Principles of Modern Radar

Vol. II: Advanced Techniques

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Dedicated to the many students of Georgia Tech's professional education courses, who inspired this book's development; and to our families, for all of their support and understanding.
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Preface

This is the second volume in the Principles of Modern Radar series. While the first volume, Principles of Modern Radar: Basic Principles provides fundamental discussions of radar operation, Principles of Modern Radar: Advanced Techniques discusses key aspects of radar signal processing, waveforms, and other important radar techniques critical to the performance of current and future radar systems. It will serve as an excellent reference for the practicing radar engineer or graduate student needing to advance their understanding of how radar is utilized, managed, and operated.

What this Book Addresses

Modern radar systems are remarkably sophisticated. They can be configured in numerous ways to accomplish a variety of missions. As a result, radar is a highly multidisciplinary field with experts specializing in phenomenology, antenna technology, receivers or transmitters, waveforms, digital design, detection, estimation and imaging algorithms, electronic protection, tracking, target identification, multi-sensor fusion, systems engineering, test and evaluation, and concepts of operation. In addition to tremendous advances in computing technology, a trend is afoot in radar to move the digitization step closer and closer to the antenna element. This places great emphasis on the importance of the collection approach, sensor topology, and the particular algorithms and techniques applied to the incoming data to produce a superior product.

Principles of Modern Radar: Advanced Techniques addresses this aforementioned trend and the most important aspects of modern radar systems, including quite current subtopics. Readers will find modern treatment of multi-input/multi-output (MIMO) radar, compressive sensing, passive bistatic radar, signal processing, and dismount/human detection via radar. The chapters are organized in five sections: waveforms and spectrum, synthetic aperture radar, array processing and interference mitigation techniques, post-processing considerations, and emerging techniques.

Why this Book was Written

We and radar practitioners are aware of many very fine single subject radar reference books that build from core principles with in-depth treatment, and most of them are referenced within this book for further reading. However, we and SciTech felt strongly that selected advanced radar topics could be gathered and organized logically into a single volume. Moreover, such a volume could incorporate textbook elements, most notably problem sets, for use within academic programs and training classes often taught, and necessarily so, within industry and government. Even practicing engineers engaged in self-study appreciate logical development of topics and problems with answers to test their understanding. Very few advanced radar books, however, are written in a textbook style and include problem sets. The chief impediment to the advanced radar textbook idea
Preface

has always been the unlikelihood of any one, two, or even three authors possessing such a broad, yet deep, knowledge of, and experience with, so many advanced radar subjects. We are very proud to say that the chapters in this volume are written by noted experts in the radar field, all of whom are active researchers in their areas of expertise and most of whom are also instructors of short courses for practicing engineers. We are thankful to each of the contributing authors who share our vision of a long-needed advanced radar book covering a diverse array of topics in a clear, coherent, and consistent framework. Their unwavering dedication to quality and content — evidenced by their multiple rewrites in response to reviews and the volume editors’ suggestions for improvements — inspires us all.

How the Content was Developed

Each chapter has also been thoroughly vetted for content and technical accuracy by outside radar experts who volunteered to take part in SciTech Publishing’s community review process. All of the chapters received multiple reviews at different phases in the development cycle, starting with chapter outlines and proceeding through multiple manuscript drafts. It is most evident that the quality of *Principles of Modern Radar: Advanced Techniques* has been tremendously improved by the selfless and enthusiastic work of the volunteer engineers, scientists, and mathematicians who invested their own time to review book chapters, sometimes individually and sometimes in related chapter sequences, all to help develop a high quality and long-lasting single source advanced radar book. The reviewers of the manuscript are gratefully acknowledged and listed by name in later pages of this opening section.

The History of the POMR Series

It should be no surprise that organizing and publishing a book of this nature is a significant and challenging undertaking. It is an interesting fact that the *Principles of Modern Radar* series evolved from the initial goal of a single book. From early reviews and the enthusiasm of chapter contributor candidates, the single book became two: *POMR: Basic Principles*, published in early 2010, and the planned “advanced applications and techniques”, which then became three. Why? The second volume had grown to over 30 planned chapters, and it quickly became apparent that we needed to divide the second volume into two distinct volumes: *Advanced Techniques* and *Radar Applications*. Over the past two years, as chapters were written, reviewed, and revised, *Advanced Techniques* edged slightly ahead in progress and became our primary focus over the past nine months. *Principles of Modern Radar: Radar Applications* therefore follows the issuance of this book.

Acknowledgements

As editors for this volume, we are very grateful to the SciTech Publishing team. We thank them for their support, professionalism, and certainly their patience. We are especially appreciative that the publisher, Dudley Kay, President and Editorial Director, set the highest expectations on book quality as his primary goal. Robert Lawless, Production Manager,
tracked, organized, and refined the many disparate elements to bring them together as a coherent and consistent whole. Brent Beckley, Sales and Marketing Director, helped gather and manage the unusually numerous volunteer reviewers as an explicitly stated “community effort” and consequently understood our content and audience objectives far in advance of publication.

Most importantly, we are thankful to our families for their patience, love, and support as we prepared materials, revised, reviewed, coordinated, and repeated. This book, in part, represents time away from the ones we love and would not have been possible without their understanding and willingness to support our passion for engineering.

To our Readers

We hope the reader will enjoy this book as much as we enjoyed putting it together. It should be clearly evident to all that read these pages that radar is an exciting, dynamic, and fruitful discipline. We expect the future of radar holds even more adventure and promise.

Please report errors and refinements. We know from the publication of the first volume, *POMR: Basic Principles*, that even the most diligently reviewed and edited book is bound to contain errors in the first printing. It can be frustrating to see such errors persist even in many subsequent printings. We have come to appreciate how committed and meticulous SciTech Publishing is about correcting errors, and even making subtle refinements, with each printing of the book. So, it remains a “community effort” to catch and correct errors and improve the book. You may send your suspected errors and suggestions to:

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This email will reach us and SciTech concurrently so we can confer and confirm the modifications gathered for scheduled reprints. You are always welcome to contact us individually as well.

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Overview: Advanced Techniques in Modern Radar

William L. Melvin, James Scheer

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1.1 INTRODUCTION

Modern radar systems are highly complex, leveraging the latest advances in technology and relying on sophisticated algorithms and processing techniques to yield exceptional products. Principles of Modern Radar [1] is the first in a series, covering basic radar concepts, radar signal characteristics, radar subsystems, and basic radar signal processing. This text is the second in the series and contains advanced techniques, including the most recent developments in the radar community. Specifically, much of Principles of Modern Radar: Advanced Techniques discusses radar signal processing methods essential to the success of current and future radar systems. Applying these techniques may require specific hardware configurations or radar topologies, as discussed herein.

Principles of Modern Radar: Advanced Techniques focuses on five critical radar topics:

- Waveforms and spectrum, including advanced pulse compression techniques to provide high resolution or tailor the compressed waveform’s impulse response; jointly optimized or adapted transmit waveforms with complementary receive processing; multi-input, multi-output (MIMO) radar leveraging advances in waveform generation and multichannel antenna technology; and, compressive sensing.

- Synthetic aperture radar (SAR) theory and processing techniques for stripmap, spotlight, and interferometric modes.

- Array processing and interference mitigation techniques based on multichannel processing methods, including adaptive digital beamforming (ADBF) for interference suppression and space-time adaptive processing (STAP) for target detection in clutter,
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as well as space-time coded apertures for mission-tailored beampatterns. Electronic protection considerations are also broadly discussed in this section.

- **Post-processing considerations**, including the application of polarimetry to enhance the radar product, automatic target recognition, and multitarget tracking.
- **Emerging techniques** for dismounted personnel target detection and passive radar processing strategies.

### 1.2 RADAR MODES

Radar systems are designed to detect, locate, characterize, and, in some cases, track targets of interest. Radar applications and specific modes are diverse. For example, radars are used on aircraft, missiles, satellites, ships, ground vehicles, and tripods. They attempt to detect, locate, characterize, and possibly track aircraft, missiles, ships, satellites, personnel, metallic objects, moving ground vehicles, buried objects—even mold growing within building walls. With such a wide variety of radar platforms and targets, the process of taxonomizing specific radars and their goals is a daunting task. However, considering two primary radar super modes is often general enough to cover most radar objectives. The techniques in this text correspond to one or both of these modes:

- **Moving target indication (MTI)**: the detection, location, characterization, and tracking of moving objects, such as missiles, aircraft, ground vehicles, and personnel (so-called dismounts).
- **Imaging radar**: the high-resolution estimation of the electromagnetic backscatter from stationary or moving objects that yields a spatial image of the target in one, two, or even higher dimensions. One-dimensional images are called high-range resolution (HRR) profiles, whereas two-dimensional views are called synthetic aperture radar (SAR) images. When the radar is stationary and the target is moving or when both platforms are moving, the corresponding imaging mode is usually called inverse synthetic aperture radar (ISAR).

In the MTI mode, dots on a display are the primary radar product. Figure 1-1 is an example of ground target detections on a topographical map obtained via a ground moving target indication (GMTI) airborne radar mode.

The quality of each dot is a result of the system design and signal processing applied to the received reflections from target and clutter as well as the system's ability to mitigate radio frequency interference (RFI). Radar detection is based on two models, or hypotheses: the null hypothesis, \( H_0 \); and the alternative hypothesis, \( H_1 \). The null hypothesis presumes the target is not present in the chosen radar data, whereas the alternative hypothesis corresponds to the case of target signal embedded in interfering signals consistent with the null hypothesis (viz., clutter, jamming, other interference, and uncorrelated noise responses). Each of the signals under the null hypothesis case is stochastic: the complex envelope of the return is derived from a particular statistical distribution and follows a certain temporal behavior. For example, the return from a given clutter patch is commonly assumed to have a complex envelope drawn from a Rayleigh distribution (complex Gaussian voltage) and a voltage response that decorrelates over time according to a Billingsley model [2] for an overland collection or Gaussian correlation model over water [3]. Likewise, the target response is stochastic. The corresponding \( H_1 \) distribution typically appears...
displaced relative to the null hypothesis condition due to a shift in the mean but is otherwise overlapping.

The overlap between the null and alternative hypothesis distributions leads to ambiguity in the decision-making process: a decision region (determined by a threshold setting) corresponding to one model may also lead to a false declaration of the opposite model. These false declarations are either false alarms (the alternative hypothesis is chosen when in fact no target is present) or missed detections (the null hypothesis is chosen when in fact a target is present). The optimal detector follows from the likelihood ratio test (LRT) and involves operations on collected radar signals (usually after some preprocessing); a sufficient statistic, $\psi(x)$, is a canonical detector formulation [4, 5]. Identifying the region where sufficient statistic outputs likely correspond to the alternative versus null hypotheses with a specified Type I error (false alarm rate) requires knowledge of the joint probability distributions under both hypotheses: $p_{\psi(x)|H_0}$ is the probability density function (PDF) for the null hypothesis, and $p_{\psi(x)|H_1}$ is the PDF for the alternative hypothesis. The decision region is typically chosen so that if $\psi(x) > \eta$, where $\eta$ is the detection threshold, the alternative hypothesis is chosen; otherwise, $\psi(x) \leq \eta$, corresponds to selection of the null hypothesis.

Figure 1-2 depicts the detection process. The area under $p_{\psi(x)|H_1}$ to the right of $\eta$ gives the probability of detection ($P_D$), whereas the area under $p_{\psi(x)|H_0}$ to the right of $\eta$ gives the probability of false alarm ($P_{FA}$). As seen from this depiction, the two distributions overlap, and the only way to increase $P_D$ is to lower $\eta$ and accept a higher $P_{FA}$.

Alternatively, one might ask if there is a strategy to increase the separation between the null and alternative hypothesis distributions. Generally, this increased separation can be achieved via the appropriate exploitation of the radar measurement space, or degrees of freedom (DoFs), and advanced processing methods like ADBF and STAP. The objective in exploiting DoFs is to identify a measurement space where the target and interference (e.g., clutter, jamming) are separable. For example, spatial and fast-time DoFs are used to efficiently mitigate the impact of wideband noise jamming on the detection of a target located in proximity to the jammer, but still at a slightly different angle of arrival. Advanced processing methods combine the measurement DoFs in the most effective manner possible.
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FIGURE 1-2  | Radar detection involves discriminating between the null (H₀) and alternative (H₁) hypotheses. This figure depicts H₀ and H₁ probability density functions for the sufficient decision statistic, along with threshold setting, η. The probability of false alarm, P_FA, is the area under the null hypothesis distribution curve to the right of the threshold, whereas the probability of detection is the area under the alternative hypothesis curve to the right of η.

to enhance MTI performance. The net objective of DoF selection and advanced processing methods in MTI radar is to increase the separation of the two distributions in Figure 1-2. Major sections of this text are devoted to examining these sophisticated techniques of critical importance to modern radar functionality.

The imaging radar mode typically involves moving the radar through angle while viewing a stationary target [6, 7]. (In the HRR case, a wideband waveform is used to characterize the target range response at that particular viewing angle.) As the radar moves through angle, the range between each of the various scatterers comprising the scene will vary in a manner consistent with the changing geometry. The changing range results in a time-varying phase that multiplies a complex gain term proportional to the square root of the scatterer’s radar cross section (RCS). Each resolvable scattering cell in the unambiguous region of interest exhibits a unique phase history. Figure 1-3 depicts a SAR collection geometry, where L_SAR is the synthetic aperture length, r₀ is the range from the aperture reference point to scene center, r(t) is the time-varying range to a scatterer of interest, v_p is the platform velocity in the x-direction, t is the independent variable time, and φ_c(t) is the time-varying cone angle measured from the platform velocity vector aligned with the x-axis. From this figure, the reader can envision the time variation of r(t) (or φ_c(t)) as the platform moves along the synthetic aperture baseline.

FIGURE 1-3  | SAR collection geometry showing platform moving along x-axis with velocity, v_p, and a stationary point target passing through the gray illumination beam with time-varying range, r(t). The platform is shown at the origin of the collection, and time varies from −0.5T_SAR to 0.5T_SAR, where T_SAR is the total collection time.
The received radar signal is the summation of the returns from multiple, resolvable scatterers within the scene. (Unresolvable scatterers within each cell add coherently, yielding an effect known as speckle where some distributed scatterer responses appear brighter than others.) A matched filter designed to the phase history of a specified scattering cell, appropriately normalized and projected into the ground plane, yields an estimate of the corresponding RCS.

Figure 1-4 is an example of a 1 m spotlight SAR image collected at the Mojave Desert Airport in California, USA; the reader will notice features corresponding to tarmac, aircraft on the tarmac (bright spots on top of the darker regions), aircraft hangars, and fence lines. This image is plotted in the ground plane, where the x-axis corresponds to cross-range and the y-axis is downrange.

Precisely constructing the matched filter for each scatterer is reliant on perfect knowledge of the scene geometry, platform attitude, and hardware characteristics as well as correct assumptions on the scattering behavior (viz., no interaction between scattering cells consistent with the Born approximation). Errors in this knowledge lead to degraded image quality. Additionally, applying the precise matched filter can prove computationally burdensome. SAR algorithms focus on compensating for certain types of collection errors and approximating the matched filter to mitigate computational loading. Additional SAR goals can involve extracting additional information, such as the target height. The theory of imaging radar and important processing techniques and approaches to enhance image quality are discussed extensively in this text.

1.3 Radar and System Topologies

Most fielded radar systems are monostatic: the transmitter and receiver are colocated, with the scattering phenomenology uniquely dependent on the angle of incidence and reflection being equal. In some cases, there may be the appearance of significant separation between
transmitter and receiver, yet the relative separation is small compared with the typical
detection range; the phenomenology is still monostatic in nature. Over-the-horizon radar
(OTHR) is an example of this case. Also, when the transmitter and receiver are located on
different parts of an aircraft, this is considered monostatic.

In the bistatic radar topology [9], the transmitter and receiver are separated a consid-
erable distance such that scattering phenomenology differs from the monostatic case. For
aerospace bistatic systems, the ground clutter spectral characteristics also appear much
more complicated than in the monostatic configuration. Bistatic radars also may be co-
operative or noncooperative. A cooperative bistatic radar manages, monitors, or selects its
source of illumination. In contrast, a noncooperative bistatic radar, sometimes called a
passive bistatic radar, employs transmit sources of opportunity, such as cell towers, tele-
vision and radio transmitters, and other radar systems. While the bistatic radar may not
control its source of illumination, modern radar technology still allows these systems to
apply coherent signal processing methods.

Multistatic radar involves multiple receivers and possibly transmitters. Multistatic
radar provides a diversity of spatial measurements, which can be used to minimize target
fading, improve target geolocation [10], and possibly enhance target recognition. Because
the multistatic radar can use multiple transmitters and receivers, it is sometimes considered
a multi-input, multi-output (MIMO) configuration.

However, the typical MIMO configuration is usually monostatic in nature and involves
transmitting different, ideally uncorrelated, waveforms from each antenna subaperture.
The ability to coherently transmit different waveforms from each subaperture leads to
spatial diversity on transmit, which effectively leads to a secondary phase modulation
on the received target signal that can potentially improve target location performance.
MIMO radar may also have some advantages for sparse arrays—dealing with timing
and position uncertainty and possibly mitigating spatial ambiguity—and enhancing SAR
coverage rates. Fully adaptive MIMO provides the opportunity for improved detection by
attempting to match the illumination waveform to the target class of interest. MIMO is an
area of current, active research within the radar community, and its benefits are still being
benchmarked.

This text considers monostatic, bistatic, and MIMO radar configurations. Advances
in processing technology and techniques are key enablers for bistatic and MIMO radar
topologies and are also central to significant improvements in monostatic radar perfor-

### 1.4 TOPICS IN ADVANCED TECHNIQUES

This section provides brief commentary on the major contributions of this text.

#### 1.4.1 Waveforms and Spectrum

Pulse compression waveforms are used in radar systems primarily to achieve the range
resolution of a physically shorter pulse width while providing acceptable average power
corresponding to the longer pulse. Low probability of intercept is another consideration.
A number of modulations are available and are intended to provide the most appropriate
ambiguity function for the application at hand. The ambiguity function characterizes the
waveform range impulse response and its sensitivity to Doppler modulation. The waveform
resolution is inversely proportional to the waveform bandwidth. Achieving high resolution within receiver bandwidth and other hardware constraints is yet another driving factor.

Chapter 2, “Advanced Pulse Compression Waveform Modulations and Techniques,” describes in detail three classes of waveforms intended to provide high resolution while averting receiver bandwidth and/or analog-to-digital converter (ADC) limitations. These waveforms include stretch processing, stepped chirped, and stepped frequency. Stretch processing essentially starts the radar signal processing chain within the analog receive hardware, beating the incoming waveform with a modulation that converts range delay to spatial frequency. The digital processing stage applies an ADC operating at a lower sample rate, but fully covering the lower bandwidth spectrum corresponding to a particular range swath of interest, and a Fourier transform to pulse compress the data. In this case, swath width is traded for the higher resolution corresponding to the transmit bandwidth. Stepped chirp is a coherent waveform using a series of chirps of modest bandwidth and pulse width at offset transmit frequencies. Each chirp is transmitted at a chosen pulse repetition interval (PRI) and received by a radar front end matched to the chirp bandwidth and center frequency. The digital signal processor synthesizes a waveform generally corresponding to the concatenated bandwidth of all the received chirp signals. The stepped chirp approach thereby allows for very high resolution using radar hardware with much lower instantaneous bandwidth. Stepped chirp requires increased control over the radar oscillator and timing sequence and a modest increase in processing complexity. The range swath is limited by the chosen PRI, and target Doppler is another factor limiting performance. Stepped chirp has application to high resolution SAR systems.

Stepped frequency is also discussed in Chapter 2. The stepped frequency waveform is a modulation of choice in instrumentation radars. The waveform generator sends a series of narrowband frequencies through the transmitter for a specified target viewing angle. The narrowband receiver collects each frequency and reconstructs a waveform corresponding to the composite, much higher bandwidth signal. Stepped chirp waveforms are not especially Doppler tolerant, requiring compensation for any scatterer motion (e.g., turntable movement). Chapter 2 also covers waveforms of a particular bandwidth whose design or receive processing tailors the sidelobe response while minimizing signal-to-noise ratio (SNR) loss. This analysis includes nonlinear frequency modulated (NLFM) waveforms and mismatched filtering methods. Quadrature coded waveforms are also examined as a means to manage spectral sidelobes and thus mitigate electromagnetic interference (EMI) among different electronic systems.

For decades, radar systems have applied adaptive signal processing within the receive signal processing chain. Constant false alarm rate (CFAR) algorithms are the prime example: they estimate the ambient disturbance power and then apply a threshold multiplier, which is a function of the CFAR method and number of training samples, to set a detection threshold that ideally leads to a design false alarm rate [11, 12]. ADBF and STAP are more recent examples, where the signal processor modifies spatial or spatio-temporal weights in response to changes in the interference or clutter environment in an attempt to maximize output signal-to-interference-plus-noise ratio (SINR). CFAR, ADBF, and STAP have improved radar performance immensely. Chapter 3, “Optimal and Adaptive MIMO Waveform Design,” considers extending the success of adapt-on-receive methods to the joint adaptation of both transmit and receive characteristics. As mentioned earlier, radar detection enhancement is largely dependent on choosing the appropriate radar DoFs and modifying the system response to the changing interference environment to instantaneously improve output SINR. Extending this idea to the transmit side suggests modifying
the waveform frequency, spatial, temporal, and polarimetric features. Chapter 3 discusses the approach to design jointly optimized transmit waveforms and receive processing to maximize SINR. The transmit waveform, for example, can be optimized to shape spectral content to avoid bands where interference is present or to place energy where a specific target response may be greatest. The adaptation of the transmit waveform can prove challenging, but in this era of readily available auxiliary data (e.g., map data, information on building layouts), knowledge-aided pseudo-optimizations may prove quite useful [13].

Chapter 3 generalizes the transmit waveform adaptation over the spatial domain through the appropriately configured vector formulation to handle MIMO configurations. The concept of MIMO radar from the system perspective is then discussed in further detail in Chapter 4, “MIMO Radar.” MIMO radar, as described herein, generally refers to a monostatic radar with the ability to transmit different waveforms from a number of antenna subapertures and collect all reflected transmissions with a multichannel receive array. Unlike Chapter 3, Chapter 4 focuses on deterministic waveforms with ideally low cross-correlation functions. Moreover, it explores the benefits of the additional phase diversity on transmit, which has the potential to enhance the system’s ability to resolve targets in angle. The benefits of these increased spatial DoFs have application to SAR and MTI radar: MIMO radar may, under the right circumstances, increase SAR area coverage rate and lead to potentially better minimum detectable velocity (MDV) for a fixed coverage rate in the MTI mode.

Chapter 5, “Radar Applications of Sparse Reconstruction and Compressed Sensing,” covers the last topic in the waveforms and spectrum section of this text. The idea behind compressed sensing theory is that a desired radar signal can be represented relatively sparsely—with a small number of basis functions—and that this compression can be achieved or enhanced through the measurement process. As presented in Chapter 5, the theory of compressed sensing presumes a linear signal model of the form \( y = Ax + e \), where \( y \) is the vector of measurements, \( A \) is a matrix whose columns represent the measurement bases, \( x \) is the complex valued signal vector of interest, and \( e \) is additive noise. For example, \( x \) may be the vector of complex gain terms proportional to the square root of the reflectivity values of various points on the earth’s surface, the columns of \( A \) then represent the unique phase history of each point, and \( y \) is the vector of radar measurements to be converted into a radar image. Sparse reconstruction is focused on efficiently and accurately solving for the true value of \( x \) through regularization. As emphasized in Chapter 5, sparse reconstruction is not compressed sensing; rather, compressed sensing combines sparse reconstruction with constraints on the measurement matrix. These constraints are often satisfied through randomization of the measured signal, for reasons described in mathematical detail within the chapter. The benefits of compressed sensing to modern radar include the potential to reduce the vast amount of data collected by the radar while still being able to generate a product comparable to that resulting from Nyquist sampled signals.

### 1.4.2 Synthetic Aperture Radar

SAR systems sample a particular, fixed scene and then employ signal processing methods to convert the measurements to estimates of the reflectivity of each resolvable pixel of interest. SAR can be applied to remote sensing (e.g., Earth resources management), military missions, and planetary exploration.

The two primary SAR modes are called stripmap and spotlight. The distinction is a result of the manner by which data are collected and processed; otherwise, the objective of
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FIGURE 1-5 Comparison of stripmap and spotlight SAR collection geometries, where $L_{\text{SAR}}$ is the length of the synthetic aperture, and $\theta_{\text{int}}$ is the integration angle. In stripmap mode, the antenna beam “drags” through the scene of interest, whereas in spotlight mode the beam is continually re-steered to the center of the scene of interest.

As Figure 1-5 indicates, the spotlight mode focuses a higher gain beam at a particular point on the earth’s surface. The beam is steered to the center of the scene as the platform takes samples over angle. The spotlight mode is the most popular when fine resolution is needed, since large integration angle is possible. Chapter 6, “Spotlight Synthetic Aperture Radar,” discusses spotlight imaging and corresponding algorithms. The primary viewpoint is that collected data represent the Fourier transform of the scene reflectivity. The polar formatting algorithm is a mainstay of spotlight image formation and is used to compensate for scatterer motion through resolution cells (MTRC). Polar formatting resamples data collected along radial lines corresponding to each measurement angle onto a two-dimensional grid. Essentially, a two-dimensional inverse Fourier transform yields a radar image. Chapter 6 also explores multiplicative noise ratio (MNR), a key SAR metric that is a function of quantization noise, integrated sidelobe level, and ambiguity ratio. It varies as a function of signal strength in accordance with its constituent elements. Covered in this chapter also are the impact of phase errors and the most common autofocus methods used to improve image quality: phase difference autofocus and phase gradient autofocus. Autofocus is an adaptive method used to enhance image quality.

Stripmap mode and corresponding algorithms are discussed in Chapter 7, “Strip Map SAR.” The stripmap mode surveys the passing terrain using a sidelooking collection geometry. Stripmap mode has important application to large scene imaging for remote sensing (e.g., to examine deforestation, characteristics of polar ice, etc.). Chapter 7 discusses stripmap image formation algorithms in a sequence of increasingly sophisticated methods. The starting point is Doppler beam sharpening (DBS), which forms a range-Doppler map from the collected data over relatively small integration angle at long range and exploits the coupling between scatterer angle and Doppler frequency. Unfortunately, DBS image quality is limited by the occurrence of nonlinear phase as integration angle increases. Although the phase function is hyperbolic, an azimuth dechirp based nominally on a quadratic phase assumption is possible. Combining enhancements in range resolution with integration angle, range migration becomes a concern. DBS performance is extensible
to higher-resolution imaging by introducing range migration compensation and azimuth dechirp into the signal processing chain. However, higher-quality imagery requires better approximations to the individual point scatterer matched filter. Range-Doppler algorithms provide responses that more closely correspond to the scatterer point spread response (PSR), even precisely matching scatterer responses at certain ranges. Depth of focus—the range swath over which the PSR approximation yields acceptable image quality—is a primary limitation of such methods. The range migration algorithm (RMA) is presented as the culmination of the various stripmap SAR imaging formation methods discussed in this chapter. RMA makes no approximations to the PSR and is computationally efficient; it is the method of choice for higher-resolution stripmap imagery.

Interferometric SAR (InSAR or IFSAR) involves coherent exploitation of SAR imagery to derive terrain height information. Generally, terrain height is measured using pairs of SAR complex imagery (or multiple coherent collects) at slightly offset baselines, as described in Chapter 8, “Interferometric SAR and Coherent Exploitation.” The offset baseline provides diversity in range measurements as input into the InSAR terrain height estimation process. InSAR processing involves registration, phase unwrapping, and several other steps to calibrate the pixel height estimate. Airborne and spaceborne radar have successfully provided digital elevation maps (DEMs) for a number of years. Chapter 8 also describes other related techniques involving coherent exploitation of multiple, registered SAR collections, including coherent change detection and subsidence measurement.

1.4.3 Array Processing and Interference Mitigation Techniques

Section 1.2 suggests that measurement diversity and the ability to adapt to the changing characteristics of the interference environment are critical to enhanced detection and imaging performance.

Chapter 9, “Adaptive Digital Beamforming,” introduces the fundamentals of adaptive array radar technology. The concept of adapting an array of antennas to suppress interference dates to the late 1950s—with the work of Howells and Applebaum [14]—and has formed the basis for much of the field of adaptive signal processing. Advances in sensor and computing technology in recent years have led to increased emphasis on ADBF research and development.

Radar systems must provide adequate power-aperture to detect a target of a given RCS at a specified maximum range. Additionally, the radar must provide a mechanism to suppress interference and clutter. ADBF is used to suppress directional sources of RFI. The radar receive antenna design must include multiple spatial channels, which are used to discriminate the direction of arrival of a propagating electromagnetic wave. Digital beamforming uses the flexibility of digital signal processing to form multiple, simultaneous beams; the steering vector used to focus the array of antenna elements in a given direction corresponds to the spatial matched filter that maximizes output SNR. When colored noise is present, adapting the elements of the array to tailor the receive pattern is essential, as the RFI may be many orders of magnitude stronger than the target signal. ADBF attempts to maximize the array’s output SINR (the “I” indicates colored noise is present) by weighting array elements using estimates of the interference environment. The corresponding adaptive pattern, for example, will show nulls on sources of RFI—to within the limits of spatial channel availability—while forming a beam in the desired target direction. ADBF leads to significant performance improvement over the conventional solution when the target and RFI are sufficiently separated.
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in space. The required separation at which improvement is possible can be fractions of a beamwidth.

Chapter 9 comprehensively addresses ADBF theory and practical considerations. Multiple approaches to adapt the array are given, including the Wiener filter formulation; the maximum SINR weighting; constrained optimization, including the minimum variance distortionless response (MVDR) beamformer; the generalized sidelobe canceller, which is an approach to convert a constrained optimization into unconstrained form; and derivative and eigenvector constraints. Additionally, this chapter outlines a number of available approaches to calculate the weight vector in practice, including the batch sample matrix inverse (SMI) method and iterative methods. Element-level and subarray-based array architectures are explored, including key challenges associated with grating lobe effects. Chapter 9 also describes important hardware and computational considerations. The chapter culminates by describing several important adaptive antenna topologies, such as the sidelobe and beamspace cancellers, and considers methods for wideband cancellation based on space- and fast-time or sub-band architectures.

Chapter 10, “Clutter Cancellation Using Space-Time Adaptive Processing,” describes key issues in two-dimensional adaptive filtering using spatial and slow-time degrees of freedom to mitigate ground clutter. STAP is a generalization of ADBF techniques to two dimensions and is an important technology for aerospace radar searching for targets competing with stationary clutter reflections. This chapter formulates the space-time signal vector, discusses approaches to characterize space-time signals, and then develops a space-time ground clutter model. It is shown that ground clutter exhibits a distinct coupling in angle and Doppler; the STAP detection strategy is to identify signals whose angle-Doppler behavior differs from that of stationary clutter. In this vein, Chapter 10 then explains the essence of space-time processing, including key performance metrics such as probability of detection, SINR, SINR loss, and improvement factor. Several space-time adaptive algorithms are described as extensions of their one-dimensional counterparts given in Chapter 9. The chapter then covers STAP architectures, including reduced-dimension STAP and reduced-rank STAP. The reduced-dimension strategy is the most practical method of implementing STAP due to significant reduction in computational burden and training data requirements as well as performance benchmarking closely to the bound set by the joint-domain, optimal space-time processor. Benchmark results are given in the chapter using the SINR loss metric. A maximum likelihood estimator of target angle and Doppler response is given and is shown to integrate closely with the standard STAP solution. The chapter concludes with a summary of an end-to-end detection architecture and the practical issues of nonstationary or heterogeneous clutter impacts on STAP implementation.

It is important to point out that both ADBF and STAP exhibit super-resolution performance: they have the ability to null signals to within a fraction of a beamwidth, thereby providing acceptable performance even when the interference or competing clutter are within the mainlobe of the target beam. This makes them important in radar system design trades, where advanced signal processing coupled with modest size aperture replaces large, costly, conventional antenna systems.

Chapter 11, “Space-Time Coding for Active Antenna Systems,” describes space-time coding for multichannel arrays. This chapter primarily focuses on several limitations of the traditional approach to antenna transmit and receive—such as beamshape conflicts for multiple mission performance—and considers the flexibility afforded by transmitting different waveforms through separate spatial channels. In this sense, Chapter 11 combines
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key MIMO elements of Chapters 3 and 4; however, it is unique in that it primarily focuses on array design issues in more detail than the prior chapters and provides several additional, practical applications. Moreover, this chapter looks at several waveform selections distinct from Chapter 4 and assesses their impact on array performance.

Chapter 12, “Electronic Protection,” discusses general strategies to protect the radar system from hostile denial or manipulation of the electromagnetic spectrum. It commences with detailed discussion of the two foremost classes of electronic attack (EA): noncoherent, or noise, jamming; and coherent jamming. A noncoherent jammer degrades radar sensitivity by injecting a noise-like waveform into the radar receiver; depending on the jammer configuration, the basic goal is to deny either the radar detection or range. A coherent jammer receives, delays, modulates, and retransmits the radar waveform; this EA approach takes advantage of radar signal processing gain, thus allowing the EA designer to employ much lower effective radiated power (ERP) than in the noncoherent jamming case. Coherent EA goals include masking and deception. A number of jammer deployments (e.g., stand-in, escort, distributed) are possible for both classes of jamming. Critical jammer formulae are subsequently given in Chapter 12. After the nature of EA is delineated, the goals and features of electronic protection (EP) are then comprehensively discussed. EP takes place throughout the radar implementation and can include the use of waveform diversity, low sidelobe or adaptive receive antenna designs, specialized signal processing methods, specific hardware designs, and variable radar concepts of operation (CONOPs). The EP attempts to deny the EA, including its electronic support (ES), key information needed to maximize effectiveness (e.g., operating frequency or waveform modulation) or to make the radar robust to the jamming signal (e.g., high dynamic range, adaptive jammer cancellation). The most effective EP methods are anticipatory, staying ahead of the deployed EA technique and thus minimizing degradation to the radar product in spectrally contested electromagnetic environments. Chapter 12 comprehensively discusses a variety of EP techniques. Adaptive digital beamforming, described in Chapter 9, is but one of many EPs; detailed understanding of ADBF from Chapter 9 is useful in comprehending aspects of the broad EP vantage of Chapter 12.

1.4.4 Post-Processing Considerations

Radar post-processing involves estimating target parameters, such as angle and range rate; placing the target in track; and determining the target class or specific features. Often times, angle and Doppler estimation is considered part of the front-end radar signal processing, since it closely integrates with the antenna design and these parameter estimates may be used to mitigate false alarms (e.g., the processor may excise a detection if the corresponding angle-Doppler response is too close to the clutter ridge [13, 15]).

In typical, modern radar design, the post-processor ingests target detections and parameters and tracks the target trajectory or accepts complex range profiles, SAR imagery, and Doppler spectra to automatically recognize the target type. This section is primarily focused on automatic target recognition (ATR) and multi-target tracking. Radar polarimetry is also discussed in this part of the text, as ATR serves as a primary driver of polarimetric diversity.

Chapter 13, “Introduction to Radar Polarimetry,” discusses the polarimetric properties of propagating waves and their interactions with radar targets. Key concepts include the various forms of linear, circular, and elliptical polarization and the polarization scattering matrix (PSM). The PSM is a complete description of the scattering object’s polarimetric
properties and is an important consideration in ATR, remote sensing, and system design to mitigate certain classes of clutter and interference.

A primer on target identification is given in Chapter 14, “Automatic Target Recognition.” Here a unified framework is given for ATR involving the following four steps:

- Identify the target set of interest.
- Select the feature set to enhance the probability of correct classification.
- Observe the feature set, which involves collecting the appropriate measurements to enhance target identification.
- Test the measurements for those features corresponding to a particular target or target class.

Example target features might include a specific engine modulation encoded onto the Doppler signature or a specific combination of target bright spots and polarimetric behavior in complex SAR imagery. Different target sets must exhibit different features in the measurement domain if the processor is to achieve acceptable target recognition performance. The radar employs a variety of strategies to collect measurements appropriate to separate the features of one type of target or class from another. HRR profiles, for example, measure the range response of the target and might uncover a specific distance between two dominant scatterers unique to that target class; fully polarimetric, complex SAR imagery encodes a number of details about the target that the processor correlates with library templates, where the shortest deterministic or statistical distance leads to a particular target declaration. And, as suggested earlier, the Doppler spectrum of an airborne target may disclose characteristics of a particular engine construction, hence revealing the target class. Chapter 14 considers each of these unified steps in extensive detail.

After a target has been detected, target parameter measurements—typically of target range, velocity, and angle—are assembled into tracks. The measurements are sometimes called dots, as they instantaneously appear as such on an operator display. The accuracy of each measurement is affected by the radar system design, target characteristics and geometry, and other environmental considerations such as clutter and interference residue. A challenging issue in target tracking is handling multiple, closely spaced targets. Chapter 15, “Multitarget, Multisensor Tracking,” discusses this important radar topic in detail. It introduces fundamental track concepts, including the interpretation of the track covariance and measurement-to-track association concepts. Track filtering involves propagating the state forward in time and then updating the state with a new measurement after the association step. The extended Kalman filter (EKF) is one track filtering method detailed in the early sections of the chapter. One of its limitations is that it applies the same propagation function to all targets, which may not be applicable to the multitarget environment. The multiple-hypothesis tracker (MHT) is used in multitarget tracking scenarios due to its ability to mitigate measurement-to-track association ambiguity; a significant portion of Chapter 15 is devoted to developing the MHT. Also, the interacting multiple model (IMM) is described as a way to mitigate mismatch between the presumed and actual target dynamical behavior. This chapter also covers multisensor tracking, which sometimes is also called track fusion.

1.4.5 Emerging Techniques

As a result of the maturation of subsystem technology—especially antenna and computing capability—the class of targets of interest in air-to-ground radar has quickly evolved
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from large collections of vehicles to single large vehicles to personal conveyance to dismounts. Dismounts, as the name suggests, are walking or running humans. Chapter 16, “Human Detection with Radar: Dismount Detection,” explores methods to detect and characterize human targets. It first develops a time-varying, human RCS model. This model approximates the target response as the superposition of the returns from the head, torso, upper and lower arms, and upper and lower legs. The Thalman model characterizes target locomotion. The corresponding spectrogram of the dismount target is quite unique, exhibiting a time-varying sinusoidal Doppler response corresponding to the torso, with distinct, semiperiodic responses resulting from appendage reflections. The challenging aspect of the dismount response is that it is generally weak compared with typical ground vehicles. Moreover, the response time variation suggests that traditional approaches to pulse integration are not viable: as the energy smears over Doppler, a single Doppler hypothesis is inappropriate. On the positive side, though, the uniqueness of the dismount response is exploitable: the key is to employ model-based matched filters that search for plausible dismount returns in the collected radar measurements. Considering all possible dismount responses is a combinatorial challenge. Chapter 16 discusses practical matched filter strategies based on efficiently estimating dismount model parameters, which is extensible to dictionary-based approaches, such as orthogonal matching pursuit.

Passive bistatic radar (PBR), or passive coherent radar (PCR) as it is sometimes called, involves exploiting transmitters of opportunity—such as those on cell phone towers, carried by satellites, and used for direct broadcast communications—and generally, lower-cost receivers to detect moving targets or image fixed scenes. The vast improvements in digital signal processing technology serve as the enabler for PCR. Chapter 17, “Advanced Processing Methods for Passive Bistatic Radar Systems,” discusses such PBR signal processing strategies. These primary steps include beamforming the reference channel and surveillance channel, mitigating clutter and interference, match filtering the surveillance channel using waveform information in the reference channel, and then forming and thresholding a range-Doppler map. System performance is determined by a number of factors, including the two-dimensional cross-correlation function (viz., the ambiguity function) for the passive waveform. This topic is considered at length, along with comprehensive discussion of practical PBR processing strategies and issues.

1.5 | COMMENTS

This text is generally organized by technical area, as described in Section 1.1 and summarized in Table 1-1, covering a number of contemporary topics. The topics primarily emphasize processing techniques that tend to serve as critical drivers in enhancing radar performance when combined with the appropriate measurement DoFs. Measurement DoFs set the physical limit on algorithm performance; the separation of target features, clutter response, and interference in the measurement domain is key to improved detection, estimation, and identification performance, thereby ultimately yielding better tracking capability. Electronic protection expands on the idea of exploiting measurement DoFs to all aspects of the radar design to provide resilience to electronic attack.

As seen from Table 1-1, this text broadly covers the most important, current, and emerging radar techniques. In this regard, Principles of Modern Radar: Advanced Techniques will serve as an invaluable reference for the student and radar practitioner.


TABLE 1-1 = Summary of Text Organization by Technical Area and Chapter

<table>
<thead>
<tr>
<th>Technical Area</th>
<th>Chapters</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveforms and spectrum</td>
<td>2, 3, 4, 5</td>
<td>Advanced pulse compression, MIMO techniques, compressive sensing</td>
</tr>
<tr>
<td>Synthetic aperture radar (SAR)</td>
<td>6, 7, 8</td>
<td>Stripmap SAR, spotlight SAR, interferometric SAR, imaging or coherent exploitation algorithms</td>
</tr>
<tr>
<td>Array processing and interference mitigation techniques</td>
<td>9, 10, 11, 12</td>
<td>Adaptive digital beamforming, space-time adaptive processing for clutter mitigation, space-time MIMO coded apertures for multimode radar, electronic protection</td>
</tr>
<tr>
<td>Post-processing considerations</td>
<td>13, 14, 15</td>
<td>Polarimetry, automatic target recognition, multitarget and multisensor tracking</td>
</tr>
<tr>
<td>Emerging techniques</td>
<td>16, 17</td>
<td>Human or dismount detection and characterization, passive bistatic radar processing methods</td>
</tr>
</tbody>
</table>

Each chapter ends with problem sets the interested reader may elect to solve. While a number of these may be solved in a traditional sense with pen and paper, many also require the use of MATLAB or another suitable programming language. With an emphasis on processing techniques, the best strategy to master the material herein is the hands-on approach.

1.6 REFERENCES

CHAPTER 1  I  Overview: Advanced Techniques in Modern Radar


