CHAPTER

1

Radar Applications

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Chapter Outline

1.1 INTRODUCTION

Radio detection and ranging (radar) involves the transmission of an electromagnetic wave to a potential object of interest, scattering of the wave by the object, receipt of the scattered energy at the receive site, and signal processing applied to the received signal to generate the desired information product. Originally developed to detect enemy aircraft during World War II, radar has through the years shown diverse application, not just for military consumers, but also for commercial customers. Radar systems are still used to detect enemy aircraft, but they also keep commercial air routes safe, detect speeding vehicles on highways, image polar ice caps, assess deforestation in rain forests from satellite platforms, and image objects under foliage or behind walls. A number of other radar applications abound.

This book is the third in a series. *Principles of Modern Radar: Basic Principles*, appearing in 2010, discusses the fundamentals of radar operation, key radar subsystems, and basic radar signal processing [1]. *Principles of Modern Radar: Advanced Techniques*, released in 2012, primarily focuses on advanced signal processing, waveform design and analysis, and antenna techniques driving tremendous performance gains in radar system capability [2]. This third text, *Principles of Modern Radar: Radar Applications*, combines the developments of *Basic Principles* and *Advanced Techniques* to illustrate a myriad of radar applications.

Principles of Modern Radar: Radar Applications is comprised of three sections:

- *Tactical Radar*, covering continuous wave radar, with application to missile seekers and other low-cost radar needs; millimeter wave radar, used in areas such as battlefield fire-control systems and automotive radar; fire-control radar principles; airborne pulse Doppler radar, the heart of airborne interceptor radar; multifunction radar used to search, track, and engage airborne targets and employing sophisticated and costly phased array antennas, processing software, and resource management; and ballistic missile defense radar.
- *Intelligence, Surveillance, and Reconnaissance*, including early warning detection of aircraft and missiles preceding handoff to a tracking radar; surface moving target indication, used to detect and monitor targets on Earth's surface; and spaceborne surveillance used to remotely monitor Earth resources, cultural sites, and military facilities.
- *Specialized Applications*, including passive radar, which uses noncooperative sources of illumination and receivers displaced a considerable distance from the various transmit sites; air traffic control radar; weather radar; foliage-penetrating radar; ground- and materials-penetrating radar; and police radar.

Individual chapters discuss the aforementioned topics within these three sections in further detail, identifying key considerations and the practical application of radar technology, principles, and techniques to accomplish the specific radar objective: detecting, locating, and tracking targets moving on Earth's surface; imaging a stationary target under foliage; detecting approaching or receding targets from an airborne pulse Doppler radar; detecting and tracking ballistic missiles from large, ground-based phased array radar; protecting ground troops from mortar attack using mobile, counterbattery surface radar; and so on.

1.2 | HISTORICAL PERSPECTIVE

The earliest radar developments appear to have taken place independently in a number of countries. World War II accelerated the development of radar to address the direst of situations. That military application has served as a primary motivation for radar technology development complicates an exposition on its history due to sundry requirements for secrecy. Consequently, spirited debate amongst radar developers over who deserves acclaim for certain innovations is not uncommon.

Reference [3] provides a remarkable overview of the earliest beginnings of radar. The possibility of a system to detect objects based on reflected electromagnetic waves dates to the 19th century and the work of Heinrich Hertz, with James Clerk Maxwell's work on electromagnetism suggesting this possibility. Other great minds invariably associated with the earliest beginnings of radar include Christian Hulsmeyer, Nikola Tesla, Guglielmo Marconi, Sir Robert Wattson-Watt, and Hoyt Taylor. As [3] discusses, highly protected programs to develop radar took place leading up to and during World War II in a number of countries, including England, France, Germany, Japan, Canada, and the United States. Robust radar programs were further known to exist in the Soviet Union, Italy, and the Netherlands.

The detection of air raids was of paramount importance during World War II. Generally, surface-based radars, such as the British Chain Home radar system [4], were developed for this purpose. These original surveillance radars provided an early warning function so citizens could take shelter and service personnel could launch interceptor aircraft. The interceptors similarly required radar to acquire and engage enemy bombers and provide self-protection from enemy escort aircraft. Early warning and fire-control radar were also necessary for naval shipboard protection. World War II applications solidified the need for microwave transmitters and receivers and pulsed waveforms. As pointed out in [4], this period of extensive innovation involved the efforts of multiple researchers and engineers, resulting in radar having no single lineage, but a collection of forefathers.

The earliest radar experiments involved continuous waveforms and bistatic configurations to achieve sufficient isolation between transmitter and receiver [4, 5]. The technology available at the time could only support detection; range information was not available to the operator. Moreover, many of these initial investigations involved longer wavelengths – in the vicinity of 60 cm or greater. A requirement for range information and improved spatial accuracy led to microwave developments and pulsed radar modes. For years beyond World War II, noncoherent pulsed radar systems were used for a number of important applications.

A coherent radar employs a stable, coherent oscillator to transmit and receive signals. In this manner, the radar keeps track of the phase of the receive signal over time. A time-varying phase leads to a frequency shift in the receive signal. If the range between the radar and the object of interest is changing, the time it takes the signal to propagate to the object and return to the radar is $\tau(t) = 2r(t)/c$, where $r(t)$ is the time-varying range and c is the velocity of propagation (nominally, the speed of light). The corresponding phase is $\phi(t) = \omega\tau(t)$, where ω is frequency in radians. Frequency is the time-derivative of phase, $\dot{\phi}(t) = \omega\partial\tau(t)/\partial t$. Suppose $r(t|t = nT) = r_0 + n\Delta r$, with T the sample time, n the sample index, r_0 the initial range, and Δr the constant change in range between sample times resulting from a constant velocity target. The corresponding derivative of the phase function is $\dot{\phi}(t|t = nT) = (4\pi/\lambda)(\Delta r/\Delta t)$, with Δt the change in time; we recognize $\Delta r/\Delta t$ as the radial velocity (or range–rate), v_r, and $\dot{\phi}(t|t = nT) = \omega_d = (4 * \pi/\lambda) * v_r$ (or, $f_d = 2v_r/\lambda$ in Hz) as the well-known Doppler shift [4, 6].

The ability to take advantage of the target Doppler shift was revolutionary, providing the radar with additional information on target motion and enabling a mechanism to better separate target returns from those of background clutter due to reflections from Earth's surface or even from weather phenomenon. Thus, the extensive development of coherent radar systems followed the major accomplishments of the World War II era and occupied the minds of radiofrequency scientists and engineers for subsequent decades. The pulsed Doppler mode is the cornerstone of modern radar technology, integral to surface and aerospace military radar systems. Pulsed Doppler radar has important civilian and commercial applications, permeating everyday life in the form of television weather newscasts with detailed radar weather maps and air traffic control radar making the skies safe for travelers of all types. Coherent continuous wave radars are also important, providing target Doppler information for applications ranging from missile engagement to police traffic surveillance.

Coherency also makes all-weather terrain and stationary target mapping possible via a technology known as *synthetic aperture radar* (SAR) [2, 6–8]. SAR was invented in the 1950s, with Carl Wiley of Goodyear Aircraft Company viewed as its originator, and multiple parties greatly contributing to its development. The primary objective of SAR is to create a high-resolution map of the scene reflectivity; the resulting product has image-like quality and is generally interpreted by a trained analyst. In its most basic form, SAR uses knowledge of the collection geometry, generating a matched filter tailored to the phase history of a particular, resolvable, stationary scatterer of interest. As previously discussed, the phase history is $\phi(t) = \omega\tau(t)$, where in this case the change in range over time typically leads to a nonlinear characteristic for $\tau(t)$, and consequently a response comprised of time-varying frequency. The SAR is built and deployed in such a way that ideally the various scatterers possess unique phase histories, though practically there are basic limitations affecting the quality of the reflectivity estimate. Image-formation processing is the series of steps applied to the phase history data to generate the SAR map.

SAR has played important military roles in areas such as nuclear arms treaty monitoring and battlefield surveillance, preparation, and damage assessment. Meeting these stringent and critical applications required extraordinary effort to achieve pristine coherency over relatively long periods of time – data are collected over periods of hundreds of milliseconds to tens of minutes or more, a duration required to traverse sufficient viewing angle to achieve a desired cross-range resolution – and conceive computationally feasible approaches to approximate the matched filter condition. Indeed, system coherency and signal-processing algorithm development have served as hallmarks of SAR technology development. Early SAR image formation used optical signal-processing methods, with digital signal-processing techniques replacing the former after a relatively extended period of time needed for available technology to sufficiently advance. With some delay, civil applications of SAR emerged, including Earth resources monitoring, polar ice cap monitoring, and extraterrestrial planetary exploration.

Over the past twenty years or so, the radar community has significantly focused on radar subsystem hardware improvement, signal-processing algorithm development and implementation, and diverse applications. The development of phased array radar has been a major undertaking and a critical step in radar deployment for air and missile defense and multimode airborne radar systems [9]. Advances in computing technology have made digital beamforming (DBF) and space-time adaptive processing (STAP) possible [2, 9–11]. DBF and STAP are key elements in radar electronic protection, superior clutter mitigation techniques, and advanced concepts such as passive radar where DBF makes “pulse chasing” feasible [5]. Radar’s diverse applications made possible through technology maturation include through-the-wall radar for law enforcement support; the detection, location, and characterization of dismount targets (persons of interest traversing Earth’s surface) from airborne radar [12]; remote sensing of ocean currents; border surveillance; gait analysis for threat monitoring (e.g., detection of a perimeter breach by unauthorized personnel) and medical diagnosis (e.g., assessment of indicators of traumatic brain injury); automotive radar for intelligent highways; and the development of low-cost passive surveillance radar hosting off of commercial communications broadcasts [13].

Radar has proven its importance to society. As such, radar development and implementation has generally received favorable treatment under situations of competing interest. An emerging conflict over spectrum allocation among users of the electromagnetic spectrum will intensify, leading radar developers to innovate and conceive new technology and capabilities [14]. In addition to spectrum, energy is placing pressure on radar: The proliferation of wind farms as an alternative energy source creates a whole new class of interference requiring mitigation to ensure effective radar performance. Radar will also be asked to solve new and challenging problems, such as identification of humans in emergency management situations resulting from such natural phenomena as earthquakes; the detection of small vessels traversing the littoral zone expanse; and the beneficial exploitation of multipath in urban settings to enable non–line-of-sight radar detection and tracking of objects [15].

This book summarizes and puts into perspective a select number of important and modern radar applications, as well as the requisite constituent technology. As such, it builds on the exposition set forth in the first two volumes of the *Principles of Modern Radar* series [1, 2].

1.3 | RADAR MEASUREMENTS

Radar operation requires an active source of illumination. Monostatic and cooperative bistatic radar use a coordinated transmitter. Noncooperative bistatic radar exploits the transmissions from other electronic systems, including radio towers, communication transmit antennas, and other radars. Cooperative systems attempt to tailor the transmit waveform to the extent possible to maximize important radar quality measures, such as signal-to-noise ratio (SNR), signal-to-interference-plus-noise ratio (SINR), range resolution, target class separation, and resilience to radiofrequency interference (RFI).

The radar generates its product based on target-induced modulation of the reflected waveform. Radar design allows access to the following primary measurements:

- Fast-time – collected at the analog-to-digital converter rate, these voltages correspond to sampling in the range dimension.
- Slow-time – collected at the pulse repetition interval (PRI), the corresponding voltages are the pulse-to-pulse measurements for a given range cell. The Fourier transform of slow-time is Doppler.
- Spatial – samples generated at the output of a multichannel or multibeam receive antenna, where each channel or beam has its own receive chain. Angle information follows from the Fourier transform of the spatial channel measurements; the inverse transform of the multibeam output restores spatial sample information. The measured angle corresponds with azimuth, elevation, or cone, where cone is an ambiguous measurement related to a specific direction cosine in the antenna coordinate system.
- Polarimetric – consists of two basic forms, dual-polarization and quad-polarization. In dual-polarization, the transmit polarization is fixed and the receive antenna collects orthogonal polarizations (e.g., the transmitter sends out a vertically polarized wave, and the receiver collects both vertical and horizontal polarizations). Quad-polarized operation requires the transmitter to interleave transmissions of orthogonal polarizations, and the receiver simultaneously collects two orthogonal polarizations as in the dual-polarized case.
- Multipass – the radar can collect data at a common operating frequency, polarization, and bandwidth over distinct orbits and then process the data to look for scene changes. When the processing is coherent from pass to pass, the mode is called

coherent change detection (CCD); naturally, noncoherent change detection operates on magnitude-only data from pass to pass. Change detection makes it possible to detect subtle changes in the scene, such as the presence of tire tracks on a dirt road or areas of trampled grass.

It is the purpose of the radar signal processor to operate on the radar measurements and generate the radar data product. A data signal processor, such as a tracker, operates on this output to assist the operator or analyst in interpreting events.

Regarding radar measurements, it is worth pointing out the difference between monostatic, bistatic, and multistatic systems [2]. The radar transmitter and receiver are collocated in monostatic radar. The bistatic configuration employs transmit and receive sites separated by an appreciable distance [5]; the distance is not precisely defined, but it is instructive to consider the bistatic configuration one in which target and clutter-scattering phenomenology are distinct from the monostatic case, and hence include different information content. A cooperative bistatic system controls its illumination source, whereas a noncooperative bistatic system employs illuminators of opportunity. Multistatic radar merges data from multiple bistatic nodes and can yield substantially enhanced geolocation performance resulting from the combination of the diverse target measurements [19].

Invariably, radar applications involve collecting and exploiting distinct measurements to achieve a given mission objective. Different measurement domains enable the radar to better differentiate a desired target from interference and other potential targets. At times, practical considerations – cost, deployment issues, etc. – affect the measurement domains collected by the radar.

1.4 | RADAR FREQUENCIES

Radar operating frequency is chosen based on a number of considerations. Important trade factors include but are not limited to the following.

- Spatial resolution: For a fixed aperture size, beamwidth is proportional to $\lambda/L_{a,m}$, where λ is wavelength and $L_{a,m}$ is the aperture length in the mth dimension.
- Propagation: Lower frequencies propagate farther and are used in very long range surveillance systems. As frequency increases, so does atmospheric attenuation due to water vapor, rainfall, and other weather effects as well as from dust and suspended particulates [16].
- Materials penetration: Radar systems that must find targets under foliage, behind walls, under canopies, or below soil favor lower frequency operation. Foliage-penetrating (FOPEN) radar systems typically operate at frequencies from several tens of megahertz up to 1 GHz; ultrahigh frequency (300 MHz to 1 GHz) is a popular choice, trading off attenuation for resolution. Through-the-wall radar favors L-band (1–2 GHz) as a good trade between attenuation through the wall, resolution, and aperture size.
- Electromagnetic interference/electromagnetic compatibility (EMI/EMC): The characteristics of spectrum use in the vicinity of the radar siting or operating environment influence frequency selection. For example, placing a radar in the vicinity of a

high-power communications transmitter influences frequency selection and the general system design.

- Electronics: The availability and cost of electronic components at a given frequency influence the design. There are many radar systems built at X-band, for instance, leading to lower-cost electronics than at Ku-band, making it more challenging to justify Ku-band designs without other compelling factors.
- Target properties: Target phenomenology varies with frequency selection [16, 17].
- Fractional bandwidth limitations: High resolution requires wider waveform bandwidth and design consideration to accommodate dispersion and hardware mismatch effects. Generally, instantaneous bandwidths drive the system design up to higher operational frequency as a means of simplification.
- Radiofrequency interference: Radar frequency may be selected to avoid operating in a band covered by jamming systems [2, 18].

Table 1-1 summarizes the radar frequency operating bands. Specific frequency allocations for radar are designated by governing bodies: the International Telecommunications Union (ITU) in particular, with coordination among other national agencies.

Example applications for the various frequencies are given in Table 1-1. The nomenclature relates to the function. For example:

- the “L” in “L-band” refers to long range application;
- Ku is “K under” and Ka is “K above,” respectively, due to their frequency ranges relative to K-band;

TABLE 1-1 ■ Radar Frequency Bands

Frequency	Range	Example Application(s)
High frequency (HF)	3–30 MHz	Ground-penetrating radar, over-the-horizon radar (OTHR), very long range surveillance radar
Very high frequency (VHF)	30–300 MHz	Foliage-penetrating radar, very long range surveillance radar
Ultrahigh frequency (UHF)	300–1,000 MHz	Foliage-penetrating radar, airborne surveillance radar, long range ballistic missile defense radar
L-band	1,000–2,000 MHz	Weapons location radar, air traffic control radar, long range surveillance radar
S-band	2,000–4,000 MHz	Naval surface radar, weapons location radar, weather radar
C-band	4,000–8,000 MHz	Weather radar
X-band	8,000–12,000 MHz	Fire-control radar, air interceptor radar, ground-mapping radar, ballistic missile–tracking radar
Ku-band	12,000–18,000 MHz	Air-to-ground SAR and surface-moving target indication
K-band	18,000–27,000 MHz	Limited due to absorption
Ka-band	27,000–40,000 MHz	Missile seekers, close-range fire-control radar
Millimeter wave (mmw)	40,000–300,000 MHz	Fire-control radar, automotive radar, law enforcement imaging systems, airport scanners, instrumentation radar

- the "X" in X-band stands for "X marks the spot," due to the common use of this frequency for fire-control systems (some suggest that the X is the roman numeral representing 10, the approximate center frequency in GHz for the X-band); and
- "C-band" is a "compromise" between a selection of X-band and S-band.

The radar center wavelength is given as $\lambda_o = c/f_o$, where f_o is the center frequency. Wavelengths on the order of a millimeter technically start just slightly above 30 GHz.

1.5 | RADAR FUNCTIONS

All radar systems operate on the same physical principle: an active source illuminates a target, a receiver then collects scattered target energy, and a processor generates the radar product (e.g., dots on a screen representing target detections or a synthetic aperture radar image). From this basic concept of radar operation arise different radar functions. Radar mode design implements variants of these core functions: search, track, and recognition. In general, the purpose of the core radar functions falls into one of two primary categories, as given in [2]:

- *moving target indication* (MTI), with subsequent steps to estimate target motion and type, perhaps followed by a tracker to refine target position and velocity estimates and predict where the target will next appear; or
- *radar imaging*, the process of collecting data, estimating radiofrequency reflectivity over the local coordinates of interest, and then mapping the estimates to a geo-referenced framework.

In *search*, the radar system attempts to acquire targets of interest. Examples include an airborne early warning (AEW) radar scanning the sky for incoming aircraft and an air interceptor (AI) radar scanning for enemy fighter aircraft. In a similar vein, imaging radar typically "lay down" a certain number of beams per specified time interval to collect spotlight SAR data, or scan a certain area on Earth's surface in stripmap mode with the objective of searching for certain target types; in the former case, the target of interest might be a missile launcher, whilst in the latter scenario the analyst may be trying to identify deforestation or degradation of polar ice caps.

Oftentimes, radar systems that implement the search function are called *surveillance radar*. The surveillance radar may detect the same target multiple times, thereafter tracking the target through the skill of the radar analyst via something tantamount to "grease pencil markings on a radar display" or by feeding radar measurements into an automated tracker; however, the radar continues to search for new targets with a very similar scan pattern and waveform previously employed to generate existing target indications; and, as already suggested, the nuances of correlating these target detections from scan to scan are left to either the analyst or an automated tracker. Radar resources are not diverted upon detecting a given target; rather, if engagement is to occur, the surveillance radar "hands off" the target to a tracking radar.

The *tracking* function involves focusing radar resources more acutely on a particular target or set of targets. The radar dedicates resources to ensure adequate measurements are collected to maintain track quality. Information from the tracker is used to direct the transmit beam to anticipated target locations. For example, an L-band search radar persistently detects an incoming target, thereafter handing off the acquired target to an X-band tracking radar that refines estimates of target state (position, velocity, and possibly acceleration) by frequently collecting target measurements. The product from the tracking radar function is subsequently provided external to the radar system to a command-and-control function.

It is possible that a single radar performs both search and track. Moreover, a single radar can, under the appropriate set of constraints, simultaneously implement both functions in what is known as *track-while-scan*. In track-while-scan, sufficient radar timeline is available so that, between required tracker updates, the radar can allocate its resources to search for new targets or reacquire targets dropped by the tracker.

In addition to searching for targets and placing them in track, *recognition* is another important function. Recognition involves coarsely or finely determining the target type through the following steps: discrimination, classification, and identification. Discrimination bins the target according to level of interest – for example, a potential military target versus generic ground traffic. Classification determines the threat category, such as ground transport, tank, or missile launcher. Identification then narrows the assessment to a particular target class, such as the tank, missile launcher, helicopter, or aircraft model. Different levels of recognition place varying demands on radar resources: discrimination only requires relatively coarse resolution, whereas identification requires greater information and hence higher resolution. These demands force the radar system to modify its operation in a manner distinct from search and track functions.

Recognition may take place at the hands of a trained analyst. An overview of automatic target recognition is given in [2].

1.6 | U.S. MILITARY RADAR NOMENCLATURE

Radar nomenclature acknowledges many different radar applications. Table 1-2 shows the nomenclature system used to catalog radar systems in the U.S. military. The first letter designates the platform, the second the equipment type, and the third the

TABLE 1-2 ■ Some Elements of the Joint Electronics Type Designation System (JETDS)[a]

Platform	Equipment Type	Application
A – Airborne	L – Countermeasures	G – Fire control or searchlight directing
F – Ground fixed	P – Radar	N – Navigation
M – Ground mobile	Y – Processing	Q – Special or multipurpose
S – Surface ship	B – Communications security	Y – Surveillance
T – Ground transportable	Q – Sonar	R – Receive (passive) only
U – Ground utility	W – Armament	S – Detecting, range and bearing, search
B – Underwater		
G – Ground		
K – Amphibious		
P – Man portable		

[a] The Joint Army–Navy Nomenclature System was previously used to catalog electronic equipment.

application; typically, these letters are preceded by the designation “AN/” (for joint service Army–Navy equipment) and followed by the model number. For example:

- The AN/APY-1 is the radar on the E-3A and E-3B Sentry Airborne Warning and Control System (AWACS). AN/APY-1 reads as “Army–Navy equipment,” airborne platform, radar, surveillance, model number 1. The AN/APY-2 is the radar on the E-3C AWACS and includes a maritime capability.
- The AN/APG-63 is the radar used on the F-15E fighter aircraft. APG-63 stands for airborne platform, radar, fire-control, model number 63.
- The AN/TPQ-53 is the Quick Reaction Capability Radar, sometimes called the Enhanced Firefinder radar. TPQ-53 stands for ground transportable, radar, multipurpose, model number 53. The TPQ-53 is a counterbattery radar used to defend ground troops from rocket, artillery, and mortar attack. The TPQ-53 is replacing the TPQ-36 Firefinder radar.
- The AN/SPY-1 is part of the U.S. Navy’s Aegis Combat System. It is a passive, phased array surveillance radar used to protect the ship from air and missile attack. SPY-1 stands for shipborne platform, radar, surveillance, model number 1.

A vast array of radar systems comprise the U.S. military inventory, covering a tremendously wide range of applications. Moreover, military radar innovation has led to civil and commercial opportunities. This book considers a number of different radar applications, discussing key issues, constraints, and technology resulting in a particular radar capability.

1.7 | TOPICS IN RADAR APPLICATIONS

This book is organized into three sections: tactical radar; intelligence, surveillance, and reconnaissance (ISR) radar; and specialized radar applications. Topics assigned to a particular section are done so based on predominant use but may hold broader applicability.

1.7.1 Tactical Radar

Tactical radar systems are used to execute an action within a limited timeframe, as opposed to information gathering that indirectly supports future activities. As a military example, tactical radar is used to track and engage an incoming missile. Police radar is used to evaluate speeds of individual vehicles relative to allowable limits and is a civilian safety example. Determination of liquid levels in industrial storage tanks, known as *level gauge measurement*, is a commercial example.

Continuous wave (CW) radar systems imply low-cost, low-complexity radar. These radar systems typically operate at short range, and their applications include missile seekers, altimeters, active protection systems used to direct a kinetic kill response at incoming rockets, police radar, and automotive safety. Chapter 2 discusses CW radar in detail, covering the basic configuration types; CW radar performance issues and analysis; modulated CW waveforms, including the commonly used linear frequency modulated CW (FMCW) waveform; and applications leveraging the benefits of CW radar.

Chapter 3 discusses millimeter wave (mmw) radar. As mentioned earlier, the millimeter wave regime technically ranges from 30 GHz to 300 GHz. The shorter wavelength is appealing for compact radar applications, as would be the case on a missile, in an unmanned aerial vehicle (UAV), or in a personal conveyance. A key benefit of the higher frequency is narrower beamwidth for a fixed aperture size, an important consideration for target engagement and operation in clutter-limited environments. A mmw radar can operate using both CW and pulsed waveforms; current applications tend to favor CW, consistent with the discussion in Chapter 2. Other mmw radar applications include concealed weapon imaging, automotive radar, and autonomous landing systems. In each of these applications, the short wavelength benefits the system application: higher resolution for concealed weapon imaging and autonomous landing; and compact system design with appropriately narrow beamwidth yielding finer angular resolution, as well as improved electromagnetic compatibility, in support of effective automotive radar. As discussed in Chapter 3, interest in mmw radar continues to grow; this interest will lead to improvements in the cost and performance of mmw electronic components.

Fire-control systems seek to detect, track, and recognize targets as part of the engagement process. While a number of sensor modalities can be used for fire control, radar proves very appealing, as Chapter 4 discusses, due to its improved range performance and all-weather capability relative to infrared and optical sensors. There is a broad range of fire-control radar systems supporting a number of missions, including air-to-air combat, air-to-ground fixed-site targeting, shipboard protection, and ballistic missile defense. Chapter 4 broadly considers fire-control radar objectives, implementation considerations, and example systems. This information is a good segue into subsequent chapters.

Pulse Doppler waveforms are a critical element of current and future radar systems. This waveform is the mainstay of most radar modes; the pulse Doppler waveform is particularly useful since it provides superior transmit-to-receive isolation. While SAR, AEW, and surface moving target indication (SMTI) all use pulse Doppler variants, air-to-air pulse Doppler radar is the focus of Chapter 5. Chapter 5 discusses basic airborne pulse Doppler radar principles and concepts, characterizes target and clutter Doppler properties as seen from an airborne platform, and examines the various pulse repetition frequency (PRF) selections.

The design of the antenna subsystem plays a critical role in modern radar capability and sophistication. Multifunction phased arrays offer superlative performance, since a single radar can carry out multiple tasks. As Chapter 6 describes, multifunction phased arrays provide beam agility through fine control of the elements comprising the antenna. Surface air and missile defense radars, such as the AN/TPY-2 Terminal High Altitude Area Defense (THAAD) radar, and airborne radars, such as the AN/APG-81 radar on the F-35 Lightning, provide multifunction capabilities to search, provide track-while-scan on many targets, and support weapons engagement. The multifunction phased array radar rapidly focuses a beam in space, transmits and receives an appropriate waveform for that specific objective, and then rapidly moves the beam electronically to the next dwell position. In addition to leveraging advanced antenna technology, multifunction phased array radar systems require detailed software architectures to manage system resources. Chapter 6 discusses resource management, as well as multifunction phased array design and performance assessment.

Ballistic missile defense (BMD) is an important application for multifunction phased array radar. BMD is an extraordinarily challenging problem, dealing with vast detection ranges and targets of lower RCS and higher velocity than typically seen in other applications. The BMD problem is sometimes stated as “hitting a bullet with a bullet" due to its complexity. Chapter 7 describes in detail BMD radar and its corresponding reliance on large, costly, and highly capable phased array radar systems. These phased array radar systems provide exquisite sensitivity and agility to detect, track, and engage ballistic missile targets. Moreover, as Chapter 7 describes, the radar systems comprising the BMD system usually accomplish other important missions as well, including shipboard defense for Aegis BMD, space situational awareness at some of the large ground-based radar sites, and measurement and signature intelligence (MASINT).

1.7.2 ISR Radar

ISR radar systems gather information in support of other actions. Examples include the collection of spotlight SAR imagery to determine if activity is taking place in the vicinity of a missile site and detection of troop movement using ground moving target indication (GMTI) radar [20].

Radar systems dedicated to early warning are also considered ISR assets. Early warning served as the original motivation for radar development. The British Chain Home radar is among the earliest early warning radar systems, and it played a pivotal role in the Battle of Britain during World War II. Since these early days, early warning radar systems continue to flourish, and many experts recognize their capabilities as critical to national defense. These early warning radar systems feed into command-and-control networks and provide handoff to tracking and engagement radar. Ground-based, shipborne, and airborne variants exist. Chapter 8 focuses on ground-based early warning radar, complementing some of the discussion in Chapter 7 on ballistic missile warning. Discussion in Chapter 8 covers the objectives of early warning radar; antenna, transceiver and electronics, signal processing, tracking, and electronic protection design considerations; and characteristics of fielded early warning radar systems. This chapter provides international exposure to the topic.

Chapter 9 covers SMTI radar design and implementation. (GMTI is the most prominent instantiation of SMTI.) SMTI is a radar mode whose fielded history started in the early 1990s with Joint STARS [20]. This chapter discusses the fundamentals of SMTI, including clutter and target modeling, performance measures, system design considerations, and signal-processing requirements. Clutter mitigation is a critical topic in SMTI, and substantial effort is devoted in Chapter 9 to this topic. As described in the chapter, at its very essence, SMTI radar attempts to discriminate the angle-Doppler response of a potential target from the background clutter. The chapter describes an end-to-end detection processing chain and a standard approach to bearing and Doppler estimation. An overview of several critical topics affecting SMTI implementation, such as the impact of heterogeneous clutter on detection performance and requirements for dismount detection, conclude the chapter.

Deploying radar on Earth-orbiting satellites is appealing due to the access such platforms provide. In recent years, international interest in developing and deploying satellite-based synthetic aperture radar has exploded. Spaceborne SAR has numerous applications, including remote sensing of natural resources, monitoring of oceans and gulfs, emergency management, and treaty monitoring. Chapter 10 discusses spaceborne SAR. The chapter presents an array of internationally developed SAR systems, exhaustively covers a number of critical design issues and considerations, and describes SAR implementation and performance assessment applied to spaceborne assets. The chapter summarizes the characteristics of a number of operational spaceborne SAR systems.

1.7.3 Specialized Applications

Innovation in radar technology continues. Advances in RF electronics and antenna technology, as well as remarkable improvements in high-performance computing, enable the conception and deployment of numerous new radar capabilities. This section of the book examines the emerging or specialized applications of radar technology.

Passive bistatic radar systems exploit ambient signals, such as those from broadcast stations and communications towers, to detect and localize moving targets. Original observations on radar potential were a result of target-induced modulation on noncooperative signals viewed at a receive site; early radar systems were bistatic owing to a requirement to isolate the transmit and receive function, and the history of radar in general and that of the bistatic topology are inseparable. The availability of lower-cost electronic components and computing devices is a key enabler in the design and deployment of passive bistatic radar, and it is a primary reason for an international surge of interest in this area. Chapter 11 discusses passive bistatic radar in detail, providing a historical perspective; details of bistatic radar geometry and fundamental operation; characteristics of plausible, passive bistatic radar waveforms, such as FM and DTV broadcast, cell-tower emissions, and wireless computer network signals, via the complex ambiguity function; processing requirements; and a survey of some practical systems. Digital modulation has been a boon to passive bistatic radar interest, owing to the potential for reasonably good range resolution. As Chapter 11 details, digital signal processing (DSP) is critical to passive bistatic radar utility, allowing the receive site to broadly capture scattered transmit energy through the formation of multiple surveillance receive beams; enabling direct path receipt and creation of the replica signal needed for pulse compression; allowing pulse compression implementation with different Doppler hypotheses to filter scaled, time-delayed versions of the replica signal; and providing a mechanism to mitigate the impact of the strong, direct path signal interfering with the surveillance channels.

Chapter 12 discusses radar application to air traffic control. Air traffic control radar systems are used throughout the world to maintain safe and efficient aviation. These radar systems have a long and proud heritage. While the role of air traffic control radar is evolving due to direct broadcast navigation systems, radar will continue to be pivotal in commercial aviation safety. Chapter 12 looks at the objectives of air traffic control, discusses the purpose of primary and secondary surveillance radar capabilities, and describes design issues for both surveillance modes; this chapter considers requirements for detection of weather effects as well.

From its earliest days, it was known that radar detects weather phenomenon. Most people are familiar with radar due to its extensive use on weather newscasts, and the term *Doppler radar* is widely recognized for this reason. Chapter 13 discusses weather radar in detail, surveying available weather-surveillance radar systems, describing the radar range equation and Doppler processing for weather surveillance, characterizing weather volume reflectivity, and discussing the manifestation of distinct effects (e.g., rainstorm versus tornado) in the weather-surveillance radar product. In addition to weather radar outputs showing up on the evening news, terminal Doppler weather radar detect downbursts and wind shear in support of aviation safety, and aircraft use radar to avoid localized weather. The incorporation of polarization to characterize raindrop size is a current endeavor. Advanced concepts for weather surveillance include the Multifunction Phased Array Radar (MPAR), the newest design from the Federal Aviation Administration (FAA) whose purpose includes replacing aging air traffic control radar and providing a simultaneous capability to monitor weather.

During the Vietnam War, insurgents realized they were safely hidden under foliage from the X-band fire-control radars of the time. Shorter wavelengths associated with higher-frequency radar are known to poorly penetrate foliage. The need to detect and engage troops under foliage drove the development of foliage-penetrating radar. Of all the technologies available for surveillance of concealed targets, radar is the most appealing. Chapter 14 discusses the history of FOPEN radar and then focuses on key issues around forming SAR images using lower-frequency, ultrawideband airborne radar. The chapter characterizes propagation through foliage as a function of frequency, examines clutter and target properties, and details SAR image-formation processing. Due to the overlap of FOPEN radar waveforms with a preponderance of other signal sources, radiofrequency interference mitigation techniques are critical in FOPEN; in this regard, Chapter 14 discusses waveform design approaches and both transmit and receive-side waveform notching. FOPEN radar systems leverage polarization to assist in separating manmade and natural objects and in enhancing target characterization, important issues included in this chapter's exposition.

Ground-penetrating radar (GPR) is used to detect buried mines in military applications. GPR is also widely used by commercial industry to detect buried utilities. Moreover, GPR is used in archaeology and has been deployed in emergency management situations to detect life signs under rubble. An extensive discussion on GPR application, principles, and system design is given in Chapter 15. GPRs typically operate at lower frequencies of several MHz, but they can be deployed at operating frequencies in the microwave regime; frequency selection is a function of the properties of the material to penetrate, as well as target features. The system typically couples to the surface via direct contact of the transmit and receive antenna system. Chapter 15 discusses hardware implementation issues and provides sample product outputs. The chapter also more broadly discusses materials-penetrating applications, such as the characterization of objects within concrete building material.

The final application considered in this book is police radar. Police radar is used to calculate the speed of roadway traffic. As in the case of weather radar, police radar is well known to the general public. Chapter 16 discusses police radar in significant detail. Current police radar systems are CW (see Chapter 2), operate at X-band, and apply Doppler processing to generate range–rate estimates. These radar systems were initial by-products of radar development during World War II, thereafter leveraging technology readily available at the time to implement product improvement. This chapter also discusses sources of error in police radar application and steps taken to improve deployment.

1.8 | COMMENTS

While titled *Radar Applications*, this book is only able to cover select applications due to the vastness of the radar discipline; in this sense, *Select Radar Applications* is a more precise title. Important topics are excluded from the text for practicality's sake, something we certainly regret.

The reader may also notice that some topics are not basic principles, nor are they techniques; they appear closer in alignment to applications. The chapters on CW radar and mmw radar fall into this category. So, an argument can be made that *Select Radar Technology and Applications* is even more accurate titling.

This consternation aside, we hope the reader benefits from the detailed descriptions provided in this book, *Radar Applications*. The chapters herein build on the legacy of the first two books in the *Principles of Modern Radar* series; taken as a whole, many important aspects of modern radar principles, techniques, and applications have been covered.

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