classes of targets visible. Signal processing will produce a time–frequency signature of each return as shown in Figure 3.5(b). This would produce a display of each return signature file organized by range and direction as shown in Figure 3.6(a). Either the radar operator, or preprogrammed signal controls could then synthesize a signal matched to armed pickup trucks. The new display of Figure 3.6(b) will then enhance the returns from trucks and suppress other returns because they do not match the expected target return waveform set in the correlation detectors.

### 3.3.3 Target and Signal Matching Possibilities

The advanced UWB radar can use a virtual-impulse signal to determine the time–frequency profile and characteristic resonances of specific target classes with resonances included in the impulse signal bandwidth. This target-signal matching feature can expand the radar capabilities for searching for specific target classes. The concept has potential applications across a wide range of radar functions and opens new possibilities for practical applications.
Barrett’s Chapter 4 discusses the various time–frequency methods available. Sukarevsky’s Chapter 5 presents a method for predicting how an object will scatter UWB impulse signals. Chapter 6 describes nondestructive testing that could benefit from signal analysis. Chapters 7 and 8 present biolocation applications that could benefit from these target return analysis techniques. In Chapter 12, Francois LeChevalier presents another approach to tailoring signals to targets to enhance specific performance objectives.

3.4 The Advanced UWB Radar

Many researchers have advanced the idea of intelligent or active radio signal processing to enhance target detection or communications. I as well as other researchers have suggested the basics of this concept in earlier books and papers (Taylor, J.D. 2012; Taylor, J.D. 2013). This section includes ideas similar to those of Joseph Guerci’s *Cognitive Radar* (Guerici, J.R. 2010) and Simon Haykin’s *Cognitive Dynamic Systems: Perception-Action Cycle, Radar, and Radio* (Haykin, S. 2011). The advanced UWB radar concept draws heavily on Barrett’s RAMAR for the methods and benefits of matching signal waveforms to specific targets (Barrett, T.W. 2012).

3.4.1 Performance Objectives

This section presents an intuitive overview of the performance objectives, technical issues, and an advanced UWB radar system that can modify signals to match specific target classes.
3.4.2 Fixed Signal UWB Radar Limitations

Why build an advanced UWB radar for target and signal matching? Currently UWB radar systems operate in a passive fixed signal mode with respect to their targets. These systems transmit a single UWB waveform signal appropriate to the particular radar design objective and probable target characteristics. Conventional UWB receivers and signal processors detect reflected energy and the signal arrival time to determine the range for each reflector. Range resolution depends on the signal duration or autocorrelation time of the particular signal. The correlation (matched filter) detection process assumes a strong resemblance between the transmitted and reflected signals for a maximum detector output. Collected received energy returns recorded against the arrival time produces a matrix of high-resolution range information about targets in the field of view. The material-penetrating radar (MPR) shown earlier in Figures 1.1 through 1.3 illustrate this type of signal processing.

For large targets, the target data matrix shows the returns from the multiple parts of a large object, as shown in Figures 1.4 through 1.7. Signal-processing methods can produce an output for a specific purpose. In each case, the fixed signal waveform and target characteristics set inherent limits on system performance. The fixed signal approach provides practical benefits and economical solutions to specialized requirements. The advanced UWB radar with target return time–frequency analysis could provide a remote sensor for special applications.

3.4.3 The Advanced UWB Radar Architecture

The signal target to matching concept described earlier could improve radar performance for a wide range of special applications. A radar with return signal analysis could adjust the transmitted signal format to achieve maximum returns for detecting specific target classes. For example, the radar could match the signal to targets such as classes of mines, underground objects, diseased biological tissues, imperfections in dielectric composite materials, and flying, or ground based objects.

An advanced UWB radar architecture would have the same functional elements for all applications, but different configurations depending on the particular operational purpose (Taylor, J.D. 2013). For example:

- Ground-penetrating radar (GPR) signal processing could search for specific objects, soil differences, and other useful conditions. In Chapter 2, Pochanin described a GPR that analyzes the return signal waveform to achieve precise ranging and to identify layers of asphalt pavement in highways. In Chapter 7 Liu describes a radar for searching victims buried under collapsed buildings. Both these applications could potentially benefit from an advance UWB radar approach with target signal matching to increase detection performance.

- Nondestructive testing radars could search for changes in material layers indicating flawed or damaged dielectric parts or structures. In Chapter 6 Cristofani describes applications of radar to inspecting composite aircraft parts that could benefit from signal to target matching.

- Medical radars as shown in Figure 1.3 could search a patient for changes in tissue characteristics and reflectivity. Doctors operating in austere conditions, such as a field hospital or remote clinic, could use the advanced UWB radar to quickly image internal tissues and evaluate injuries without X-rays.
• Through-the-wall and security imaging radars as shown in Figures 1.5 and 1.6 could use optimal signals for contraband and weapons detection. Chapter 11 presents the basics of through-the-wall radar systems.

• A long-range surveillance and tracking radar could modify its signal to enhance the detection of specific target classes. Barrett’s RAMAR could evolve to this way.

An advanced UWB radar architecture would look like Figure 3.7 and the signal optimization process like Figure 3.8. The architecture assumes overall control using artificial intelligence with active user inputs to determine the types of targets emphasized. For example, the user could direct the radar to switch back and forth between target types.

The target identification signal process would follow the general process shown in Figure 3.8. In this case the term *impulse signal* refers to any signal format that can provide a range of frequencies covering the targets of interest. As Barrett points out, the *impulse* could include the modulation of some powerful carrier signal. For high power systems, the carrier signal could exist in some designated frequency band with a UWB modulation appropriate to the target (Barrett, T.W. 2012).

![Digital signal generation](image)

**FIGURE 3.7**
Notional advanced UWB radar architecture for determining target time–frequency characteristics, identifying targets, and adapting the signal for a maximum target return.
3.5 Advanced UWB Radar Technology Requirements

The advanced UWB radar shown in Figures 3.7 and 3.8 for locating and measuring the target characteristics will require the following components:

- A receiver with both frequency and time-domain signal-processing capabilities.
- A digital receiver which can preserve the signal waveform. The nonsinusoidal UWB waveform will present special problems for accurate analog to digital conversion. Section 3.6 UWB signal registration sections will discuss potential analog-to-digital converter (ADC) solutions. Chapter 2 discussed the received signal digitization problem and presented one solution.
- A range bin memory to store and integrate multiple weak signal returns to accurately reconstruct the nonsinusoidal (multiple frequency) waveform for time–frequency analysis.
• Return signal time–frequency analysis processing to determine characteristics of targets in the field of view. Chapter 4 presents a summary of signal analysis techniques for UWB signals.

• A library of known or predicted target time–frequency signatures for target class identification.

• A search mode using different signal waveforms to search for previously unknown target signatures.

• Capability for storing unknown signatures for further processing and identification.

• Signal modification software to optimize returns from a class of targets.

• A digital waveform synthesizer to translate the target time–frequency profile into a transmitter input.

• A signal generator that converts the selected target class time–frequency characteristics and produces a signal to match the target and control the transmitter signal. This will involve special digital-to-analog converter (DAC) technology and a special transmitter power amplifier.

• Digitally controlled transmitter and an antenna.

• Artificial intelligence system controller to adapt to changing target conditions.

In conventional radars, frequency domain processing locates targets based on the reflected energy time delay. Practical range sensors use many techniques based on matched filtering and return signal integration in range bins for detection.

Time-domain processing requires recording the reflected signal waveform for further analysis. This could mean some single pass digitization, or the collection and integration of multiple signal digital conversions to get the waveform details needed for successful operation. The notional drawings of Figures 3.1 through 3.3 showed how target material and physical characteristics can modify a UWB radar return waveform. Analysis of the time-domain response can identify the electrical and geometrical characteristics of radar targets for identification.

The following sections will discuss signal ADC methods and UWB transmitter types.

### 3.6 UWB Signal Registration

Current UWB radar receivers treat target reflections as energy bundles received with a given time delay indicating the range to a specific point on a target. The advanced UWB radar can overcome the limits of systems using one signal format for all targets. If we approach the radar design using communications system theory, then we can use an impulse signal to excite and determine the target transfer function which shapes the return signal spectrum. Although the ideal Dirac-delta pulse has an infinite spectrum extent, a practical Dirac-delta pulse will have a limited spectrum because only such signals can be generated and radiated. At the same time, target-specific probing pulses need to cover the spectrum of natural resonances and not waste energy beyond that spectrum.

The receiver capabilities will limit the radar performance by its ability to capture the target return from the impulse probing signal for time–frequency analysis. Adequate ADC of the complicated target waveform can use many approaches including special methods.
and approaches based on compressive sensing and other mixed analog-to-digital methods such as time lenses. We can make a reasonable stationarity assumption that each received return from a given target will repeat periodically, which means we can integrate successive returns or use lower ADC sampling applied to different parts of successive signals. Some systems will need real-time or near real-time operation to acquire the waveform within a few successive signal repetitions.

### 3.6.1 Technical Considerations in Digitizing Received UWB Signals

The advanced UWB radar receiver performance will depend on an ADC for signal data acquisition, measurements, and automation. All ADCs process continuous real-world signals into discrete digital formats for efficient storage. The ADC output will go to central processing units (CPUs), digital signal processors (DSP), field-programmable gate arrays (FPGAs), or graphical processor unit (GPU) to support major signal-processing routines required to implement advanced radar concept. Now we need to examine how well an ADC can convert a nonsinusoidal short period signal.

Modern ADCs have many architectures including the sigma-delta, successive approximation register (SAR), high-resolution, and high-speed ADCs (Kester, W. 2004; Pelgrom, M.J.M., 2010). Commercial electronics in the audio and video bands for communication applications such as 3G, software-defined radio (SDR) and other systems now use ADCs. The radio frequency (RF) and microwave bands for UWB radar applications have much higher data throughput and dynamic range requirements which limit ADC applications for real-time operations.

This section focuses on real-time operations with high-speed and high-dynamic range ADCs. Applying high-speed ADCs front-ends in broadband and UWB EM systems has many technical issues dominated by the following:

1. Performance trade-offs between conversion speed and conversion accuracy (resolution) while mitigating associated excessive power consumption. For example, some ADCs have high sampling rates but not the best signal-to-noise ratio (SNR). ADCs with a good SNR typically have lower sampling rates. The capability to simultaneously achieve good SNR and high speeds is mutually exclusive for single-core ADCs. This condition forces advances in multi-core ADCs or an ADC made from cascaded and properly clocked low-rate ADC units (Rolland, N. et al. 2005).

2. Implementation complexity and integration with other subsystems. The engineer must consider the radar performance objectives and architecture as a whole, when designing the digital time-domain receiver. The overall systems architecture must integrate both the hardware and software parts of the entire system into a functioning unit.

3. Economic factors could make the cost of high-speed ADCs prohibitive for many applications. The systems engineer must clearly understand and consider all the above factors separately and in their mutually conflicting relations when planning the radar architecture. The lack of systematically published references means the designer must consult many datasheets, application notes, webcasts, and other sources. The final selection of a particular ADC architecture and components will come to a question of systems cost versus user benefits.

This section will present the technical considerations of ADC devices in a compact and comprehensive form.
3.6.2 ADC Operating Principles and Performance Metrics

3.6.2.1 ADC Theory and Limitations

To understand the problem of UWB signal digitizing we need to understand how ADC converters work and the design assumptions behind them. We must also understand the nature of reflected UWB impulse signals modified by the target.

Our discussion of the advanced UWB radar receiver will treat the ADC as a black box. Functionally the ADC takes in a continuous analog input signal (voltage) and emits a stream of digital words indicating the measured input value at given discrete time intervals (Baker B., 2011; Pearson, C. 2011). Signal digital conversion requires two consecutive processes: (1) signal sampling and (2) digitization (quantization) as shown in a high-level time domain functional scheme in Figure 3.9.

First, the ADC samples the input analog signal at the sampling frequency $F_s$ which is at least twice the known signal frequency, or maximum expected signal frequency of the target response, $F_{max}$ according to the Nyquist theorem. Then the sampled signals are transformed into a digital format as illustrated in Figure 3.9 for the 3-bit case when a quantized number of a closed digital bit is assigned at the output. The nomenclature of the major parameters in this presentation level includes the following:

1. $n$ is the number of output bits (resolution)
2. $A_{IN}$ is the analog input voltage that must not exceed $V_{max}$
3. $V_{REF}$ is the reference voltage (or current) used to compare the input signal

More ADC operational features can be assessed in the frequency domain. This type of information is provided in datasheets for a set of single harmonic input signals as sketched in Figure 3.10 for frequency $F_1$. Table 3.2 shows the key ADC parameters.

The ADC SNR is the first important characteristic. There are two SNR interpretations, namely the ideal (or theoretical) and the practical (or real). The ideal SNR for an $n$-bit ADC is the ratio of the root-mean square (RMS) full-scale, digitally reconstructed, analog input $V$, that is $0.5V/\sqrt{2}$, to its RMS quantization error (i.e., $V_{LSB}/\sqrt{12}$, where LSB is the least significant bit Equation 3.1):

$$SNR = 2^n \sqrt{3}/\sqrt{2} = 1.225 \cdot 2^n$$  \hspace{1cm} (3.1)

![FIGURE 3.9](image)

The ADC works in the time-domain to sample the broad spectrum input voltage at the sampling frequency $F_s$. This 3-bit ADC provides an output of the input signal. Accurate signal digitizing requires prior knowledge of the signal amplitude and frequency.
or on the logarithmic decibel (dB) scale (Equation 3.2)

\[
\text{SNR}_{\text{dB}} = 6.021 \cdot n^2 + 1.763
\]  

(3.2)

This quantity can be considered also as the theoretical dynamic range (DR) limited only by quantization noise. Other noise contributions involved degrade the DR as further shown. For the given signal spectral presentation in Figure 3.10(2), the SNR is defined as (Equation 3.3)

\[
\text{SNR}_{\text{dB}} = 10\log(\frac{P_s}{P_n})
\]  

(3.3)

SNR and DR are both functions of input signal frequency \( F_i \), because the ADC operates across certain bands. This single tone signal is often called the \textit{carrier} and SNR is then characterized in dBC units which means dB to carrier.

Most ADC datasheets provide the frequency-dependent \( \text{SNR}(F) \) and \( \text{DR}(F) \) for the several operational conditions defined as follows:

1. For a number of characteristic frequency points below the Nyquist limits.
2. At several input signal magnitudes below its maximum permitted extent, \( V_{\text{max}} \) in Figure 3.9.
3. For one or a few conversion rates.

The ADC is by its nature a nonlinear device that outputs a number of harmonics which are unwanted byproducts that contribute to the overall output noise as shown in Figure 3.10.

---

**TABLE 3.2**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal power</td>
<td>Power ( P_s ) associated with a single tone signal ( F_1 )</td>
</tr>
<tr>
<td>Noise floor power</td>
<td>The inherent noise ( P_n ) within the ADC input channel caused by thermal noise, interference, and so on. Limits the smallest resolvable increment</td>
</tr>
<tr>
<td>Power of harmonics</td>
<td>Signal power ( P_i (i = 1, 2, 3 \ldots 6) ) of corresponding harmonic frequencies ( F_i = F_1 )</td>
</tr>
<tr>
<td>Power of highest spur</td>
<td>Signal power ( P_H ) associated with the highest power harmonic (4th harmonic in Figure 3.10)</td>
</tr>
</tbody>
</table>

---

**FIGURE 3.10**

ADC frequency domain operation with the input signal tone numbered by 1 (fundamental) and a set of harmonic products numbered from 2 to 6, among which the harmonic 4, in this particular example, shows highest power and, thus, would be used in SFDR (3.6) calculations.
Several such harmonics, labeled from 2 to 6 are typically specified in datasheets and contribute the total distortion power (Equation 3.4)

\[ P_D = P_2 + P_3 + P_4 + P_5 + P_6 \]  

(3.4)

Then the total harmonic distortion (THD) is defined as (Equation 3.5)

\[ \text{THD} = 10 \log \left( \frac{P_5}{P_0} \right) \]  

(3.5)

The spurious-free dynamic range (SFDR, \text{dB}) is defined as (Equation 3.6)

\[ \text{SFDR}_{\text{dB}} = 10 \log \left( \frac{P_3}{P_{N+P_D}} \right) \]  

(3.6)

where, \( P_H \) is next highest spur, for example \( P_H = P_4 \) in Figure 3.10. The ratio of the signal power to the overall power of noise and harmonic distortions defines the signal-to-noise and distortion (SINAD) (Equation 3.7):

\[ \text{SINAD} = 10 \log \left( \frac{P_S}{P_N+P_D} \right) \]  

(3.7)

An important ADC performance measure is the effective number of bits (ENOB), which is derived by combining Equations 3.2, 3.3, and 3.6 as (Equation 3.8):

\[ \text{ENOB}_{\text{bits}} = \frac{(\text{SINAD} - 1.763)}{6.021} \]  

(3.8)

An ADC can have several composite figures of merits (FOM). The one shown below gets the most consideration:

\[ \text{FOM} = F_s \cdot 2^{\text{ENOB}} \]  

(3.8a)

This FOM suggests that adding an extra bit to an ADC is just as hard as doubling its bandwidth (Walden, R.H. 1999).

The sampling frequency stability is important for the ADC performance. Any instability, often called collectively jitter, contributes to degradation of the key ADC parameters, for example, SNR, SINAD, and ENOB.

### 3.6.3 UWB Signal ADC Time Interleaved Digitizing Strategies

In many cases, ADC technology may not support single pass UWB signal digitization. In this case we can apply digitizing techniques based on the known or assumed signal repeatability. Pochanin described a stroboscopic approach in Chapter 2. Time interleaved digitizing provides a fast hardware approach to solving the problem (Pelgrom, M.J.M., 2010).

Using several ADCs running in an interleaved mode might resolve the tradeoff between achieving a good SNR and high sampling rates. As shown in Figure 3.11, a modern multicore time interleaving ADC combines several ADCs, say \( N \) units, of lower sampling \( F_s \) rate within the same package. All ADC cores operate in parallel being clocked at the same rate \( F_s \) with mutually adjusted time shifts to enable resulting higher sampling rate \( NF_s \). The samples produced by each core are then combined into one data stream at the output. This increases the power consumption for \( N \) converters by the factor \( N \). A block-diagram for \( N = 4 \) is illustrated in Figure 3.11(a) and timing diagram is shown in Figure 3.11(b),
shows the clock phase shift of 90 degrees with respect to each consecutive ADC unit (Hopper, R.J. 2015).

In an ideal case, the composite SNR has a performance roughly equivalent to an individual ADC core. However, the real hardware of multicore ADCs introduces errors that degrade the overall spurious-free dynamic range (SFDR). Figure 3.12 shows three such potential analog errors including misalignment in channel gain, DC offset, and timing shift for a two-core ADC used for a simple example. Their combined effect translates to spurious products in the captured signal spectrum as shown in Figure 3.13. In particular, the offset error introduces a discrete spurious tone and their quantity depends on the number of interleaved cores. For a four-core interleaved ADC, the interleaving spurs are located at $F_s/4$ and $F_s/2$ in Figure 3.13. The signal dependent errors of gain and clock phase yield images that are centered on the discrete frequencies $F_s/4$ and $F_s/2$ also shown in Figure 3.13. (Hopper, R.J. 2015)

It is potentially possible to construct an interleaved ADC from several off-the-shelf chips that will require quite advanced treatment of all involved signal integrity and board design issues (Rolland, N. et al. 2005).

However, there are some commercial ADC chips that are already based on the time-interleaved principle discussed above. The dual ADC ADS54J60 chip from Texas Instrument uses four interleaved cores per channel to achieve a 1 Gigasample per second.
(GSPS) output sampling rate. This converter employs a proprietary digital interleaving correction block to adjust for the core imbalances. This correction scheme always works in the background so there is never an interruption to the output data stream and achieves better than 80 dBc correction. The Texas Instrument ADC12J4000 chip uses four interleaved cores to achieve a 4 GSPS output sampling rate. This device operates with several options embedded for interleaving correction that can generally keep interleaving spurs better than 70 dBc at room temperature. (Hopper, R.J. 2015; TI ADC083000. 2015; TD ADC 12J000. 2015).

3.6.4 Nonconventional ADC Front-Ends

There are some cases that apply ADCs for RF, although benefiting from running them in anomalous modes that seem to violate the general basis of ADC operation dictated by proper selection of the Nyquist sampling frequency. The sampling theorem states that the sampling rate must be at least twice the largest bandwidth of the signal. However this can be changed to have it lower (undersampling) and higher (oversampling) with interesting practical advantages as discussed in the following subsections (Hopper, R.J. 2015).
3.6.4.1 Aliasing an ADC Mixer with Undersampling

A common way to perform ADC sampling at the Nyquist frequency to avoid aliasing as illustrated for a sinusoidal signal in Figure 3.14(a). In Figure 3.14(b), the signal frequency is increased six times, although the same sampling frequency is preserved and the original signal still yet to be sampled at the same temporal sample points as in Figure 3.14(a). Normally this situation is treated as aliasing, when the higher frequency will alias down to the ADC’s capture bandwidth. From another perspective, the ADC in the case of Figure 3.14(b) acts like a conventional RF mixer implemented with such a properly set under-sampling ADC technique. This can substantially simplify the receiver architecture by providing both a down-conversion mixing and digitization functions performed in a single down-conversion digital mixer built on a single ADC (Hopper, R.J. 2015).

To better understand this approach, that exploits benefits from aliasing, the overall signal spectrum is split into separate Nyquist zones in Figure 3.15. The first Nyquist zone represents the maximum sample bandwidth, that is equal to the sampling rate, $F_s$, divided by two. The higher Nyquist zones represent the adjacent spectrum bands with equivalent

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**FIGURE 3.14**
Higher-frequency aliasing used to operate as a digital down-conversion mixer. (a) Signal sampled at the Nyquist frequency and (b) signal of (a) at six times the frequency, but still sampled at the same time intervals as the lower frequency.

---

**FIGURE 3.15**
Nyquist spectrum zones with the first Nyquist zone for the maximum sample bandwidth and a sequence of higher Nyquist zones folded back onto the first Nyquist zone due to aliasing.
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bandwidth. The down-conversion that happened in the aliasing mode can be interpreted through the spectrum folding back onto the first Nyquist zone like an accordion. Each signal that ultimately resides in the first Nyquist zone has a counterpart located in a higher Nyquist zone. With proper analog filtering, the ADC can capture a desired signal in one of the higher Nyquist zones, equivalent to a higher RF frequency (Hopper, R.J. 2015).

3.6.4.2 ADC Oversampling

In some practical cases such as a GPR with sequential sampling, the bandwidth or the output frequency is not excessive and could be in the audio band. For normal practice, a low-speed ADC device with matched Nyquist sampling needs to be employed. However, there is still an advantage to utilizing the higher sampling rate capabilities of RF sampling converters. This case is called oversampling (also called averaged sampling) aimed to improve the SNR. This method measures the relative level between the desired signal power and the entirety of the noise power within the first Nyquist zone that represents the entire bandwidth of the device. The Nyquist zone bandwidth is the sampling rate divided by two, namely \( F_s/2 \) in Figure 3.16. As discussed above, all signals and noise from higher Nyquist zones will fold back into the first Nyquist zone of Figure 3.16 (Hopper, R.J. 2015).

There are several practical benefits to oversampling in RF systems. Most evident is that the image signal components in the higher Nyquist zones are separated farther in frequency space for higher sampling frequency as in Figure 3.16. If so, then we can implement antialiasing analog filtration with a simpler and substantially smaller roll-off to eliminate interfering signals that can alias down into the captured bandwidth. Another benefit of oversampling is improving the SNR performance beyond the theoretical quantization noise limitations. In general, the quantization noise is equally distributed across the Nyquist bandwidth. By increasing the sampling rate, the same quantization noise is spread over a larger Nyquist bandwidth while the desired signal remains fixed. To the end, downsampling (decimation) is typically performed in a digital filter to return to the

![FIGURE 3.16](image)

Two-sampling cases: one signal at the top, sampled near the Nyquist rate and one, at the bottom, that is oversampled with wider separation between Nyquist zones.
original bandlimited spectrum of the signal of interest and decrease the noise bandwidth (Hopper, R.J. 2015).

### 3.6.4.3 Signal Voltage Dithering Improves ADC Performance

Dithering means the addition of some white noise to analog signals before their digitization. This method helps resolve the trade-off between the bandwidth and dynamic range in ADCs. Figure 3.17(a) shows the usual method of adding external noise at the ADC input. This might look like a counterintuitive and wrong approach since it might degrade the SNR. However it does not degrade the SNR. Furthermore, the dither can be interpreted as a method of statistical linearization, namely smoothing the staircase-like ADC transfer functions. This technique originated in the audio field, where it improved quality of the sound of analog audio signal by extending the dynamic range in magnetic tape recorders back in the 1930s. Similarly this approach works for ADCs to enhance dynamic range by spreading the spurious spectral contents of the signal over its spectrum. Dithering gives this positive effect because of decorrelation noise in time and decorrelation between noise and signal. Applications where the spectral distortion caused by the quantization of low level signals is particularly undesirable will especially benefit from applying dither. Apparently a level of white random noise needs proper setting to maximize the SNR while avoiding rising of the spurious free dynamical ranges (SFDR) as shown in Figure 3.16(b). For ideal converters, the optimum dither is white noise at a voltage level of about 1/3 LSB rms (Analog Devices, 2004; Baker B. 2011; Hopper, R.J. 2015; Leon Melkonian, L. 1992; Pearson, C. 2011; Pelgrom, M.J.M. 2010).

### 3.6.5 Compressive Sensing and Sampling

Moving more wireless systems operational, signal processing into the digital domain has produced promising advances. Both software radio (software defined radio) and cognitive radio rely on a number of features observed in signal channels. Exploiting the sparse nature of real signals in the time or frequency domain, or both, can work greatly to improve the major functionality of wireless and sensing systems.

### 3.6.5.1 Compressive Sensing Signal Acquisition and Analog to Information Converters

Nyquist sampling for modern broadband systems requires the expensive, fast, and power-hungry ADCs discussed earlier in this chapter. In addition this will produce a tremendous flood of data forwarded to the digital processing elements. This situation results

![FIGURE 3.17](image)

Dithering, the addition of white noise to the ADC input can improve the ADC SNR.
from the traditional brute force approach to capture and digitize radar return signals of UWB radar systems.

To understand the significance, we can consider signals in a broader sense using 2D signal spectrograms in the time–frequency coordinates shown in Figure 3.18. In this diagram, signals appear only in one or a few localized areas while most of the diagram is virtually blank. In the traditional brute force approach, the whole area with dominant blank spaces must be acquired, digitized, and processed.

Digitizing blank spaces produces many redundant computations with no significance to the system performance. Brute force ADC also produces apparent penalties of increased cost, size, weight, and power consumption. These hardware oriented approaches can produce a flood of data that will overwhelm downstream processing and information extraction algorithms. Resolving the signal-processing bottleneck with more computer power, these hardware based approaches will fail to produce an optimal system with regard to the bandwidth-bits product figure of merit.

For many, if not most, of the radar and sensor operational scenarios, the full signal spectrograms are similar to those in Figure 3.18 with signals that are inherently sparse in the sense that only a few spots are occupied across limited bands during limited periods of time. This means, for example, from a mathematical perspective, that the total time–bandwidth product (TBWP) occupancy might be much smaller than the total collection TBWP area \( \text{TBWP}_{\text{MAX}} = (T_{\text{max}} - T_{\text{min}})(F_{\text{max}} - F_{\text{min}}) \).

For example, if \( F_{\text{max}} - F_{\text{min}} = 6 \text{ GHz} \), this instantaneous bandwidth will traditionally define the Nyquist sampling rate that must be as high as \( F_s \geq 12 \text{ GHz} \) and the ADC needs at least a 12 GSPS capability for this case. If the receiver works at the 12 GHz Nyquist sampling frequency, then only a fraction of the recorded data \( O(\text{TBWP}/\text{TBWP}_{\text{MAX}}) \) will have any meaning and empty digital recordings will take most of the data storage volume because of the sparse signal nature. Hence, we need a smart approach to resolve the issue by exploiting new hardware architecture designed to avoid the redundancy indicated above, that will much improve the size, weight, and power (SWAP), functionality, and cost (Davenport, M.A. et al. 2010; Donoho, D.L. 2006; Ender, J. 2013).

Many attempts have been made to properly record the real-world sparse radar signals pictured in Figure 3.18. One such successful attempt employs compressive sensing (CS), that this study considers only partially from a relevant perspective of subNyquist sampling. In other words, CS provides simple and efficient signal acquisition method at a low rate below the Nyquist limit followed by computational reconstruction. Using CS signal-processing techniques enables signal sampling with fewer randomized samples than Nyquist sampling (Laska, J.N. et al. 2006; Liu, Y. and Wan, Q. 2011).

**FIGURE 3.18**

Signal occupancy in the time–frequency plane shows a sparse structure. Compressive sensing eliminates digitizing and processing the areas with no information.
CS assumes that the signals have a sparse representation. This also assumes that the signals are compressible in some mathematical sense, for example, by the $O(TBWP/TBW_{\text{MAX}})$ sparsity measure simultaneously in the frequency and time domains. Thus the CS signal sampling framework enables sampling at subNyquist rates as small as $F_s/M$ where $M \approx TBWP/TBW_{\text{MAX}}$. Practically speaking, the number $M$ can be in the range of tens and hundreds depending on the particular operational specifics. A number of theoretical developments made in the CS field can leverage the structure of sparse signals into reduced sampling rates to implement so-called compressive sampling for direct analog to information conversion (AIC). A typical AIC combines the hardware-software architecture and consists of a front-end hardware encoder and a back-end software decoder with a low-rate subNyquist shown in Figure 3.19 with low-rate ADC sampling in between (Liu, Y. and Wan, Q. 2011).

The hardware portion of the AIC in Figure 3.19 includes an analog mixer (modulator) operating on a pseudorandom number generator (PRNG) $\pm 1$ sequence clocked at the Nyquist sampling rate. The sampled signals are fully recoverable in the CS framework if certain conditions are met and the recovery performed in the digital domain using a number of reported algorithms. Figure 3.20 shows some results for AIC performance prediction simulated in MATLAB®. In this model, the 12-bit ADC used in the AIC converter, samples a test signal composed of two continuous wave (CW) signals of 1.85 GHz and 6 GHz. This represents two signals that are sparse in the frequency domain and sampled in time-domain, making them treatable in the CS framework. The Nyquist sampling requires 12 gigabits per second (GBPS), but the subNyquist sampling is performed at two frequencies: (i) four times lower, that is, 3 GSPS, shown at the left in Figure 3.20 and 10 times lower, that is, 1.2 GSPS, shown at the right in Figure 3.20. The original and recovered signals are depicted in Figure 3.20 by their power spectral densities (PSD) that allow for estimation of the resultant SFDR, defined similarly to an ADC. In this simulation, signal recovery was performed via convex programming supported by the l1-magic MATLAB® package (l-1 Magic, 2006). The SFDR range is defined earlier in Figure 3.14(b) as the difference between the original signal amplitude and the highest spur. It turns out that sampling at 3 GHz (four times lower the Nyquist frequency) preserves nearly the full dynamical range of the 12-bit ADC used in the model Figure 3.20 at the left, while the lower rate subNyquist sampling degrades the SFDR in Figure 3.20 at the right (Baraniuk, R. and Steeghs, P. 2007).

3.6.6 UWB Signal Real-Time Time Stretching, Time Lens, or Time Imaging

Beyond the standard techniques for digital real-time UWB signals registration exists an alternative approach based on time stretching, time lens, or time imaging (Kolner, B. 1994; Kolner, B.H. and Nazarathy, M. 1989). This approach originated from the optical domain
for measurement of ultrafast optical waveforms. Such measurements made by using high speed photodiodes and sampling oscilloscopes are typically limited to a resolution of several picoseconds. To achieve femtosecond resolutions, the ultrafast optical waveforms can be stretched to timescales compatible with high speed electrical instruments (Coppinger, F., et al. 1999; Jalali, B. and Han, Y. 2013). This explains in part the meaning of temporal imaging in Figure 3.21. Additional meaning comes from the analogy between the spatial problem of diffraction and the temporal problem of dispersion and general time-space duality in Figure 3.22.

An interpretation of the time-space duality uses simplified solutions to the general wave propagation problem. For such solutions, the slowly varying envelope equations corresponding to modulated plane waves in dispersive media have the same form as the paraxial equations describing the propagation of monochromatic waves of finite spatial extent (diffraction). There is a correspondence between the time variable in the dispersion problem and the transverse space variable in the diffraction problem.

**FIGURE 3.20**
Simulated AIC sampling of two CW signals at 1.85 GHz and 6 GHz with their original PSD, at the top, and recovered, at the bottom, from subNyquist samples: (left) sampling is performed at 3 GSPS that is four times lower the Nyquist 12 GSPS with 70 dB SFDR signal recovering; (left) sampling is performed at 1.2 GSPS, that is, ten times lower the Nyquist 12 GSPS with 29 dB SFDR signal recovering.

**FIGURE 3.21**
Signal temporal magnification by stretching (zooming) in time.
Figure 3.22 shows a simplified overview of the optical analogy. In this case, an optical microscope uses a convex lens to magnify the image of the original object. A signal pump, for example, a chirped pulse and a nonlinear multiplier (mixer) operates similarly to the optical lens. Before mixing, the input signal goes through the input dispersion block and the pump signal passes through the pump dispersion block. The mixer output then passes through the output dispersion block to get a magnified version of the input signal. A magnification factor as for the lens, is mainly defined by the dispersion factor of the three dispersion blocks, although the pump source spectrum needs to agree with the initial signal spectrum. Simple math shows how this signal conversion works. Its practical implementation in real-world hardware introduces some restrictions and certain imperfections compared to just ideal mathematical case.

Optical band dispersion is made using dispersive fibers (Coppinger, F. et al. 1999). In the RF and microwave bands stretching applies two typical approaches: (1) transition to the optical band, perform stretching in optical band, and convert the optical signals back to their electrical counterpart; (2) perform all functions in the electrical domain. Both approaches have been demonstrated so far for RF and microwave bands with some degree of success (Schwartz, J.D. et al. 2007). Stretching such signals in time, enables sampling with slower rate ADCs below their initial Nyquist limits without loss of information (Kolner, B. 1994; Kolner, B.H. and Nazarathy, M. 1989).

Note how time compression of pulses is also possible by changing the order of the pump dispersion that applies dispersive lines. This can work for signal shape/spectrum control in addition to the methods considered in this chapter (van Howe, J. et al. 2004). For example, a waveform can be generated using a slow rate direct digital synthesis (DDS) as described further and then transformed to higher band by its compression in time.
3.7 Target Adaptive UWB Radar Transmitter Requirements

3.7.1 Targets and Signal Modulation Objectives

Target-adaptive UWB radars must generate signals with wavelength twice the size of the target of interest, as discussed in Section 3.6.2.2. The target matched signal will cover the range of resonances expected for a particular class of targets, for example, mines, vehicles, and tumors. The transmitted target matched signal may have two formats:

1. A short duration UWB impulse with components between \( f_{\text{low}} \) and \( f_{\text{high}} \) determined by the generating pulse width and shape, for example, Gaussian and square wave. This will be a typical case for short-range systems.

2. Modulation of a carrier about a center frequency as found in frequency-modulated continuous-wave and similar radars. Long-range systems will probably use this approach, as exemplified by the Haystack UWB Satellite Imaging Radar (HUSIR) described in Chapter 1. In Chapter 9 Ram Narayanan describes progress made in using noise signal radars.

In either case, the signal bandwidth must cover the resonances of the target class (Barrett, T.W. 1996; Barrett, T.W. 2012). The target matched signal will have components with wavelengths twice the electrical size of the target \( d \). The target size will determine \( f_{\text{low}} \) and either the spatial resolution or the highest target resonance of interest will determine \( f_{\text{high}} \). Figure 3.23 shows the frequency as function of target size based on a half wave dipole resonance frequency \( f_{\text{res}} = c/2d \). Actual objects may have more complicated frequency relations with the physical size.

![Graph (Figure 3.23)](image)

**FIGURE 3.23**
Estimated target resonant frequency versus size based on \( f_{\text{res}} = c/2d \) where, \( d \) indicates some characteristic target component size, for example, diameter, length, wing, and span. A real object can respond with multiple frequencies higher than the lowest shown here for the maximum dimension.

The advanced UWB radar systems transmitter will need special hardware implementations to provide reconfigurable diverse pulse shapes and frequency spectra. Each radar application will have special requirements to achieve more functional capabilities for lower power, lower complexity, and lower cost. Reviewing the modern literature and
Internet sources leads to the following classifications of available methods to generate such tunable UWB signals:

1. Traditional Gaussian pulse generation
2. Frequency up-conversion
3. Analog filtration
4. Digital logic
5. Analog–digital synthesis

### 3.7.2 Direct Digital Synthesis

Some relevant technical developments have been demonstrated for UWB communication systems, where tunability means modulation (Win, M.Z, and Scholtz, R.A. 2000). Note that such generated signals need the necessary power for successful transmission. This requires high power amplifiers that will not distort the UWB pulses, or operate with controllable and acceptable distortions.

The transmitter must transmit two types of signals: the virtual-impulse covering the range of potential target resonances and the target matched signal consisting of the target resonance frequencies. The main technical issues will center on the specialized signal generation and power amplification needed for adequate radar function levels. Such devices will have the general form shown in the block diagram of Figure 3.24.

The following sections describe methods for generating UWB signals with specific power spectral characteristics.

#### 3.7.2.1 Traditional Signal-Generation Methods

Early techniques for generating Gaussian-like impulse signals cannot meet the operational requirements of advanced UWB radar systems. These methods based on semiconductor active elements such as step recovery diode, drift step recovery diode, avalanche transistors and so on have demonstrated limited flexibility for generating tailored signals. (Protiva, P. 2007)

#### 3.7.2.2 Frequency Up-Conversion

Analog carrier-based methods for creating UWB pulses exploit two major generation techniques (1) heterodyning as shown in Figure 3.25 and (2) time-gated oscillators as shown in Figure 3.26.
In heterodyning as shown in Figure 3.25, a pulse is first generated at baseband with a low-pass spectrum, that is typically easier to do. In turn, a baseband signal source can be made using one of the options above from 4 to 6 as described later. Secondly, the baseband signal is up-converted to a higher target frequency band using a local oscillator (LO) and a mixer (multiplier). The LO can use either fixed or variable CW sources. Obviously, frequency up-conversion relaxes to some extent requirements for the baseband signal source. However, conversion efficiency might be low and require power boosting as shown in Figure 3.28. This approach can use several available tuning options including: (1) initial baseband signal adjustments and (2) center frequency adjustments controlled by LO (voltage controlled oscillator, etc.).

Short duration sinewaves (less than 5 cycles) have UWB characteristics. Figure 3.26 shows how to generate a short duration sine wave with the time gated oscillator. In this case, a continuously running LO provides the basic sine wave. A time gated switch controlled by a broadband pulse turns the continuous wave signal on and off to form short duration sine wave pulses. Another approach switches the LO itself on and off to achieve the same output (Song, F. et al. 2008). A typical output in this case is made of a few cycles of the LO having a rectangular amplitude envelope in time domain and sinc-like frequency spectrum. The resulting output signal will have the power spectral density with the bandwidth shown. This approach has narrow tuning capabilities changed by the LO frequency and the number of cycles permitted by the on/off control (Song, F. et al. 2008).
3.7.3 Analog Filtering

Another established method generates baseband pulses and then analog filters them to shape the desired pulse as shown in Figure 3.27. This approach has a very limited tuning capability defined by the baseband source made, using one of the options above from 4 to 6. The baseband source mostly defines the center frequency and bandwidth. Note that such a filter transformation often happens unavoidably in antennas when baseband signals need to radiate (Rajesh, N. and Pavan, S. 2015).

The antenna frequency response characteristics will also shape the pulse. The engineer must account for pulse distortion by the antenna in the exciting pulse shaping process. This requires considering the antenna and transmitter antenna characteristics together (Boryssenko, A. and Schaubert, D.H. 2006). Optical means can provide another approach to pulse shaping with low energy efficiency (Hedayati, H. et al. 2011).

3.7.4 Digital Logic Signal Generation and Transmitters

Tunable UWB pulse generation using digital logic shows many possibilities. Pulse generators have many specific features, but all employ several delays, inverters, and NOR/NAND gates in their signal generating circuits (Bourdel, S. et al. 2010; Chang, K.C. and Mias, C. 2007). Figure 3.28 shows a simplified typical scheme made from a single inverter delay and a single NOR gate. The example pulse generator trigger splits a pulse into two signal paths with a delay in one of them. The signals from both paths with a proper mutual delay enter the NOR gate that produces output impulses on every falling edge of the trigger pulse. NAND gates can be employed instead of NOR gates. This enables impulses with the opposite polarity on every rising edge of the trigger. The circuit of Figure 3.28 shows only two signal phases for simplicity. Practical circuits of this type will have many signal phases and many logic functional elements. Such pulse generators can be built using discrete digital logic (Schwoerer, J. et al. 2005). However their functionality would be limited because of many technical challenges. Those challenges could be collectively related to signal integrity issues due to tolerances in the printed circuit board, time mismatching, and other effects associated with discrete-built electronics compared to integrated circuit (IC)-based electronics. IC-based digital logic elements can provide more accuracy, functionality, bandwidth, and performance. Two approaches exist here with custom IC logic using complementary metal-oxide semiconductor process and reprogrammable off-the-shelf FPGA logic. Their advantages and disadvantages present the designer several pros and cons. The custom IC logic approach has a major drawback in higher development costs. A lack of bandwidth and special features could become a major bottleneck of reprogrammable off-the-shelf FPGA logic (Strackx, M. et al. 2013).
3.7.5 Analog–Digital Signal Synthesis

Analog–digital synthesis generates signals by combining multiple copies of baseband pulsed signals, that are individually delayed and weighted to get a given magnitude and polarity. Figure 3.29 shows how an array of $N$ baseband pulse generators (BPG) generates the signal copies in a distributed waveform generator. The process starts by sending a trigger to a digital delay line made of cascaded $T_D$ delays with a sampling frequency of $f_s = 1/T_D$. This approach provides flexibility for pulse shaping and spectral tuning if the necessary BPG are available or can be built. BPG arrays seems the most realizable way to use custom mixed analog–digital ICs. Figure 3.30 shows another version of this analog–digital signal synthesizer that avoids BPGs by directly weighting the delayed edges of the trigger signal and combining them for a proper pulse shaping (Cutrupi, M. et al. 2010; Zhu Y. 2007; Zhu Y. 2009; Zhu, Y. et al. 2009).
3.7.6 Direct Digital Synthesis (DDS)

A more promising and universal approach for UWB pulse generation uses high speed DAC waveform synthesis. Figure 3.31 shows a generic DAC waveform synthesizer. In theory, a high speed DAC with good resolution could directly generate signals with necessary time-spectral features, although being fully reconfigurable (reprogrammable). However, like the ADCs considered earlier, such DACs need to operate with high sampling rates. For example, the DAC will must have a sampling frequency of at least 20 GHz for a 3–10 GHz UWB pulse and with 6-bit resolution or better. The high sampling rate poses a performance challenge for the DAC and generating the input digital data stream from a digital memory as shown in Figure 3.31. This approach increases the design complexity and power consumption. If the UWB pulse usually lasts a few nanoseconds, then
there are only tens of samples in a single pulse. Since the pulse shape does not need to change at high speed, a time interleaved DAC seems a promising path similar to time-interleaved ADC to obtain high sampling rates. In general, the overall technical challenges to get the necessary DAC capabilities is comparable to those of advanced UWB radar systems ADC.

There are off-the-shelf DAC chips that operate in a few GHz bands. For example, DAC3482 from Texas Instruments, Dallas, Texas is a very low power, high dynamic dual-channel, 16-bit DAC with a sample rate as high as 1.25 GSPS. The AD9912 from Analog Devices, Norwood, Massachusetts is a 1 GSPS DDS chip with an integrated 14-bit DAC. The AD9119/AD9129 from Analog Devices are high performance, 11-/14-bit RF DAC that can support data rates up to 2.85 GSPS (Baranauskas, D. and Zelenin, D. 2006).

A variant of the DDS approach associated with software-defined radio (SDR) can operate up to a few GHz but with a signal bandwidth not exceeding 100 MHz (e.g., the Analog Devices AD936x SDR on chip) (Pu. D, et al. 2015).

3.8 Advanced UWB Radar Conclusions

The advanced UWB radar concept offers many possibilities for expanded remote-sensing capabilities. The full development of the advanced UWB radar including signal and target interactions phenomenon, digital receiver design, signal-processing methods, variable waveform transmitter design, and the control architecture would require a dedicated book. This summary provides an overview of the concept, the potential technical issues, and suggestions for further innovations.

Special UWB radar systems will evolve to fully exploit the possibilities of return signal analysis and signal matching. The remaining chapters of this book present concepts for better performance and new applications.

This chapter presented an introduction to the major technical considerations required for building an advanced UWB radar that can

1. Identify target classes through time–frequency analysis of signals reflected by targets.
2. Change the transmitted waveform to match the target characteristics and enhance the returns from a specific target class.
Building an advanced UWB radar for a specific function will require the following:

1. Understanding the target class and virtual-impulse signal interaction.
2. Tailoring the signal bandwidth and spatial resolution to the target class.
3. Building a time-domain receiver that can digitize each reflected signal for time-frequency analysis. This will require matching of ADC capabilities with techniques such as selective sampling, compressive sensing, and other techniques.
4. Building a signal synthesizer that can build a target matched signal from the time-frequency analysis information.
5. Building a transmitter and antenna that can synthesize and transmit the target matched signal.

Advanced UWB radar performance will depend on the available ADC technology capabilities. The ability to synthesize target matched UWB signals will restrict applications to specific signal modulation bandwidths and classes of targets. Further ADC technology evolution will increase the range of applications. Although the general principles remain the same, each new realization will depend on the functional objective. For example, an advanced GPR for plastic mine location will have a much different design than a radar for area surveillance against specific classes of aircraft, vehicles, or watercraft.

We have presented the major performance objectives and technical considerations for building an advanced UWB radar. Depending on the target class and functional performance objectives, each case will require understanding the interaction of the signal and target at a new level. Chapter 12, *Wideband Wide Beam Motion Sensing* will discuss targets and signal tailoring from a different perspective.

References


