Chapter 1

Ultra-Wideband Radar Overview

James D. Taylor

CONTENTS

I. INTRODUCTION

This book is about radar systems using wide relative (proportional) bandwidth signals called ultra-wideband (UWB) waveforms. The potential advantages of using UWB waveforms for radar include better spatial resolution, detectable materials penetration, easier target information recovery from reflected signals, and lower probability of intercept signals than with narrowband signals. Designing UWB radar systems requires considering what happens when a signal is no longer a single, long duration sinusoidal wave. This book presents principles needed for understanding UWB radar concepts and their potential capabilities and provides a basis for further investigation, design, analysis, and fabrication.

Radar systems use radiated and reflected electromagnetic waves to detect, locate, and identify targets. Radar systems is a broad term including everything from small police and ground-probing systems to the large radars for ballistic missile defense and airspace surveillance and tracking. Radar targets may include ground discontinuities, buried objects, stationary objects for navigation, and moving objects including vehicles from automobiles to reentry vehicle systems. Each reader's experience and professional interest slants his personal concept of radar systems. The radar system designer's problem is to balance the user's needs and desires with available technology, achievable performance, and affordable cost. The designer's objective is to satisfy the radar user's needs effectively and cheaply. The radar system user is the final judge of acceptable radar performance and cost.

The second section of this chapter is about UWB concepts and the differences between UWB radar and conventional narrowband radar. The third section is about potential applications for UWB radar. The fourth section is about approaches to handling an UWB system's electromagnetic compatibility and interference issues. The fifth section is an introduction to and summary of each chapter of this book.

II. UWB RADAR TERMINOLOGY AND CONCEPTS

Ultra-wideband terminology and definitions are not standardized as of this writing, and this may cause some confusion in literature searching. Terms such as narrowband and wideband can have several meanings depending on the subject, i.e., communications, radar, etc. This section will discuss what UWB radar is generally accepted to be and some of the alternative, but related terminology. Assumptions concerning meanings can be misleading. When in doubt, see how the writer uses the term and determine what is being described in basic functional concepts. The best advice is to be aware that *ultra-wideband* may also be called impulse, time domain, nonsinusoidal, baseband, video pulse, ultrahigh resolution, carrierless, super wideband, and other terms.

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UWB DEFINED

The Defense Advanced Research Project Agency's (DARPA) 1990 *Assessment of Ultra-Wideband Radar* advised that "definitions need liberal interpretation and that mathematical definitions are difficult to achieve and seldom useful in a practical sense." The following definitions were given.

Energy Bandwidth, B_E: The energy bandwidth is the frequency range within which some specified fraction, say 90 or 99%, of the total signal energy lies. This must be defined for a single pulse, if all pulses are the same, or for a group of pulses that are processed together to yield a single decision. The upper limit of this range is denoted here by f_H and the lower limit by f_L.

Time-Bandwidth Product, TB: The time-bandwidth product of a signal is defined as the product of the energy bandwidth and the effective duration of a single pulse or pulse group. It is the measure of the increase in peak signal-to-noise ratio that can be achieved in the radar receiver by appropriate signal processing.[1]

Bandwidth is defined as fractional and relative:

$$\textit{Fractional Bandwidth} = \frac{2(f_H - f_L)}{(f_H + f_L)} \tag{1.1}$$

$$\textit{Relative Bandwidth} = \frac{(f_H - f_L)}{(f_H + f_L)} \tag{1.2}$$

The DARPA panel accepted the following definition: "Ultra-wideband radar is any radar whose fractional bandwidth is greater than 0.25, regardless of the center frequency or the signal time-bandwidth product."[1]

The term *ultra-wideband* refers to electromagnetic signal waveforms that have instantaneous fractional bandwidths greater than 0.25 with respect to a center frequency. There is no accepted standard usage for UWB terms; writers also use *percent* bandwidth and *proportional* bandwidth instead of *fractional* bandwidth. There are two other radar classes identified by signal fractional bandwidth: *narrowband,* where the fractional bandwidth is less than 1%, and *wideband,* with a fractional bandwidth from 1 to 25%.[1] These terms were specifically proposed for describing radar systems in 1989. Some confusion results because narrowband and wideband have very different meanings when describing communications channel bandwidths.

Most narrowband systems carry information, also called the *baseband* signal, as a modulation of a much higher carrier frequency signal. The important distinction is that the UWB waveform combines the carrier and baseband signal. Baseband or impulse radar (or radio) are other names for UWB radar and radio signals.[2] The UWB signals generally occur as either short duration impulse signals and as nonsinusoidal (e.g., square, triangular, chirped) waveforms. The rule of thumb is that sinusoidal wave signal bandwidth *(Bw)* for pulse signals are inversely proportional to pulse duration (τ), or $Bw \approx 1/\tau$.[3] When the duration of a short sine wave pulse signal approaches several periods, then the relative bandwidth starts becoming a larger fractional value. There are also long duration nonsinusoidal waveforms having significant power at multiples of its fundamental frequency. Figure 1.1 shows some typical UWB waveforms and power spectral density plots based.

UWB TERMINOLOGY AND USAGE

The term ultra-wideband (also ultrawideband) is a new term associated with radio and radar technologies called impulse, nonsinusoidal, baseband, video pulse, super wideband, time domain, carrierless,

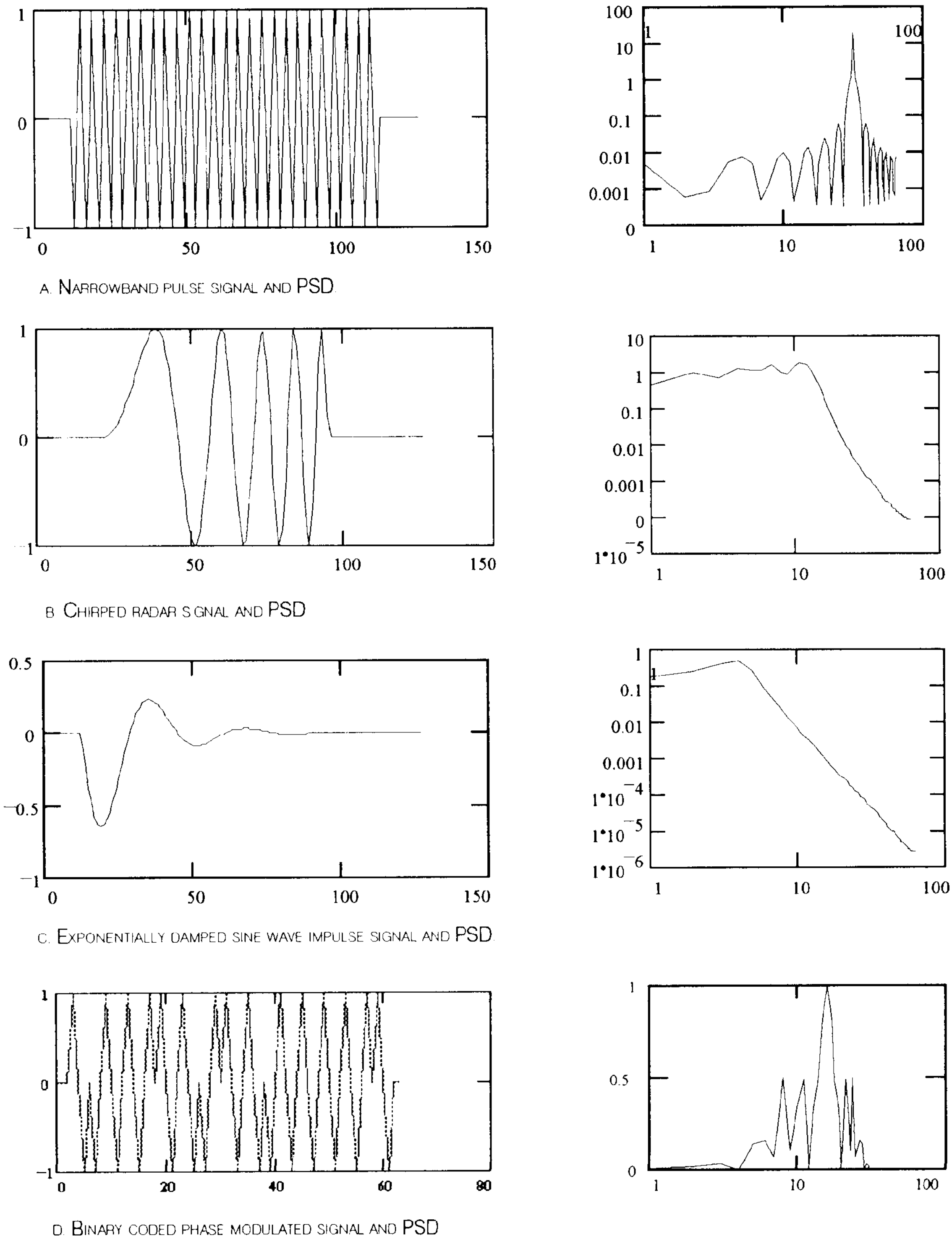

Figure 1.1 Waveforms for comparison: (A) narrowband; (B), (C), (D) UWB waveforms.

and other related concepts. Before about 1989, UWB technology literature generally used one of the associated terms. Because ultra-wideband is a new term, it is best to look for the writer's definition or to determine the meaning in context and the accompanying details, and then apply the mathematical descriptions loosely. Some physical reason for assigning the breakpoints between narrowband, wideband, and UWB would be much more satisfying. Interpretation of systems as UWB should be kept loose. For example, an argument that a system with a 24% fractional bandwidth signal is wideband and not UWB defies common sense and engineering judgment. Other examples of UWB usage include describing narrowband receivers and devices with a broad tuning range[4] or broad proportional bandwidth RF amplifiers with a 1 to 18 GHz bandwidth.[5]

UWB AND SPREAD SPECTRUM SIGNALS

The term UWB may be confused with *spread spectrum,* thus we need to discuss the difference. Spread spectrum systems have a transmitted signal that is spread over a frequency band much wider than the minimum bandwidth required to transmit the information being sent. A spread spectrum system takes a baseband signal with a bandwidth of only a few kilohertz, such as a voice channel, and modulates it with a wideband encoding signal that distributes it over a larger bandwidth. The resulting signal might be a megahertz modulation signal on a several hundred megahertz carrier signal with a fractional bandwidth near 1%. Because the spread spectrum signal has a much larger bandwidth than narrowband receivers in the same range and requires a knowledge of the wideband encoding method to demodulate it, it does not interfere with, or is not intercepted by, narrowband systems because so little power falls in the bandpass of any given narrowband receiver. Some general types of spread spectrum signals include

1. Direct sequence modulated systems which modulate the carrier with a digital code sequence whose bit rate is much higher than the information signal bandwidth.
2. Frequency hopping systems change the transmitter frequency within some predetermined order set by a code sequence. The signal never stays on any one frequency long enough to interfere with or be intercepted by a receiver without the frequency sequence.
3. Pulsed-FM or "chirp" modulation in which the carrier is swept over a wideband during a given pulse interval. The receiver follows the frequency change.
4. Time hopping systems, which have a time of transmission with a low duty cycle and short duration governed by a code sequence. Time-frequency hopping systems control both the time and frequency of transmission by a code sequence.[6]

While spread spectrum signals have a wide bandwidth with respect to other signals, they generally do not fit the UWB definition because their fractional bandwidth is well below 25%. Radar signals such as binary-coded and chirped waveforms are sometimes misleadingly called spread spectrum.[3]

III. POTENTIAL APPLICATIONS OF UWB RADAR

Fine spatial resolution, extraction of target feature characteristics, and low probability of interception and noninterfering signal waveform are some of the features that make UWB radar appealing. Thus, UWB radar offers possible solutions to defense requirements such as passive target identification, target imaging and discrimination, and signal concealment from electronic warfare equipment and antiradiation missiles. Frequency spectrum sharing with other radar and communications systems is another potential use.

Future UWB radar applications will depend on the ability of a particular UWB system to perform a given detection or remote sensing function competitively with available alternative systems or to provide some operational advantage, such as a low probability of intercept signal.

TARGET SIGNAL INTERACTION AND FEATURE EXTRACTION

The large signal bandwidth and information carried by the UWB radar return signal may provide sensing capabilities beyond simple target detection. The waveform content of reflected UWB impulse signals has been shown to change depending on the target shape and materials. Experimental work in singularity expansion method (SEM) radar using single "impulse" signals indicated that radar return waveforms were changed by target structure and electrical characteristics. Target information processing for impulse signals is like determining the characteristics of a system from its impulse response. The reflected impulse signal characteristics seen in experiments appear unique enough to permit target identification.[7-12]

All radar signals will have some target-related change when reflected; the problem is to detect that change and uniquely relate it to the reflector. For example, compressor blade, or fan modulation, of radar return signals offers a potential identification method for narrowband systems. However, determining more complicated information such as shape or specific materials from the signal target interaction may be done more easily by identifying distinct resonances with SEM or examining the higher order characteristics by bispectral processing. SEM and bispectral processing lend themselves to UWB signals. Some useful information is in any radar return signal; the technical problem is signal processing to turn data into useful, timely, and reliable information.

TARGET IMAGING AND DISCRIMINATION

The UWB radar's fine spatial resolution gives a potential capability for target imaging and discrimination of targets from background clutter. Promising work has been done with UWB synthetic aperture radar (SAR).[13,14] The UWB SAR has the capability of imaging reflectors concealed in a forest.[15] Some success has resulted from look-down tests to detect boats by using UWB signals.[16]

Target clutter separation is a major problem in look-down radar and limits the ability to detect small radar cross section (RCS) low altitude flying targets or surface targets. Moving surface targets can be detected by radar systems such as the Joint STARS, which uses SAR and Doppler filtering. Target extraction by moving target improvement (MTI) using Doppler shift can permit some small target detection in clutter; however, reducing target RCS can keep the target clutter ratio beyond the threshold limit needed for detection. There is a possibility that UWB signals reflected from background clutter might be different enough to permit discrimination of target signals based on reflected waveform higher order signal analysis, as discussed in Chapter 11.

Geophysical surveying uses impulse ground-probing radar for buried and concealed object detection and subsurface mapping in mining, agriculture, highway and building construction, archeology, and ice field surveying. Multiple impulse radar returns can provide a picture of subsurface conditions and buried objects. The capability of impulse waveforms to penetrate solid structures and return signals from discontinuities in the index of refraction is what makes the radar useful.[17-19]

There is no free lunch in sensor systems. Fine spatial resolution in narrowband radar comes at a price, e.g., chirped waveforms that create antenna sidelobes, transmission losses, false targets, extra processing, while wide signal bandwidths mean high noise levels, etc.[3] The UWB radar can provide fine spatial resolution by using short duration impulse or coded impulse train waveforms and correlation detection, which bring their own technical problems, as shown in Chapters 8 and 10. Discrimination of targets using higher order signal processing of impulse signals can distinguish between materials that would not be otherwise distinguishable by narrowband signals, again at the cost of complex signal processing, as discussed in Chapter 11.

LOW PROBABILITY OF INTERCEPTION UWB WAVEFORMS

There are many military requirements that only radar can satisfy, but a radar must radiate to be useful and this is a disadvantage for military surveillance and detection systems. Generally, a receiver tuned to a radar's frequency can detect a radar set from its emissions farther than the radar can detect the target from its return signal. If a radar set can be an asset (source of information) or a liability ("shoot here" sign) depending on the enemy's electronic warfare capability, then any radar system with a difficult-to-detect radar signal can offer military advantages. Limiting radar and radio emissions until absolutely necessary is a practical operational solution; however, it defeats the purpose of owning the radar.

Any radar system that has a difficult-to-detect signal is worth considering for military applications. The decision to use a UWB signal in preference to some other method will involve a tradeoff of technology availability, costs, perceived military advantage, and the need to replace existing systems and to revise operating procedures. The UWB radar could provide such advantages as a detection surveillance or tracking systems with a low probability of detection by the spectral characteristics of the signal. When a designer decides to use some UWB format, the question is can a UWB system provide adequate performance for the intended role. Assuming that a UWB radar system is introduced, then the operational issue will be how long can the particular radar system remain undetectable to enemy systems. Silent, undetectable, stealthy, unobservable, low probability of intercept, low probability of detection, etc. are relative terms, because given enough time, resources, and incentive someone will build a UWB radar intercept receiver and the formerly silent radar will become a beacon again.

The name of the game in electronic warfare is to buy time and some temporary advantage. Today's countermeasure buys an advantage until the enemy finds a way to get around that countermeasure, and then the process starts again. The military advantage of a new system depends on maintaining security about the operational details to keep the enemy ignorant as long a possible. This UWB radar could offer operational advantages by providing a hard-to-detect signal, as long as security is kept.

Consider police radar for detecting speeders as a practical electronic warfare example. The speeder's countermeasure was the police radar detector, which gave a driver time to slow down before coming into effective range of the radar. Police radar detectors proliferated at a price any driver could afford. Police response to the countermeasure was to add transmitter frequencies and use false speed radar transmitters. The new frequencies were outside the range of radar detectors for awhile. The false transmitters made drivers slow down on receiving a radar alarm and decreased the drivers' confidence in their radar detectors. Another police innovation was laser radar speed measurement. The speeder's countermeasure was to add the new frequency bands and laser detectors. While the example is familiar, the same principles apply to military electronic warfare.

IV. UWB SYSTEMS FREQUENCY SPECTRUM SHARING AND INTERFERENCE ISSUES

FREQUENCY SPECTRUM SHARING

There is limited available frequency spectrum and demands for communications, and radar-based sensors may continue to grow. Any electronic system that permits sharing the same frequency band in the same location without interference will eventually be used when it becomes profitable to do so. Ultra-wideband signals have a low probability of intercept (LPI) signal with respect to narrowband systems and may be able to share frequency spectra with narrowband and other UWB systems with proper design. These UWB systems may be able to share the same spectrum by means of waveform coding schemes to exclude unwanted UWB signals.

The proliferation of personal communications systems and demands on the available frequency spectrum may create a demand for special UWB radar and radio communication links. Economic incentives for UWB radio and radar for civil applications such as private communications and short range sensors may be good.

ELECTROMAGNETIC COMPATIBILITY AND INTERFERENCE ISSUES

Electromagnetic compatibility (EMC) and electromagnetic interference (EMI) must be considered early in UWB radar or communications system design to avoid potential interference problems. If the designer does not consider EMI and EMC issues immediately, then assuredly someone else will before any further serious design continues.

The UWB signal definition can give the impression of a continuous wide spectrum signal, which is not correct. Many people have heard the definition and concluded that any UWB signal will jam everything in some portion of the frequency spectrum and be prohibited by regulatory agencies. Some reflection indicates that many UWB signals will be short duration, low duty cycle signals. The design objective for narrowband equipment is to build a set that is most sensitive to some narrowband of frequencies and attentuates all other frequency signals. A receiver acts like an integrator with a time constant of $1/Bw$. If a UWB signal has a 1-ns duration and a receiver has a 1-MHz bandwidth, then the receiver's integration time constant is 1 μs, or 1000 times as long as the UWB signal duration, and the UWB signal power will be attenuated by 30 dB by being spread over 1000 times its normal duration. Now, if the UWB signal energy is high enough or has enough power to be detected after integration over a long time period, then the resulting power level in the receiver may be high enough for detection and interference. Interference will depend on the particular UWB signal, strength, and emitter location with respect to specific narrowband equipment characteristics.

This book does not explicitly cover electromagnetic interference; however, the materials in Chapter 10, Appendix A, show how to estimate the impulse signal response of receivers. Given the impulse strength for detection (or interference) in watt-seconds, then a range can be determined at which different receiver bandwidths can detect the signal. This initial estimate should give some indication of potential interference problems with narrowband electronic systems. The best approach appears to be to take each case and evaluate it using the methods from Chapter 10. For UWB radar designs using array antennas, the resulting UWB waveform off-axis can turn into a stretched or repeated waveform with different characteristics requiring an off-axis analysis evaluation for narrowband systems interference. Chapter 5, Section 3, discusses the effects of array antennas on UWB signal waveforms and duration. There are enough signal format and power possibilities resulting from array antennas to make specific case analysis necessary.

Interference and low probability of interception are relative, and any UWB or narrowband systems properties or claims will only be valid for specific cases and conditions. The best advice is to evaluate each case on its own merit to determine if a particular UWB system will operate without interference with particular equipment in a specified environment. Chapter 10, UWB Radar Receivers, provides the background for estimating impulse signal strength necessary for detection in narrowband receivers.

V. BOOK CONTENTS

TECHNICAL ISSUES IN UWB RADAR SYSTEMS

Chapter 2, by Harold Engler, discusses UWB radar systems in overall system terms and provides a guide to the remainder of the book.

UWB ANALYSIS

Chapter 3, by Dr. Tapan Sarkar and Dr. M. Rangaswamy, discusses Fourier and Laplace transform analytical techniques and applications and limitations of Fourier and Laplace transforms. Both techniques are valuable and need to be understood before applying them to UWB signal analysis. Signal analysis is a continuously evolving subject and best followed through its own literature. Chapter 3 reviews the basics and provides background for further reading.

UWB TRANSMITTERS

Chapter 4 is about several approaches to generating UWB signals. Any pulse radar systems must store energy over long periods and then release it over short periods. Shorter discharge (transmission) intervals present more problems then longer ones, because the frequency components are higher and more subject to dissipative effects. When the discharge interval starts to approach the time constant of the storage device, which is set by its physical dimensions, then energy storage systems become a sensitive part of the design. This chapter presents two approaches to energy storage and release.

Dr. David Platts discusses Marx banks which can provide high voltage discharges over short intervals. The Marx bank charges capacitors in parallel and then uses spark gap switches to connect and discharge them in series.

Dr. Oved Zucker and Dr. Iain McIntyre give an introduction to signal synthesis using photoconductive switches to generate UWB signals. Photoconductive switches are another approach to generating high power electromagnetic impulses. Semiconductors can change from insulators to conductors when subjected to intense illumination from a laser.

UWB ANTENNAS

Chapter 5 is about coupling UWB signals into space. Ultra-wideband signals can cover the range of conditions from short duration impulses to long duration nonsinusoidal waveforms. The point to remember is that in UWB systems the modulation (information) is the waveform and must be detected as such. The UWB system antenna must be able to transmit or receive the range of frequencies in the signal without distorting any important part of the signal.

Dr. P. R. Foster provides an overview and introduction to UWB antennas theory and discusses impulse radiation from common types of antennas.

Dr. Malek Hussain describes new approaches to transmitting and receiving impulse signals called the large-current radiator and loop sensor antennas. These are radiating and receiving elements specifically designed for impulse signals. The theory of these elements and experimental measurements are presented. Dr. Hussain also describes the concepts and theory of impulse array antennas, which are different from the narrowband array theory for phased array radar.

Mr. Doss Halsey provides an introduction to UWB coded pulse waveform array antennas and provides practical theory for array antenna design. The coded UWB pulse train waveform can provide fine spatial resolution with a long duration UWB signal. Determining antenna patterns for coded pulse train waveforms requires a change in the way we think about antenna patterns. The conventional antenna pattern concept is spatial distribution of radiated power at a given frequency. When we consider nonsinusoidal signals such as coded (or chirped waveforms) or time-coded impulse trains, the antenna pattern concept will be the distribution of power that may be correlated with a reference waveform. If the received signal is detected by correlation, then what is the path of a correlatable signal from antenna array to receiving antenna. Transmitting a correlatable signal (e.g., coded waveform or impulse) from an antenna array means that the interference of signals off-boresight will produce a signal with a different waveform than the reference signal.

DIRECT RADIATING ANTENNA SYSTEMS

Chapter 6 is about how the dispersive effects of electronic components such as cables on UWB signals create a requirement for direct radiating systems or combined UWB signal generators and antennas.

Dr. David Giri describes a nuclear electromagnetic pulse installation and the problems of building short pulse, high power systems. Dr. William C. Nunnally describes a transverse electromagnetic (TEM) horn emitter which uses the light-activated semiconductor switching described in Chapter 4.

PROPAGATION AND ENERGY TRANSFER

Chapter 7 discusses how electromagnetic waves travel through the atmosphere. We included this chapter as background on how UWB and impulse propagation is a special case of steady-state narrowband propagation. These sections provide insight into the properties of short, UWB signals compared to long duration narrowband signals. Dr. Robert Roussel-Dupré discusses electromagnetic (EM) propagation and UWB waves. Dr. Terrence W. Barrett discusses UWB waves as an energy transfer phenomenon.

RADAR TRANSMITTER AND TARGET SIGNATURE

Chapter 8 is about waveforms and the target signature of radar signals. Dr. Henning Harmuth discusses the results of a coded pulse train waveform reflecting from a target much larger than the spatial resolution of the signal.

RADAR TARGET CROSS SECTION

Chapter 9 is about radar target reflection concepts. Dr. Mike VanBlaricum begins with power scattering and RCS concepts conventionally used in the radar equation. Radar scattering characteristics depend on the ratio of the target dimensions to the incident wavelength. A section covers relationships of CW, wideband, and transient scattering in terms of linear system theory. The final section discusses the singularity expansion formulation for describing electromagnetic scattering. Natural and forced response scattering components can be expressed in terms of the singularity expansion and make target identification possible based on singularity expansion parameters. Singularity expansion formulation is the basis for SEM radar.

UWB RECEIVERS

Chapter 10 discusses UWB receivers as an extension of the conventional receivers. Mr. James D. Taylor and Mrs. Elizabeth C. Kisenwether discuss threshold and correlation detection of UWB signals. One issue in UWB receiver design is waveform preservation vs. detection, which is driven by post-processing use of the signal.

Threshold detection preserves the waveform and is simple, but requires high signal-to-noise ratios (SNR). Any receiver can detect a UWB signal, or impulse, if it is strong enough. Narrowband receivers can detect strong UWB signals, and specifically designed UWB receivers can detect weaker

UWB signals. The section on threshold detection includes a discussion of receiver bandwidth and estimating received impulse strength for detection.

Correlation detection indicates the presence of a signal which resembles the reference signal and can work with lower SNRs than threshold detection. Signal processing and target identification schemes such as Fourier analysis and SEM require a high SNR, which implies a shorter range than simple signal detection. Correlation detection is a detection method for weak signals which do not require preservation. Either case will require some minimum signal strength and this chapter provides guidance for estimating it. The chapter ends with some concepts for applying photonic technology to UWB receivers and advanced signal processing concepts.

HIGH ORDER SIGNAL PROCESSING FOR UWB RADAR SIGNALS

Chapter 11 is about using kernel and bispectral analysis methods to characterize radar signal returns. Dr. Vasilis Z. Marmarelis, Dr. David Sheby, Mrs. Elizabeth C. Kisenwether, and Mr. Todd A. Erdley present high order signal processing concepts applied to impulse radar test results. This chapter describes the results of applying higher order signal processing to impulse signals reflected from steel plates, radar-absorbing material (RAM), and clutter materials. Applying kernel and bispectral analysis techniques can produce unique target signatures for each type of reflector. This chapter demonstrates an advanced concept for recovering information from reflected waveforms for target detection and identification.

UWB RADAR PERFORMANCE PREDICTION

Chapter 12 is about UWB radar performance prediction using the same principles as the classical radar equation. Dr. Terrence Barrett discusses advanced concepts in signal reception and processing and how they can affect radar performance.

VI. CONCLUSION

The UWB radar systems will evolve as technology can support UWB radar construction and as functional requirements demand some advantage that only UWB signals can provide more efficiently than other methods. In all cases there will be requirements, cost, and performance tradeoffs when deciding whether to use UWB radar in a particular role. The potential advantages of UWB radar systems are low probability of interception signals and the capability of sensing target shapes and materials through advanced signal processing. However, UWB radar is only one of many potential solutions to remote sensing and surveillance, and the user must make the final choice.

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Edited by
James D. Taylor
Retired, U.S. Air Force

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