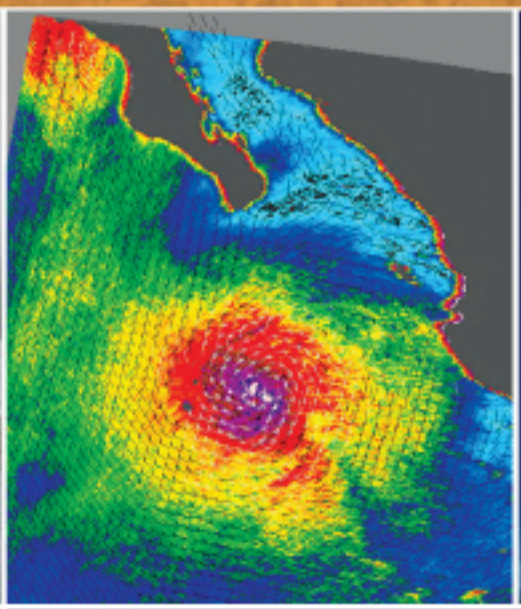
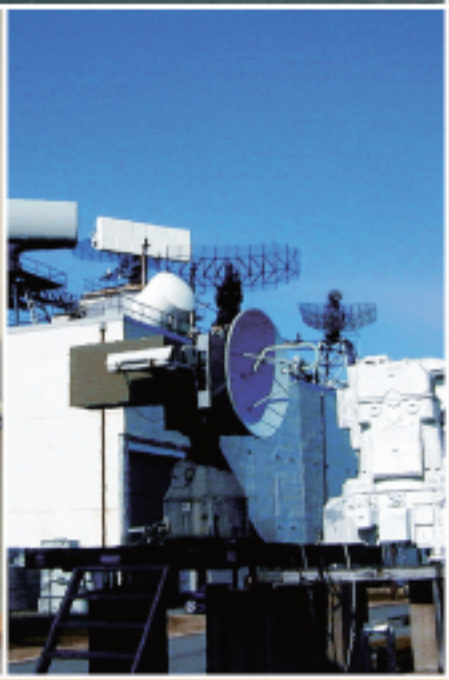
PRINCIPLES OF MODERN RADAR

BASIC PRINCIPLES


Mark A. Richards, James A. Scheer, William A. Holm (Editors)

Principles of Modern Radar

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Vol. I: Basic Principles

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Published by SciTech Publishing, Inc.
911 Paverstone Drive, Suite B
Raleigh, NC 27615
(919) 847-2434, fax (919) 847-2568
scitechpublishing.com

Editor: Dudley R. Kay
Editorial Assistant: Katie Janelle
Production Manager: Robert Lawless
Typesetting: MPS Limited, A Macmillan Company
Cover Design: Brent Beckley
Printer: Sheridan Books, Inc., Chelsea, MI

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Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

ISBN: 978-1-891121-52-4

Library of Congress Cataloging-in-Publication Data

Richards, M. A. (Mark A.), 1952-
Principles of modern radar / Mark A. Richards, James A. Scheer, William A. Holm.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-891121-52-4 (hardcover : alk. paper)
I. Scheer, Jim, 1944- II. Holm, William A. III. Title.
TK6575.R473 2010
621.3848–dc22

2010013808

Dedicated to the many students of Georgia Tech's professional education course *Principles of Modern Radar*, who inspired this book's development;
and
to our wives, Theresa, Ruby, and Kathleen, who inspire us.

Brief Contents

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Preface

Goals of the Book

As the editors of *Principles of Modern Radar: Basic Principles* (*POMR*), we had two primary goals in mind when this book was conceived. Our first goal was to design *POMR* to become the "Radar 101" textbook of choice for the next generation of radar engineers, whether students in graduate engineering courses, new hires on the job, or retraining professionals in government and industry. Our second goal was to provide a breadth of topics and modern approach that would make *POMR* the most convenient and valuable starting point for today's professionals needing to study or review a particular subject. To accomplish these twin goals, we needed to make several key trade-offs in designing the book:

1. Focus on modern techniques and systems from the start rather than historical background and legacy systems.
2. Strike a careful balance between quantitative mathematical models and tools and qualitative motivation and insight.
3. Carefully proportion the breadth of topics versus the depth of coverage of systems and external phenomenology.
4. Draw on the knowledge of a range of subject experts—and accept the intense editing effort needed to integrate their contributions into a coherent whole—versus the less comprehensive coverage but inherently consistent style and notation of just one or two authors.

What follows is a description of how these trade-offs were struck to achieve our goals.

Many in the radar community will recognize that *POMR* has evolved from the professional education short course of the same name taught to thousands of students by Georgia Tech research faculty since 1969. Some may even remember that the short course produced an earlier book, now out of print, by the same name.[1] This book is a completely new text, developed from scratch by 15 scientists and engineers working today with the most modern systems and techniques in radar technology. Each of these contributing authors brings a wealth of research and teaching experience to bear in explaining the fundamental concepts underlying all radar systems.

There are, of course, several very good books currently in use for college- and professional-level courses in radar systems and technology, so it is fair to ask why one should consider *POMR*. We believe the answer is fourfold:

- Comprehensiveness.
- Qualitative versus quantitative balance.
- Emphasis on the most modern topics and methods.
- Radar community support.

[1] Eaves, J.L., and Reedy, E.K., *Principles of Modern Radar.* Van Nostrand Reinhold, New York, 1987.

Most importantly, *POMR* provides a breadth of coverage unmatched by currently available introductory radar textbooks: chapters on fundamental concepts, propagation and echo phenomenology for targets and interference, all major subsystems of a modern radar, and all basic signal processing functions so important to modern practice. Second, these topics are presented both qualitatively and quantitatively, at a consistent level appropriate for advanced undergraduate and beginning graduate students and readers. No competing book of which we are aware strikes such a carefully constructed balance. Some competitors provide the traditional fundamental concepts but offer little on modern signal processing. Some are almost entirely descriptive, lacking the mathematical analysis students need to undertake their own analysis and modeling. A few others are highly mathematical but have limited coverage and lack the qualitative interpretation needed to develop the understanding of students new to the field. *POMR* not only provides the basic mathematical tools but also supports those tools with the explanations and insights of its experienced authors.

POMR's focus on *modern* radar is evident in its choice of topics. For example, extensive coverage is given to increasingly popular phased array antennas due to their advanced capabilities. Coherent systems, a prerequisite to most interesting signal processing, are strongly emphasized throughout the text. Last and most importantly, because so much functionality in modern systems lies in the signal processing, a significant portion of the book is devoted to methods enabled by digital radar signal processing, from pulse compression and Doppler processing to tracking and imaging. This topic choice and organization results in coverage superior to any other "Radar 101" textbook, so that *POMR* provides the most solid foundation for students progressing to "Radar 102" texts on more advanced and specialized topics.

Finally, *POMR* benefits from an extraordinary vetting by the modern radar community. It is a joint effort among the text's highly experienced authors and editors; the publisher SciTech, with its radar focus and resulting contacts; and the volunteering global community of radar experts, mostly fellow radar instructors and radar authors. As a result, the 21 chapters have been reviewed for content and style by more than 50 radar professionals representing academia, the government and military, and commercial companies. Chapters were reviewed first in their draft versions and then again after revisions. *POMR*'s editors were assisted in integrating the many reviewer suggestions by "master reviewers," each of whom read most or all of the chapters and also "reviewed the reviews" to help coordinate the improvements and perfect the emphasis, topical flow, and consistency across chapters. This extensive process of peer review iterations within the radar community ensures that *POMR* meets the needs of students, educators, and professionals everywhere.

Organization of Content

POMR is organized into four major parts: *Overview, The Radar Environment, Radar Subsystems*, and *Signal and Data Processing.* In teaching a technology area as broad as radar, it is difficult to design a topical sequence that proceeds in a straight line from start to finish without looking ahead or doubling back. The *Overview* section solves this problem by taking readers through a high-level first pass that familiarizes them with a range of fundamental radar concepts and issues, setting the stage for a more detailed examination in the remaining parts. Chapter 1 introduces basic concepts such as properties of electromagnetic waves, target and clutter echoes, monostatic and bistatic radar, and detection in noise. It

also illustrates the scope of radar technology by describing a wide range of military and commercial applications. Finally, Chapter 1 introduces some radar cultural information such as the "band" terminology (e.g., L-band, X-band) and the AN Nomenclature for U.S. military systems. Chapter 2 delves into that most fundamental mathematical model in radar, the radar range equation. The basic point target range equation is derived, and its implications are explored. The chapter then develops several of the common variants tailored to specific radar modes. Chapter 3 provides a closer look at the most fundamental radar task of search and detection, describing search processes and introducing the idea of statistical detection and the resulting importance of probabilities in evaluating radar performance.

Part 2, *The Radar Environment*, is one of the truly distinguishing features of *POMR*. Few, if any, introductory radar texts provide the breadth and depth of discussion of propagation effects and target and clutter characteristics found here. Chapter 4 introduces all major electromagnetic propagation phenomenology of importance to radar, from simple attenuation in various weather conditions to more complex issues such as refraction, diffraction, multipath, ducting, and over-the-horizon propagation. Chapter 5 summarizes the extensive data on modeling the reflectivity and Doppler characteristics of atmospheric, land, and sea clutter and presents many of the common mean reflectivity and statistical models needed for clutter analysis. Chapter 6 introduces the mechanisms of scattering and reflection and the concept of radar cross section for targets, while Chapter 7 describes the common statistical models for radar cross section needed to evaluate detection performance. Chapter 8 delves more deeply into Doppler shift, concentrating on typical characteristics of Doppler spectra for stationary and moving targets and radar platforms.

Part 3, *Radar Subsystems*, describes each of the major subsystems of a typical modern radar system. Chapter 9 describes radar antenna technology, starting with basic antenna concepts and relations and then describing classic monopulse and mechanically scanned antennas. Half of this chapter is devoted to modern phased arrays, with detailed discussion of array patterns, wideband effects, and array architectures. Chapter 10 describes radar transmitter technology, including high-powered thermionic (tube-type) noncoherent and coherent transmitters, as well as solid-state transmitter technology. Again, significant coverage is devoted to transmitter modules and feed architectures for modern phased arrays. This chapter also addresses spectrum allocation and transmitter reliability issues, topics not found in other introductory textbooks. Chapter 11 presents radar receiver technology, beginning with the most basic types and extending to multistage superheterodyne receivers. Noise and dynamic range issues are discussed, and both classical analog synchronous detectors as well as the increasingly popular direct sampling digital receiver techniques for coherent systems are described. The coverage of coherent exciters in Chapter 12 is unique in an introductory textbook but important in understanding the architecture of modern systems. Exciter performance issues are presented, followed by a discussion of the technology available to implement modern coherent radar exciters. The importance of maintaining low phase noise for pulse-Doppler systems is also explained. Another topic unique to this textbook is Chapter 13, which discusses radar digital signal processor technology. Metrics and procedures for estimating processor loading are introduced, followed by discussion of alternative implementation technologies such as custom integrated circuits, reconfigurable hardware, and exciting new techniques such as the use of graphical processing units for real-time signal processing.

Part 4, *Signal and Data Processing*, concentrates on the increasingly sophisticated techniques used to extract ever more information from radar signals using advanced digital signal and data processing. The first half of Part 4 deals with signal processing basics, detection, and clutter rejection. It begins in Chapter 14 with a succinct summary of digital signal processor fundamentals such as sampling, quantization, and data acquisition, followed by a thorough review of discrete Fourier analysis, including windowing and interpolation. Other sections refresh the reader on digital filters, properties of random signals, and the all-important matched filter concept and its connection to data integration. Chapter 15 returns to the topic of threshold detection first introduced in Chapter 3. Here, much more attention is given to details of coherent and noncoherent integration and alternative ways of using the available data. Neyman-Pearson detection and the Swerling models are introduced, leading to optimum detectors for radar signals. Albersheim's and Shnidman's equations are presented as convenient computational aids. Chapter 16 continues the discussion by introducing constant false alarm rate (CFAR) threshold detection, a practical requirement in real interference environments. The properties, performance, and shortcomings of the basic cell-averaging CFAR are discussed in depth, and then many of the common "robust" and "adaptive" CFAR variants are introduced and compared. Chapter 17 covers two major forms of Doppler processing for clutter reduction: moving target indication (MTI), and pulse-Doppler processing. The discussion of MTI includes blind speeds, staggered pulse repetition frequencies, and airborne MTI. The sections on pulse-Doppler processing introduce the important topics of blind zones and ambiguity resolution. This chapter also includes a brief discussion of the pulse-pair processing method widely used in weather radar.

In the second half of Part 4, the focus turns to postdetection position measurements and tracking as well as high-resolution techniques. Chapter 18 addresses position measurements in range, angle, and Doppler. Basic concepts of precision and accuracy lead to the introduction of the Cramèr-Rao lower bound on precision. Several estimators of range, Doppler shift, and angle are then introduced, and their performance is evaluated. This chapter leads naturally into an introduction to tracking algorithms in Chapter 19. After a discussion of basic parameter estimation and some of the data association and resolution problems that complicate radar tracking, a number of tracking algorithms are introduced, from the basic $\alpha-\beta$ tracker to the Kalman filter. Chapters 20 and 21 introduce the techniques needed to achieve high-resolution radar imaging. Chapter 20 describes pulse compression for high-range resolution. The matched filter is investigated in more depth and is then applied to the most common wideband waveforms, including linear frequency modulation or "chirp" and phase-coded waveforms ranging from Barker codes to a variety of polyphase codes. Methods of range sidelobe control are described, and the ambiguity function is introduced as a means of designing and understanding waveform properties. Finally, Chapter 21 provides an overview of synthetic aperture radar (SAR) imaging. SAR data collection is described, and general, widely applicable resolution and sampling equations are derived. While the range of SAR image formation algorithms is too extensive and too advanced for an introductory textbook, descriptions are given of the two extremes: Doppler beam sharpening, one of the simplest imaging algorithms; and backprojection, the current "gold standard" for advanced imaging. The chapter closes with a discussion of the unique phenomenology of SAR imaging, including layover, shadows, and speckle. Collectively, the extensive coverage of signal processing in Part 4 of *POMR* provides an excellent springboard to study of more advanced topics such as advanced SAR, space-time adaptive processing, and multiple-input multiple-output radar.

An appendix reviews two basic electrical engineering topics that are important for understanding radar but not deemed necessary for inclusion within the chapters: Maxwell's equations and the use of decibels in describing radar values.

Features and Resources

POMR has been designed to ease the task of learning or teaching. Some of the features available to all readers include the following:

- Every chapter written by experts having "hands-on" experience in the design and development of radar systems.
- Every chapter reviewed by independent radar experts and edited by technical and publishing experts for content accuracy, level consistency, and readable style.
- Consistent notation and terminology employed throughout.
- Numerous illustrations integrated throughout, all newly drawn, clearly labeled, and carefully captioned.
- Table of common symbols and notation provided for quick reference.
- Table of acronyms, so plentiful in radar, presented alphabetically.
- Extensive, professionally prepared index facilitates reference use.
- At least 12 problems included in every chapter—over 250 total—to check and advance the student's understanding and capability. Answers to the odd-numbered problems are provided.

Several aids are available to adopting course instructors, with more being developed. The following aids can be obtained through request to SciTech at **pomr@scitechpub.com**:

- All problem answers and detailed solutions.
- All illustrations in the text in Microsoft PowerPoint sets or in high-resolution JPEG image formats for construction of custom viewgraphs.
- Copies of all equations in Microsoft Equation Editor format.

Several additional aids—tutorial simulations in MATLAB®[2] worked examples, additional problems for homework or exams—are expected to be available, and more are being developed and contributed by the radar community.

Publication of this first edition of *POMR* is just the first step in the development of a comprehensive set of resources for introducing radar systems and technology to a new generation of radar engineers. A website has been established to provide to readers these supporting materials, a complete and up-to-date list of reported errata, and an evolving set of new supplements. Visit the website periodically to check for the latest supplements and announcements:

http://www.scitechpub.com/pomr

[2]MATLAB is a registered trademark of The MathWorks, Inc. For MATLAB product information and cool user code contributions, go to http://www.mathworks.com, write The MathWorks, Inc., 3 Apple Hill Dr., Natick, MA 01760-2098 or call (508) 647-7101.

Companion Publications

Several remarkable publications are planned to complement, augment, and extend the material in *POMR: Basic Principles*:

Principles of Modern Radar: Advanced Techniques and Applications edited by William L. Melvin and James A. Scheer (2011)

Building on *POMR: Basic Principles*, this sequel provides extensive coverage of both advanced techniques in radar and a wide variety of specific modern applications that integrate the fundamental technologies into complete systems. Examples of advanced techniques include advanced waveforms, stripmap and spotlight synthetic aperture imaging, space-time adaptive processing, multiple-input, multiple-output radar, polarimetry, target protection, and electronic protection. Applications discussed include airborne pulse-Doppler radar, space-based radar, weather radar, air traffic control, and passive and bistatic systems. Together, the two *POMR* volumes will provide integrated and comprehensive coverage of modern radar, from basic concepts to advanced systems, all in a coherent and consistent style and notation.

Pocket Radar Guide: Key Radar Facts, Equations, and Data by G. Richard Curry (2010)

A quick reference in shirt pocket size to the very most important and commonly used facts, figures, and tables in real-world radar engineering practice.

Acknowledgments

Principles of Modern Radar could not have come into being without the dedicated efforts of many people. Each of our authors dedicated much personal time to contributing his or her individual chapters and then again to working with the entire *POMR* team to integrate the pieces into a whole that is greater than just the sum of those parts.

The authors were greatly aided by the reviewers and master reviewers. The complete list of reviewers is given in the "Publisher's Acknowledgments" section and so won't be repeated here, but every one of them had a direct hand in improving the final product in coverage, style, and correctness. Without their ability and willingness to critique the book based on their expert knowledge and their own experience with other introductory radar textbooks, we could not have achieved the level of consistency and coherency across such broad coverage and multiple authors. The authors and editors are greatly indebted to them for their efforts.

The entire *POMR* project might not have succeeded without the vision, support, and encouragement of SciTech Publishing and its president, Dudley Kay. SciTech is a wonderful asset to the radar community, and we hope this new book will add to that strength. Editorial assistant Katie Janelle managed the massive review process so important to *POMR*'s completion and quality. Production of a book is a complex endeavor requiring the efforts of many accomplished and dedicated staff. Robert Lawless is the production manager for *POMR*, responsible for managing the workflow and bringing together all the many pieces into the final product. Kristi Bennett, our copy editor, deserves great credit for bringing clarity, precision, and consistency to the writing styles of 15 authors. Freelancer Kathy Gagne conceived the eye-catching cover design. Brent Beckley has done an excellent job in marketing and promoting *POMR* so that it will reach and serve, we

hope, a large audience. All of the SciTech team has been professional and, at the same time, a pleasure to work with every step of the way.

Errors and Suggestions

We have tried to bring the radar community a carefully constructed and truly valuable new introductory textbook and professional reference in *POMR*, but we recognize that there are always some residual errors and inconsistencies. In addition, experience in using *POMR* and new developments in the rapidly evolving field of radar will inevitably bring to light a need to clarify or expand some topics and introduce new ones.

The extensive review process used to develop *POMR* raised and resolved many, many such issues. Those that remain are the responsibility of the editors. We welcome the assistance of *POMR* readers in identifying errata and in making recommendations for improvements in future printings and editions. All identified errata will be posted in a timely fashion on the *POMR* SciTech web site (http://www.scitechpub.com/pomr), accessible to all users.

One of our hopes for *POMR* is that it will be adopted for use in university, professional education, and in-house training classes. There is nothing like teaching the material to newcomers to the field to quickly identify areas where the book could be improved. We invite all instructors using *POMR* to help us design the next edition by letting us know of your experience in using it and how it can be improved in the future.

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Publisher Acknowledgments

Master Reviewers

Above and beyond the peer reviews focused on technical content, we recognized the need to bring consistency of level, notation, and writing style to an edited book composed of numerous expert contributions if we were to attain our goal of an outstanding textbook. From the initial rounds of reviews and follow-up conversations, SciTech determined which reviewers best understood our concerns, and we invited deeper involvement from them. The reviewers listed herein were called on to help resolve controversial and contradictory reviewer suggestions, to respond to editor and contributor problems, and, most of all, to work closely with SciTech as representatives of the radar community. The dedication of these "Master Reviewers" therefore merits our special recognition and appreciation.

Dr. John Milan (radar consultant): John brings more than 36 years of experience in radar systems at ITT, Gilfillan, and many years on the IEEE Aerospace and Electronic Systems Society Radar Systems Panel. He reviewed every chapter of the book for the sake of internal consistency and became the volunteer "master of figure captions," assessing every one for descriptive completeness and clarity. As impressive to us as the volume of review work undertaken, equally remarkable was John's response time to every request or question.

Mr. Byron Edde (radar/electronic warfare consultant and short course instructor, textbook author): Drawing on 40 years of experience designing and improving radar and electronic warfare systems, before reviewing materials Byron composed a hierarchal list of "What makes a textbook great?" As a successful textbook and radar study guide author who teaches courses to Navy personnel, Byron understood exactly what the *POMR* twin goals were and why they would be challenging to attain. He thus helped "set the bar" and provided broad stroke feedback on maintaining consistent depth and balance of theory, math, and practical reference to current technology. He is author of *Radar*: *Principles, Technology, Applications* and *The IEEE Radar Study Guide*.

Mr. G. Richard Curry (radar consultant and radar book author): Dick offered perceptive technical improvement comments across numerous chapters and was one of those capable of, and interested in, comparing reviewer comments objectively to help suggest the best solution. He is the author of *Radar System Performance Modeling*.

Mr. Paul G. Hannen (SAIC senior engineer, professor at Wright State University, and book author): Paul was most persistent and helpful about the first three chapters that "set the scene." He provided literally hundreds of suggested edits and worked directly with volume editor and chapter author Jim Scheer. If you perceive an especially meticulous handling of background radar facts in Part 1, give credit to Paul. He is coauthor of *Radar Principles for the Non-specialist* (3d ed.).

Dr. Randy J. Jost (senior scientist at USU Space Dynamics Lab, book author, Department of Defense consultant): Suggesting edits to various chapters for optimum organization, particularly Chapter 4, "Propagation Effects and Mechanisms," and contributing substantial content to Chapter 10, "Radar Transmitters," and always giving sound suggestions for improvements throughout, Randy proved once again why he is such an important author, reviewer, and advisor to SciTech. Randy is coauthor of *Fundamentals of Electromagnetics with MATLAB* (2d ed.).

Dr. David G. Long (professor and research director of remote sensing at Brigham Young University): David's help was invaluable in critiquing the sophisticated radar signal and data processing chapters and his contributions of content to Chapter 18, "Radar Measurements." David worked directly with volume editor and multiple chapter author Mark Richards to hone the chapters in Part 4.

Dr. Marshall Greenspan (senior systems consulting engineer, Northrop Grumman Corporation [NGC]): Marshall was not only a willing and able technical reviewer, particularly within signal processing chapters, but was also extremely helpful in suggestions and procurement of contemporary photographs via his contacts with the NGC public relations departments.

Dr. Simon Watts (deputy scientific director, Thales UK and book author): After providing excellent technical comments on several chapters, Simon was called on to assist with final edits to the organization, completeness, and notational consistency to his particular area of expertise, radar clutter, in Chapter 6. He is coauthor of the book *Sea Clutter: Scattering, the K Distribution and Radar Performance*.

Technical Reviewers

SciTech Publishing gratefully acknowledges the contributions of the following technical reviewers, who selected chapters of interest and read each carefully and completely, often in multiple iterations and often with substantive suggestions of remarkable thought and depth. Taken in aggregate, the value of their reviews was beyond measure and quite possibly unprecedented for a radar book:

Dr. Clive Alabaster, *lecturer, Cranfield University, GBR*
Chris Baker, *dean and director, ANU College of Engineering and Computer Science, Canberra, AUS*
Dr. Ronald Aloysius, *fellow engineer, Northrop Grumman Corporation*
Edward Barile, *senior principal engineer, Raytheon Corporation*
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Jim Scheer has 40 years of hands-on experience in the design, development, and analysis of radar systems. He currently consults and works part time for GTRI and teaches radar-related short courses. He began his career with the General Electric Company (now Lockheed Martin Corporation), working on the F-111 attack radar system. In 1975 he moved to GTRI, where he worked on radar system applied research until his retirement in 2004. Mr. Scheer is an IEEE Life Fellow and holds a BSEE degree from Clarkson University and the MSEE degree from Syracuse University.

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Bill Holm is the associate vice provost for distance learning & professional education at Georgia Tech, program director for the defense technology professional education program, and is a principal research scientist at GTRI. His research in radar technology, signal processing techniques, and related subjects has resulted in over 75 technical papers, research papers, and book chapters. His 30+ years of instruction experience include the “Principles of Modern Radar” and “Basic Radar Concepts” short courses and teaching in the School of Physics. Dr. Holm holds a Ph.D. degree in physics from Georgia Tech.

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Chris Bailey is a GTRI research engineer with experience in phased-array antenna design, analysis, and modeling, and phased-array radar-system engineering. His recent research efforts include digital beamforming, overlapped subarrays architectures, and low-power/low-cost arrays. Bailey has written numerous reports on phased array technology and regularly teaches phased array courses with the Georgia Tech Defense Technology Professional Education Program. He holds a M.S.E.E. from Johns Hopkins University.

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Chapter 18 – Radar Measurements and Chapter 19 – Radar Tracking Algorithms

Dale Blair is the academic administrator of the Radar Tracking GTRI Defense course. He is a senior research engineer at the GTRI Sensors and Electromagnetic Applications Laboratory (SEAL), and has been involved in the research and development and testing of target tracking algorithms and radar signal processing for more than 14 years, and is currently involved in phased array radar and multisensor tracking.

Mr. Joseph A. Bruder, PE
Chapter 11 – Radar Receivers

Joe Bruder retired from GTRI after 25 years but is actively working part-time there and Stiefvater Consultants. He has extensive experience in radar sensor technology, including radar system design, analysis and evaluation, test planning, testing and test measurements. At the USAF Rome Laboratory his research areas were space-based radar, bistatic radar, foliage penetration, and bird hazard detection. He is an IEEE Fellow, a member of the IEEE/AESS Radar Systems Panel and is the standards representative for the Panel.

Mr. Nicholas (Nick) C. Currie
Chapter 5: Radar Clutter Characteristics

Nick Currie served on the staff of GTRI for 30 years, performing measurements of the radar backscatter of the sea, rain, snow, vegetation, and sea ice, military and civilian land vehicles, small waterborne craft, missiles, and aircraft. He has consulted with DARPA and the National Institute of Justice on concealed weapon detection and through-the-wall surveillance, and with the USAF Rome Laboratory in the development of a cylindrical, bistatic RCS range. He is a Fellow of the IEEE for work in millimeter wave measurements. He has edited and coauthored four books in the field of radar measurements and clutter.

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Chapter 10 – Radar Transmitters

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Chapter 18 – Radar Measurements

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Chapter 10 – Radar Transmitters

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Chapter 10 – Radar Transmitters

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List of Acronyms

The following acronyms are used throughout this text. Some acronyms, *e.g.* SIR, have more than one meaning; the appropriate meaning is generally clear from the context.

Acronym	Definition
1-D	One Dimensional
2-D	Two Dimensional
3-D	Three Dimensional
A	Ampere
AAW	Anti-Air Warfare
AC	Alternating Current
ACF	Autocorrelation Function
ADC	Analog-to-Digital Converter, Analog-to-Digital Conversion
A-DPCA	Adaptive Displaced Phase Center Antenna
AESA	Active Electronically Scanned Array
AF	Array Factor
AGC	Automatic Gain Control
AGL	Above Ground Level
AL	Altitude Line
AM	Amplitude Modulation
AMTI	Airborne Moving Target Indication
AOA	Angle of Arrival
API	Application Programming Interface
AR	Autoregressive
ARMA	Autoregressive Moving Average
ASIC	Application-Specific Integrated Circuit
BIT	Built-In Test
bps	Bits per second
BPF	Bandpass Filter
BMD	Ballistic Missile Defense
BRL	Ballistics Research Laboratory (U.S. Army)
CA	Cell Averaging
CA-CFAR	Cell Averaging Constant False Alarm Rate
CBE	Cell Broadband Engine
CDF	Cumulative Distribution Function
CDL	Common Data Link
CFA	Crossed Field Amplifier
CFAR	Constant False Alarm Rate
CFLOPS	Complex Floating Point Operations Per Second
CMOS	Complementary Metal Oxide Semiconductor
CNR	Clutter-to-Noise Ratio
COHO	Coherent Oscillator
COTS	Commercial Off-the-Shelf
CPI	Coherent Processing Interval
CRLB	Cramèr-Rao Lower Bound
CRT	Chinese Remainder Theorem
CS	Censored
CUT	Cell Under Test
CW	Continuous Wave
DAC	Digital-to-Analog Converter
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
dbc	Decibels relative to the Carrier
DBS	Doppler Beam Sharpening
DC	Direct Current
DCT	Discrete Cosine Transform
DDS	Direct Digital Synthesis, Direct Digital Synthesizer
DFT	Discrete Fourier Transform
DOA	Direction of Arrival
DOF	Degrees of Freedom
DPCA	Displaced Phase Center Antenna
DRO	Dielectric Resonant Oscillator
DSP	Digital Signal Processing
DSX	Direct Synthesizer
DTFT	Discrete Time Fourier Transform
EA	Electronic Attack
ECM	Electronic Countermeasures
EIO	Extended Interaction (Klystron) Oscillator
EKF	Extended Kalman Filter
EM	Electromagnetic
EMI	Electromagnetic Interference
ENOB	Effective Number of Bits
EP	Electronic Protection
ES	Electronic Support
ESA	Electronically Scanned Array
EW	Electronic Warfare
f/D	Focal length to Diameter ratio
FAR	False Alarm Rate
FCR	Fire Control Radar
FDS	Fractional Doppler Shift
FET	Field Effect Transistor
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FLOPs	Floating Point Operations
FLOPS	Floating Point Operations Per Second
FM	Frequency Modulation
FMCW	Frequency-Modulated Continuous Wave

Acronym	Definition
FOPEN	Foliage Penetration
FOV	Field Of View
FPGA	Field Programmable Gate Array
ft	Foot, feet
FWHM	Full Width at Half Maximum
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gbps	Giga bits per second
gcd	Greatest Common Divisor
GCMLD	Generalized Censored Mean Level Detector
GFLOPS	GigaFLOPS
GHz	Gigahertz
GMTI	Ground Moving Target Indication
GOCA-CFAR	Greatest-Of Cell Averaging Constant False Alarm Rate
GOPS	GigaOperations Per Second
GPEN	Ground Penetration
GPR	Ground Penetrating Radar
GPU	Graphical Processing Unit
GTRI	Georgia Tech Research Institute
HCE	Heterogeneous Clutter Estimation
HPC	High Performance Computing
HPD	High Power Density
HPEC	High Performance Embedded Computing
HRR	High Range Resolution
Hz	Hertz (cycles per second)
I	In-phase channel or signal
IC	Integrated Circuit
ICBM	Intercontinental Ballistic Missiile
ID	Identification
IEEE	Institute of Electrical and Electronic Engineers
IID	Independent and Identically Distributed
IF	Intermediate Frequency
IFF	Identification Friend or Foe
IFM	Instantaneous Frequency Measurement
IFSAR	Interferometric Synthetic Aperture Radar
IIR	Infinite Impulse Response
IMPATT	Impact Ionization Avalanche Transit Time
InP	Indium Pholsphide
IPP	InterPulse Period
I/Q	In-phase/Quadrature
ISAR	Inverse Synthetic Aperture Radar
ISR	Integrated Sidelobe Ratio
kHz	Kilohertz
kVA	KiloVolt-Ampere
kW	KiloWatt
lcm	Least common multiple
LE	Leading Edge
LEO	Low Earth Orbit
LFM	Linear Frequency Modulation
LHC	Left-Hand Circular
LNA	Low-Noise Amplifier
LO	Local Oscillator
LOS	Line of Sight
LPD	Low Power Density
LRT	Likelihood Ratio Test
LSB	Least Significant Bit, Lower Sideband
LSI	Linear Shift-Invariant
LUT	Look-Up Table
LVDS	Low Voltage Differential Signaling
m	Meter
Mbps	Megabits per second
MB/s	MegaBytes per Second
MCM	Multichip Module
MCRLB	Modified Cramèr-Rao Lower Bound
MDD	Minimum Detectable Doppler
MDS	Minimum Detectable Signal
MDV	Minimum Detectable Velocity
MEM	Micro-Electromechanical
MESFET	Metal Semiconductor Field Effect Transistor
MFA	Multiple-Frame Assignment
MHT	Multiple-Hypothesis Tracking
MHz	Megahertz
MIPS	Millions of Instructions per Second
MIT	Massachusetts Institute of Technology
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
MLC	Mainlobe Clutter
MLS	Maximum Length Sequence
MMIC	Monolithic Microwave Integrated Circuit
MMSE	Minimum Mean Square Error
MMW	Millimeter Wave
MoM	Method of Moments
MOPA	Master Oscillator Power Amplifier
MOTR	Multiple-Object Tracking Radar
MPI	Message Passing Interface
MPM	Microwave Power Module
MPS	Minimum Peak Sidelobe
MTD	Moving Target Detector
MTI	Moving Target Indication
MTT	Multi-Target Tracking
mW	Milliwatt
MW	Megawatt
NCA	Nearly Constant Acceleration
NCCS2	Non-Central Chi-Square of degree 2
NCV	Nearly Constant Velocity
NEES	Normalized Estimation Error Squared
NLFM	Nonlinear Frequency Modulation
NP	Neyman-Pearson
NRA	No Return Area
NRE	Non-Recurring Engineering
NRL	Naval Research Laboratory
NRE	Non-Recurring Engineering
OLA	Overlap-Add
OS	Ordered Statistic
OTH	Over the Horizon

Acronym	Definition
PA	Power Amplifier, Power-Aperture
PAG	Power-Aperture-Gain
PC	Personal Computer
PDF	Probability Density Function
PDR	Phase-Derived Range
PDRO	Phase-Locked Dielectric resonant Oscillator
PEC	Perfect Electric Conductor
PFA	Polar Formatting Algorithm
PFN	Pulse-Forming Network
PLL	Phase-Locked Loop
PLO	Phase-Locked Oscillator
PPI	Plan Position Indicator
ppm	Parts per million
PPP	Pulse Pair Processing
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PSD	Power Spectral Density
PSM	Polarization Scattering Matrix
PSR	Point Spread Response
Q	Quadrature phase channel or signal, Quality factor
QPE	Quadratic Phase Error
QRD	Q-R Decomposition
RAM	Radar Absorbing Material
RASS	Radio-Acoustic Sounding System
RBGM	Real Beam Ground Mapping
RCS	Radar Cross Section
REX	Receiver/Exciter
RF	Radiofrequency, Radar Frequency
RFLOPS	Real Floating Point Operations Per Second
RHC	Right Hand Circular
RMA	Range Migration Algorithm
rms	Root Mean Square
RPM	Revolutions per Minute
ROC	Receiver Operating Curve, Receiver Operating Characteristic
RRE	Radar Range Equation
rss	Root Sum of Squares
RTL	Register Transfer Level
rv	Random Variable
RX	Receive, Receiver
s	Second
SAR	Synthetic Aperture Radar
SAW	Surface Acoustic Wave
SBC	Single Board Computer
SBO	Shoe-Box Oscillator
SCR	Silicon-Controlled Rectifier
SFDR	Spurious-Free Dynamic Range
SiC	Silicon Carbide
SiGe	Silicon-Germanium
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal-to-Interference Ratio
SIR-C	Shuttle Imaging Radar-C
SLAR	Side-Looking Airborne Radar
SLC	Sidelobe Clutter
SM	Standard Missile
SMT	Surface Mount Technology
SM2	Standard Missile 2
SNR	Signal-to-Noise Ratio
SOCA-CFAR	Smallest-Of Cell-Averaging Constant False Alarm Rate
SPEC	Standard Performance Evaluation Corporation
SPST	Single-Pole, Single-Throw
SQNR	Signal-to-Quantization Noise Ratio
sr	Steradian
SSB	Single Sideband
STALO	Stable Local Oscillator
STAP	Space-Time Adaptive Processing
STC	Sensitivity Time Control
SVD	Singular Value Decomposition
TB	Time-Bandwidth product
TDRSS	Tracking and Data Relay Satellite System
TDU	Time Delay Unit
TE	Trailing Edge
TFLOPS	TeraFLOPS
THAAD	Theater High Altitude Air Defense
TI	Texas Instruments
TMR	Target Motion Resolution
TOPS	TeraOps Per Second
T/R	Transmit/Receive
TRF	Tuned Radio Frequency
TSS	Tangential Signal Sensitivity
TRF	Tuned Radio Frequency
TWS	Track While Scan
TWT	Traveling Wave Tube
TX	Transmit
UAV	Unmanned Aerial Vehicle
UDSF	Usable Doppler Space Fraction
UHF	Ultra-High Frequency
UMOP	Unintentional Modulation of Pulse
U.S.	United States
USB	Upper Sideband
V	Volt
VHDL	VHSIC Hardware Description Language
VHF	Very High Frequency
VME	VersaModule Europe
VSIPL	Vector, Signal, Image Processing Library
VSWR	Voltage Standing Wave Ratio
VXS	VersaModule Europe Switched Serial
W	Watt

List of Common Symbols

The following symbol definitions are used in multiple chapters throughout this text. Each individual chapter introduces additional notation specific to that chapter. Some symbols; *e.g. R*; have more than one usage; their meaning is generally clear from the context

Symbol	Definition
α	Attenuation coefficient
χ_1	Single-sample Signal-to-Noise Ratio
χ_N	N-sample Signal-to-Noise Ratio
δ	Grazing angle; Discrete impulse function
δ_D	Dirac (continuous-time) impulse function
Δ	Difference channel; Quantization Step Size
ΔCR	Cross-range resolution
Δf_d	Doppler spectrum width
ΔR	Range resolution
ε_r	Relative permittivity
Γ	Fresnel reflection coefficient
η	Clutter volume reflectivity; Extinction efficiency
η_a	Aperture efficiency
λ	Wavelength
Λ	Likelihood ratio
μ	Permeability
ϕ	Elevation angle (from horizontal plane); General angle or phase
ϕ_3	Elevation 3-dB one-way beamwidth
ϕ_R	Elevation Rayleigh (peak-to-null) beamwidth
ϕ_{xx}	Autocorrelation function
θ	Azimuth angle; General angle or phase
θ_3	Azimuth 3 dB one-way beamwidth
θ_B	Brewster's angle
θ_C	Critical angle
θ_{cone}	Cone angle
θ_R	Azimuth Rayleigh (peak-to-null) beamwidth
θ_{scan}	Scan angle
σ	Radar cross section
σ^0	Clutter area reflectivity
σ_n^2	Noise variance
σ_x^2	Variance of random variable or process x
$\sum$	Sum channel
τ	Pulse width (duration)
$\hat{\omega}$	Normalized frequency in radians per sample
ω	Frequency in radians per second
ω_d	Doppler frequency in radians per second
Ω	Solid angle in steradians; Impedance in ohms
A_e	Effective aperture
b	Number of Bits
B	Bandwidth in hertz

Symbol	Definition
B_d	Doppler bandwidth in hertz
c	Speed of electromagnetic wave propagation
D	Antenna size; Divergence factor
D_{SAR}	Synthetic aperture size
$E\{\cdot\}$	Expected value operator
E	Energy
E_x	Energy in signal x
$\hat{f}$	Normalized frequency in cycles per sample
f	Frequency in hertz; focal length
f_d	Doppler Shift
f_s	Sampling frequency in samples per second
F	Noise factor; Noise figure; Propagation factor
FAR	False alarm rate
G	Antenna gain
G_t	Transmit antenna gain
G_r	Receive antenna gain
$(\cdot)^H$	(superscript H) Hermitian (conjugate) transpose
$h(t)$ or $h[n]$	Filter impulse response (continuous or discrete)
$H(\cdot)$	Filter frequency response
H_0	Null (target absent) hypothesis
H_1	Target present hypothesis
I	In-phase channel or signal
$\mathbf{I}$	Identity matrix
I_0	Modified Bessel function of the first kind
ISR	Integrated sidelobe ratio
$J(\cdot)$	Cramèr-Rao Lower bound
k	Boltzmann's constant
$\hat{k}_s$	Normalized total wavenumber (spatial frequency) in radians per sample
K	Discrete Fourier transform (DFT) Size
k	Total wavenumber (spatial frequency) in radians per meter
$k_x; k_y; k_z$	x; y; and z components of wavenumber (spatial frequency) in radians per meter
L	General loss; Number of range bins; Number of fast-time samples
L_a	Atmospheric loss
L_s	System loss
M	Number of pulses; Number of slow-time samples

Symbol	Definition
n	Index of refraction
N	Number of samples; Vector length
$\mathrm{N}(u; v)$	Normal (Gaussian) distribution with mean u and variance v
N_0	Noise power spectral density
$O(\cdot)$	"On the Order of"
$p_x(x)$	Probability density function of x
p_{avg}	Average power
P_D	Probability of detection
P_{FA}	Probability of false alarm
P_r	Received power
PRF	Pulse repetition frequency
PRI	Pulse repetition interval
PSR	Peak sidelobe to peak mainlobe ratio
P_t	Transmitted power
Q	Quadrature channel or signal; Power density
Q_M	Marcum's Q function
R	Range; Rain rate
$\mathbf{R_I}$	Interference covariance matrix
R_{ua}	Unambiguous range
S_{xx}	Power spectrum of random process x
SIR	Signal-to-interference ratio
$SINR$	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
$SQNR$	Signal-to-quantization noise ratio
t	Time
$(\cdot)^T$	(superscript T) Matrix or vector transpose
T	Threshold value; Pulse Repetition Interval (Interpulse Period)
T_0	Standard temperature; Period of radiofrequency (RF) sinusoid
T_{ad}	Antenna dwell time
T_d	Dwell time
T_s	Sampling interval; System noise temperature
v	Velocity
v_r	Radial velocity
$\mathrm{var}(x)$	Variance of a random variable or process x
$\boldsymbol{X}$	General vector variable
$\mathbf{X}$	General matrix variable
$\overline{x}$	Mean of a random variable or process x
$x_\mathrm{I}(t); x_\mathrm{I}[t]$	In-phase signal (continuous or discrete)
$x_\mathrm{Q}(t); x_\mathrm{Q}[t]$	Quadrature phase signal (continuous or discrete)

CHAPTER

5

Characteristics of Clutter

Nicholas C. Currie

Chapter Outline

5.1 INTRODUCTION AND DEFINITIONS

5.1.1 What Is Clutter?

Radar clutter is a radar return from an object or objects that is of no interest to the radar mission. For example, the mission of many radar systems is the detection and tracking of "targets" such as aircraft, ships, or ground vehicles. To these systems, clutter is considered to be an interfering return from a natural object such as precipitation, vegetation, soil and rocks, or the sea. However, to radars designed for remote sensing such as synthetic aperture radar (SAR) imagers, these objects may be the primary targets of interest. For this chapter, it will be assumed that targets of interest are man-made while natural target returns are unwanted (i.e., clutter).

5.1.2 Comparison of Clutter and Noise

Chapter 3 introduced detection in the presence of random noise, including noise properties and the effect on detection of targets. The returns from natural clutter can be strikingly similar to the effects of noise on detection yet also be quite different. So, how do clutter returns differ from noise effects? Figure 5-1 shows a high (fine) resolution (1 ft $\times$ 1 ft), two-dimensional (2-D) SAR image of a suburban terrain scene near Stockbridge, New York, collected from an airborne platform [1]. As can be seen from the figure, some areas appear uniform in nature (e.g., grassy lawns), while others appear quite nonuniform (e.g., trees and man-made structures). The high-resolution image shown in Figure 5-1 produces significantly different clutter properties from a lower-resolution radar, which averages out much of the structure shown in the figure. As an introductory text, this chapter will discuss the characteristics of lower-resolution (real-beam) systems.

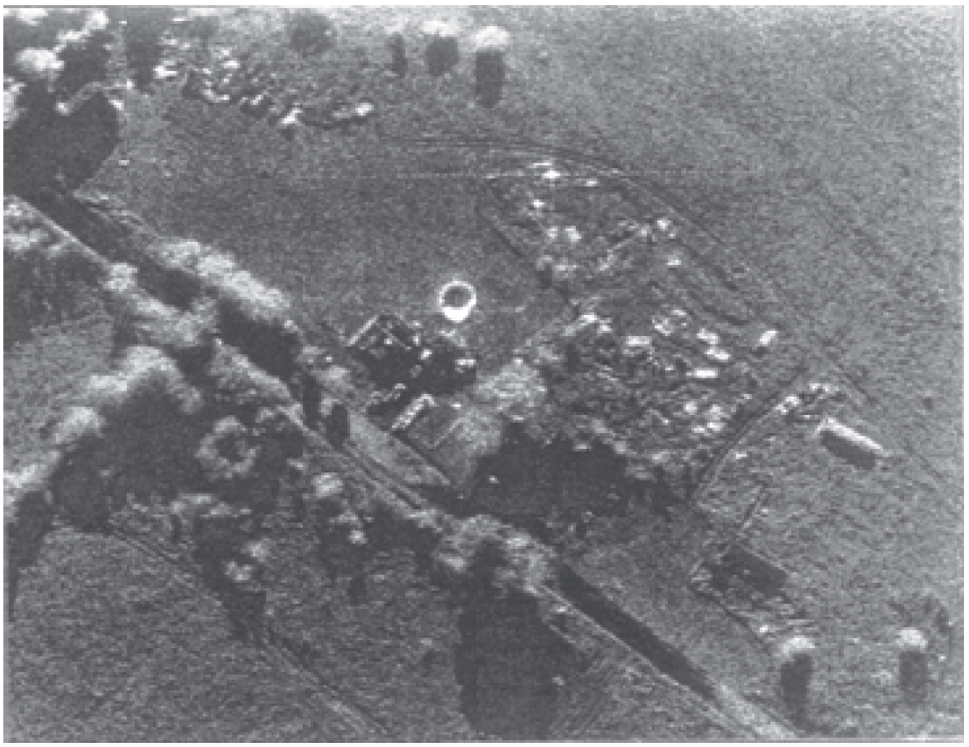

FIGURE 5-1 ■ Synthetic aperture radar image of suburban terrain. (From Novak and Owirka [1]. With permission.)

Table 5-1 summarizes the primary differences between clutter returns and receiver noise. Random noise, although varying with time, exhibits a specific set of characteristics:

- The probability density function (PDF) is Rayleigh for a linearly detected (voltage) signal, or exponential[1] for a square law detected (power) signal (see Chapter 3 for a description of the Rayleigh and exponential PDFs).
- The width of the autocorrelation function (ACF) is approximately the inverse of the receiver bandwidth.
- The power spectral density (PSD) function (power spectrum) width is approximately equal to the receiver bandwidth.

Clutter statistics can be similar to those of noise when the natural targets are composed of small, nearly equal-sized scatterers but can be quite different when the nature of the scatterers change or scatterers of differing types (e.g., a tree line) are present in the radar field of view. For this case, amplitude distributions having much longer "tails" than the Rayleigh distribution have been observed. Finally, although noise is independent of transmitted frequency, spatial position, and environmental parameters, clutter varies with all of these parameters, making clutter characterization very complex.

[1]The exponential PDF is sometimes called a *Rayleigh power* PDF. Confusingly, this is sometimes shortened to just Rayleigh PDF, even though the mathematical form intended is the exponential PDF. The Rayleigh PDF describes the amplitude (magnitude) of the noise signal; the magnitude squared (power) is described by an exponential PDF.

TABLE 5-1 ■ Clutter Signals versus Noise

Noise Signal	Clutter Signal
Amplitude independent of radar return signal level	Amplitude proportional to radar return signal level
Wide bandwidth (limited by receiver noise bandwidth)	Narrow bandwidth (created by scatterer motion)
Statistically independent between pulses	May be highly correlated between pulses
Amplitude variation described by Rayleigh statistics	Amplitude variation may vary from none to extremely wide (log normal or Weibull statistics)
Average value is constant and independent of spatial position	Time average will differ between spatial samples as the clutter types change
Independent of transmitted frequency	Varies with changing frequency
Independent of environmental parameters	Can vary with changing environmental conditions
No spatial component	Varies with beam position and resolution

Source: Adapted from Long [2]. (© 2006 IEEE. Used with permission.)

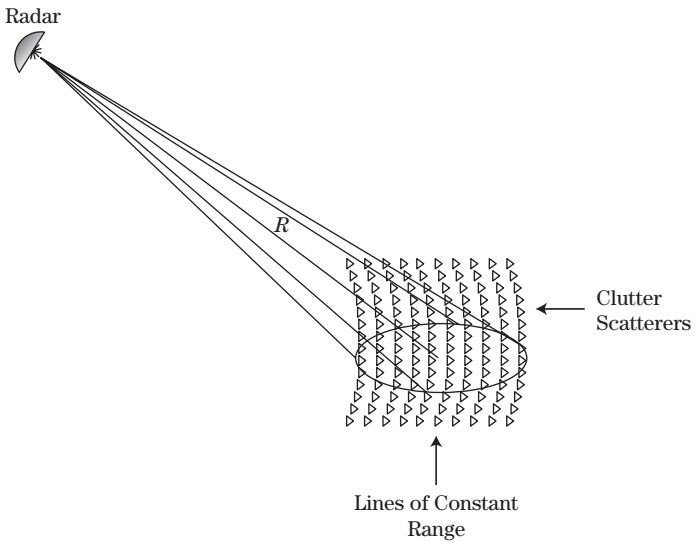

FIGURE 5-2 ■ Radar scan over clutter scatterers illustrating lines of constant range.

Figure 5-2 shows a typical situation where the radar beam illuminates a number of scatterers, each having a different reflectivity, σ_i, and distance, d_i, from the radar. Lines of constant range to the radar form ellipses on a level surface. The electric field amplitude (horizontal or vertical polarization component) measured at the radar due to the echo from the i-th scatterer will be proportional to the square root of the received power given by the radar range equation

$$|\boldsymbol{E}_i| = \left[\frac{P_t G^2 \lambda^2 \sigma_i}{(4\pi)^3 L_s d_i^4}\right]^{1/2} = k\frac{\sqrt{\sigma_i}}{d_i^2} \tag{5.1}$$

where P_t is the transmitted power, G is the antenna gain, λ is the wavelength, and L_s is the system loss (including hardware and atmospheric losses) as discussed in Chapter 2. The constant, k, absorbs all the factors that are the same for each scatterer. The phase of

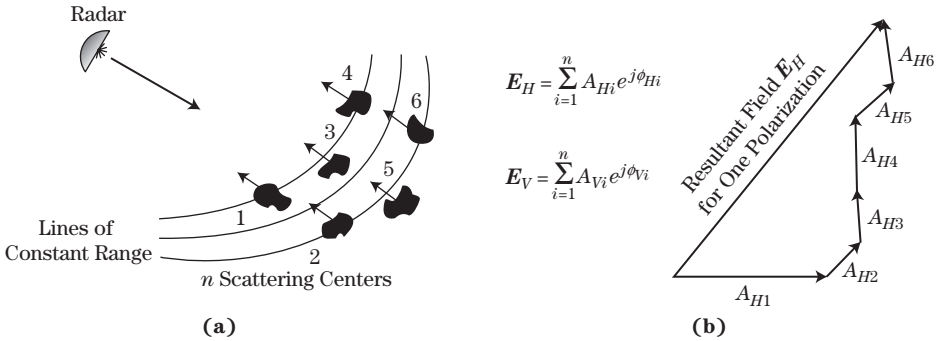

FIGURE 5-3 ■ Vector summation of scatterers at different positions and ranges. (a) Geometry of multiple scatterers. (b) Vector summation forms resultant E-field amplitude.

the received electric field, relative to the phase of the transmitted wave, is determined by the scatterer reflection phase, θ_i, and the two-way propagation distance:

$$\arg\{\boldsymbol{E}_i\} = \theta_i - \frac{4\pi}{\lambda} d_i = \theta_i + \phi_i \tag{5.2}$$

Scatterers located at the same range will generate echoes that return with the same time delay and phase at the radar, assuming that each scatterer has the same reflection phase (i.e., $\theta_i = \theta$) for some constant, θ. However, scatterers with slightly different ranges but falling within the same beam or range bin interval will have different echo phases. As shown in Figure 5-3a, the total return $\boldsymbol{E}$-field amplitude at the radar is therefore proportional to the vector summation of the electric field amplitude and phase of each group of scatterers contributing to a single radar measurement. This resultant $\boldsymbol{E}$-field is given by

$$\begin{aligned} \boldsymbol{E} &= \sum_i \boldsymbol{E}_i = \sum_i k \frac{\sqrt{\sigma_i}}{d_i^2} \exp\left[j \left(\frac{4\pi}{\lambda} d_i + \theta \right) \right] \\ &\approx \frac{k}{d^2} \sum_i \sqrt{\sigma_i} \exp\left[j \left(\frac{4\pi}{\lambda} d_i + \theta \right) \right] \\ &\equiv \frac{k'}{d^2} \sqrt{\sigma} \exp[j\phi] \end{aligned} \tag{5.3}$$

where σ is the equivalent radar cross section (RCS) of the total clutter return, and ϕ is the equivalent phase. This process is illustrated in Figure 5-3b. The complex quantity $\sqrt{\sigma} \exp[j\phi]$ is called the *backscatter coefficient* of the clutter.

As the radar beam scans across the scatterers in the scene, the range to the particular scatterers in the beam changes so that the resulting equivalent RCS changes. This variation in return has come to be known as "speckle": the "noise-like" returns resulting from the random summation of individual scatterer echoes. The reduction of this characteristic, "despeckling," is very important in SAR processing. As the beam scans farther, new scatterers enter the beam, while other scatterers leave the beam. For a mechanically scanned system, the changes are smooth, while for an electronic scan system the changes occur abruptly as the beam is step-scanned. As long as the scatterers illuminated at any given time are similar in amplitude and phase, the return will exhibit noise-like statistics with constant parameters. However, if the beam scans across a set of scatterers that are physically different the character of the return can change. An example is scanning from a grassy field to a line of trees, which would likely result in an increase in the echo strength and thus the equivalent RCS. Also, the presence of one or two large scatterers among the smaller scatterers can cause the return to exhibit very nonnoise-like statistics.

Since the returns from clutter vary by type, polarization, environmental, and geometric conditions, it is very difficult to model clutter mathematically. Attempts to do so are briefly discussed in Section 5.3. More practically, many experiments have been conducted to measure clutter returns as functions of the various dependent parameters. Practical clutter modeling usually involves a combination of empirical and theoretical results.

5.1.3 Basic Definitions

5.1.3.1 Scattering Coefficients

To use published data on clutter, methods must be defined to normalize the returns so that data can be applied to many different radars and applications. One form of the radar equation can be written as

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 L_s R^4} \tag{5.4}$$

where the variables are the same as in equation (5.1). This form of the radar equation is suitable for point targets (i.e., targets much smaller than the resolution of the radar) but is not convenient for distributed targets such as clutter, where many scatterers contribute at once to the total echo. Thus, equation (5.4) must be modified to account for the area or volume defined by the beamwidths and range resolution of the radar.

For surface clutter it is convenient to define the radar cross section per unit area, or *surface reflectivity*,

$$\sigma^0 \equiv \frac{\sigma}{A} \tag{5.5}$$

where σ is the total RCS of the contributing clutter, and A is the area of the contributing clutter defined by the radar beam intersection with the surface. The units of σ^0 are meters^2/meters^{2}so that σ^0 is unitless. It is often expressed in the literature in decibels, denoted dBsm.

For volume clutter, the radar cross section per unit volume, or *volume reflectivity,* is defined as

$$\eta = \frac{\sigma}{V} \tag{5.6}$$

where V is the volume defined by the radar beam and range resolution cell. The units of η are meters^2/meters^3, or meter^{-1}. It is expressed in the literature in decibels per meter.

Given σ^0, the area A to be used in computing clutter RCS using equation (5.5) for surface clutter is determined by the beamwidths and the range resolution of the radar. Two situations arise: (1) the case where the range resolution is large compared with the projection of the vertical beam width onto the surface; and (2) the case where the range resolution is smaller than the projection extent. Both were considered in Section 2.13. In the *beam-limited* case, the result for the beam area on the ground was

$$A = \pi R^2 \tan\left(\frac{\theta_3}{2}\right) \tan\left(\frac{\phi_3}{2}\right) \csc\delta \tag{5.7}$$

where ϕ_3 and θ_3 are the azimuth and elevation beamwidths of the antenna, respectively, and δ is the *grazing angle* of the antenna boresight with the clutter surface. For beamwidths less than about 10 degrees the small angle approximation $\tan(x) \approx x$ is valid, and

equation (5.7) becomes

$$A = \frac{\pi R^2}{4}\theta_3\phi_3 \csc\delta \tag{5.8}$$

Note that since the clutter area grows as R^2 due to beam spreading, so will the clutter RCS, σ. When used in equation (5.4), the resulting received power due to a constant clutter reflectivity will be proportional to R^{-2} instead of the R^{-4} proportionality seen for point targets. Thus, beam-limited surface clutter power does not decline with range as rapidly as does point target power.

In the *pulse-limited* case, the area defined by the beam and pulse width on the ground is given by

$$A = \left(\frac{c\tau}{2}\right) 2R \tan\left(\frac{\theta_3}{2}\right) \csc\delta = c\tau R \tan\left(\frac{\theta_3}{2}\right) \csc\delta \tag{5.9}$$

and, again, if the beam width is less than 10°, a small angle approximation gives

$$A = \left(\frac{c\tau R\theta_3}{2}\right) \csc\delta \tag{5.10}$$

Note that in this case the clutter area is proportional to R instead of R^2. Consequently, the pulse-limited echo power from constant-reflectivity surface clutter declines as R^{-3}. If the radar uses pulse compression techniques (see Chapter 20) to obtain fine-range resolution, then the radar range resolution in meters should replace the factor $c\tau/2$ in equations (5.9) and (5.10).

The grazing angle at which the clutter cell area transitions from the beam-limited case to the pulse-limited case can be found by setting the pulse- and beam-limited areas equal to one another and is given by

$$\tan\delta = \frac{2R\tan(\phi_3/2)}{c\tau/2} \tag{5.11}$$

or, for small antenna beamwidths,

$$\tan\delta = \frac{2R\phi_3}{c\tau} \tag{5.12}$$

When the value of $\tan\delta$ exceeds the value in equations (5.11) or (5.12), the beam-limited case applies. Conversely, when $\tan\delta$ is less than that value, the pulse-limited case applies.

Note that the beamwidths used in the previous equations are assumed to be the 3 dB two-way beamwidths. Actual radar beams are not rectangular, so some errors can occur in beam area and clutter power estimation based on the actual beam shape and sidelobes. These errors can be significant for airborne pulse-Doppler processors.

The previous discussion can be applied to area clutter (e.g., ground, sea). For computing the equivalent RCS of atmospheric clutter using equation (5.6), the reflectivity, η, and the resolution cell volume, V, defined by the radar beam and the pulse width are needed. The formula for V was given in Chapter 2. Since air search radars are almost always narrow beam, the small angle approximation formula is usually adequate. This is given by

$$V = \pi\left(\frac{R\theta_3}{2}\right)\left(\frac{R\phi_3}{2}\right)\left(\frac{c\tau}{2}\right) = \left(\frac{\pi R^2\theta_3\phi_3}{4}\right)\left(\frac{c\tau}{2}\right) \tag{5.13}$$

Again, the actual range resolution should be used in place of the $(c\tau/2)$ term in pulse compression radars.

5.1.3.2 Clutter Polarization Scattering Matrix

The scattering properties of clutter are dependent on the transmitted and received polarization. This effect is quantified by the use of a 2-by-2 matrix known as the *polarization scattering matrix* (PSM), **S** [3]. Equation (5.14) gives a form of the matrix expressed in terms of vertical and horizontal polarization:

$$\mathbf{S} = \begin{bmatrix} \sqrt{\sigma_{HH}}\, e^{j\phi_{HH}} & \sqrt{\sigma_{HV}}\, e^{j\phi_{HV}} \\ \sqrt{\sigma_{VH}}\, e^{j\phi_{VH}} & \sqrt{\sigma_{VV}}\, e^{j\phi_{VV}} \end{bmatrix} \tag{5.14}$$

The first subscript represents the received polarization, while the second represents the transmitted polarization. For example, the lower left term in the matrix describes the vertically polarized received voltage signal component in response to a horizontally polarized transmitted signal. In fact, a matrix can be developed in terms of any two orthogonal polarizations, including circular and elliptical polarizations.

The terms in the complex matrix **S** represent the backscattering coefficients of the clutter for four polarization cases: (1) transmit and receive horizontal polarization; (2) transmit horizontal and receive vertical polarization; (3) transmit vertical and receive horizontal polarization; and (4) transmit and receive vertical polarization. For a specific frequency and geometry of the radar and a specific set of environmental parameters, the polarization scattering matrix contains all of the available information about the clutter return at the time of the measurement.

Unfortunately, a radar that can transmit and receive all four polarizations is both complex and expensive. Fortunately, for the case of a monostatic radar the *reciprocity theorem* [3] requires that the two "cross polarized" terms are equal, that is, $\sigma_{VH} = \sigma_{HV}$ and $\phi_{VH} = \phi_{HV}$. Thus, only three complex polarization values must be measured to determine the full scattering matrix.

Much work has been done to try to exploit the information inherent in the scattering matrix to identify targets in the presence of clutter. Holm [4] and others have attempted to use the scattering matrix to separate targets from clutter as well as to identify classes or types of targets on the theory that the PSMs of man-made targets and natural clutter will be significantly different. He determined that, to be effective, high-range and azimuthal resolution is required so that individual range-azimuth cells contain only target returns or only clutter returns. If cells contain a mixture of both target and clutter returns, the results are much less useful even if the clutter returns are much lower in amplitude than the targets.

In the past, attempts to use partial polarization matrix information to discriminate between targets and clutter have been tried with mixed results [3,5]. Such discriminants have included the following:

- Parallel/cross polarization ratio: $\sqrt{\sigma_{HH}}/\sqrt{\sigma_{VH}}$.
- Vertical/horizontal polarization ratio: $\sqrt{\sigma_{VV}}/\sqrt{\sigma_{HH}}$.
- Polarimetric phase: $\phi_{HH} - \phi_{VV} \equiv \phi_{H-V}$.

Polarimetric phase is usually expressed as quadrature components $\cos(\phi_{H-V})$ and $\sin(\phi_{H-V})$. These discriminants have the advantage of requiring only the polarimetric amplitude or phase instead of the entire PSM and can improve target detectability in clutter under some conditions.

5.2 GENERAL CHARACTERISTICS OF CLUTTER

5.2.1 Overview

Because clutter is one of the major limitations in target detection for practical radar, clutter measurements have been performed since the advent of radar use in World War II. The development of digital recording techniques has greatly improved the quality (and quantity) of data in the last 20 years. Because clutter exhibits noise-like fluctuations in echo strength, clutter is characterized in terms of statistical parameters describing the variability of σ^0 and η, including the following:

- Mean or median values.
- Standard deviations or variances.
- Probability density functions.
- Spectral bandwidths for temporal variability.
- Autocorrelation functions or power spectral density functions for temporal and spatial variations.

These measured values almost always include propagation factor effects (see Chapter 4). Usually, for clear air measurements of surface clutter at moderate to high angles the propagation factor effects are negligible. However, for measurements of atmospheric precipitation or for low grazing angles for surface clutter, attenuation due to multipath can be significant. These effects can be minimized by using calibration targets located near the clutter region being measured but can never be totally eliminated. For this reason, data from precipitation or surface clutter at large ranges tend to have more variability than measurements of surface clutter at steeper grazing angles. Since an operational radar will experience these same effects under the same conditions, this situation is not necessarily bad.

5.2.2 Surface Clutter

5.2.2.1 General Dependencies

Given that the radar-received clutter power in a particular application affects the detection performance and influences radar design, a simple and accurate way is needed to estimate clutter levels for a variety of scenarios. The goal is to develop models that include in a mathematical form all the known parameter dependencies of the backscattering coefficient that have been identified through experimental measurements. Fundamentally, clutter model development starts with theoretical calculations of reflectivity and comparison with the interpretation of experimental observations, which leads to an understanding of the underlying scattering mechanisms. Some of the observed dependencies are as follows:

- *Grazing angle*: Grazing angle, δ, is the angle at which the illumination energy strikes a clutter surface.
- *Vertical variation of the clutter scatterers*: Rough surfaces have a larger σ^0 than smooth ones for low grazing angles; at very high grazing angles (near 90°), smooth surfaces have a higher σ^0 than rough ones.
- *Wavelength*: σ^0 is a function of vertical texture expressed in wavelengths.

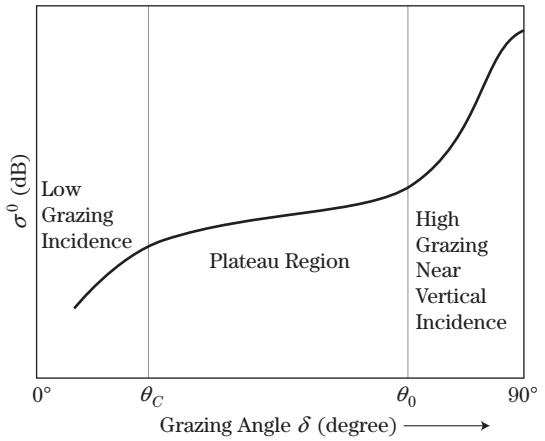

FIGURE 5-4 ■ General dependence of σ^0 on grazing angle. (Adapted from [6]. With permission.)

Depression angle is closely related to grazing angle. It is the angle below the radar's local horizontal at which the illumination energy is transmitted from the radar. For a flat horizontal clutter surface the depression and grazing angles are identical. Grazing angle is the most relevant for describing scattering, but clutter reflectivity data are often reported as a function of depression angle in the literature because the grazing angle may not be known precisely. In this chapter, the two are generally assumed to be the same unless otherwise stated, and the discussion is framed in terms of grazing angle. Depression angle is used when referring to previous published results given in terms of depression angle.

Rough surface theory and experimental measurements have determined that the backscattering for both land and sea surfaces—as a function of grazing angle—exhibit a common general dependence on grazing angle as shown in Figure 5-4. From this figure, three distinct regions of clutter behavior can be identified: (1) a low grazing angle region; (2) a plateau region; and (3) a high grazing angle region. The boundaries of these three regions, defined by θ_C and θ_0, change with frequency, surface condition, and polarization [6].

The *low grazing angle region* extends from zero to a *critical angle,* θ_C, determined by the root mean square (rms) height of surface irregularities in wavelengths. This critical angle is the grazing angle below which a surface seems "smooth" by Rayleigh's definition and above which it is "rough." Based on Rayleigh's definition, a surface is smooth if

$$\sigma_h \sin\delta < \frac{\lambda}{8} \tag{5.15}$$

where σ_h is the rms height of the surface irregularities, δ is the grazing angle, and λ is the radar wavelength. Thus, the critical angle is given by

$$\sin\delta_C = \frac{\lambda}{8\sigma_h} \tag{5.16}$$

In the *plateau region* the incident wave encounters the surface irregularities in such a way that the dependence of σ^0 on grazing angle is much less than at lower angles. Chapter 7 provides an introduction to the "rough surface" theory applicable to this regime.

For a constant σ^0 and beam-limited geometry, it is expected that the return power for surface clutter would vary as $R^{-4} \times R^2 = R^{-2}$ since the power from a point target varies as R^{-4} while the area of surface clutter increases as R^2. However, measurements have indicated that clutter power often varies as R^{-3}. For this to be the case, σ^0 must vary as

R^{-1}. The grazing angle satisfies the equation $\sin\delta = h/R$, where h is the radar altitude and R is the slant range. If the height of the radar is constant, then $\sin\delta$ is proportional to $1/R$. This fact led to the definition of the so-called *constant gamma model* for clutter reflectivity, given by

$$\sigma^0 = \gamma \sin\delta = \frac{\gamma}{R} \tag{5.17}$$

Here γ is a constant depending on terrain type, surface roughness (sea state and terrain type for sea and land, respectively), and frequency. If equation (5.17) applies, then clutter reflectivity will be proportional to R^{-1}, and the R^{-3} clutter power dependence would be expected. Note that the constant gamma model is applicable only in the plateau angular region.

In the *high grazing angle region* the scattering becomes more directional and rapidly increases to a maximum value based on the reflectivity and smoothness of the clutter, in a manner somewhat analogous to the behavior of the main lobe of a rough flat plate at near perpendicular incidence (see Chapter 6).

Figure 5-5 gives the RCS of a conducting sphere of diameter a normalized to its projected area as a function of the circumference normalized to the wavelength. As can be seen from the figure, the relative RCS increases with frequency, $1/\lambda$, until λ equals twice the circumference, whereupon the RCS varies rapidly until λ is about $1/5$ the circumference, at which point the RCS equals the projected cross sectional area of the sphere and is independent of frequency. Thus, for large wavelengths (low frequencies), the return from a sphere would be expected to increase with increasing frequency until the point known as the *resonance region*, where the RCS fluctuates rapidly with frequency. Cylinders exhibit similar frequency dependence relative to the ratio of circumference to wavelength. Since most clutter scatterers can be considered to be approximately either spherical or cylindrical in shape, clutter RCS should be expected to increase with decreasing wavelength up to a wavelength in the millimeter wave region for most scatterers. At high frequencies facets or ripples create resonance effects that overcome this effect. As will be seen in the data, this effect does exist, although variations among different types of clutter return can often be much greater than frequency effects.

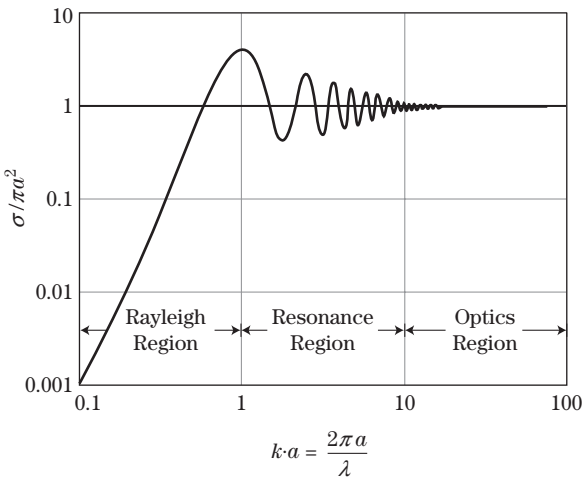

FIGURE 5-5 ■ Dependence of the RCS of a sphere on wavelength.

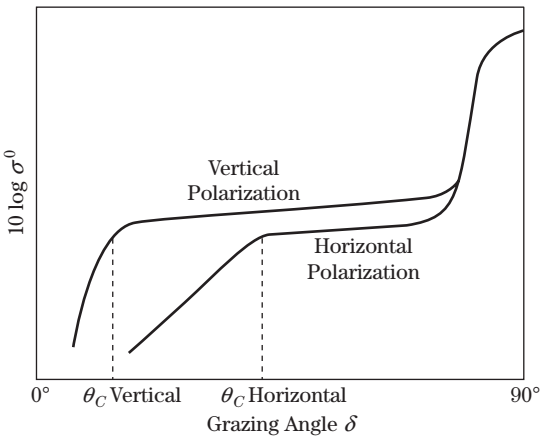

FIGURE 5-6 ■ Theoretical polarization dependence of a relatively smooth surface. (From Long [6]. With permission.)

Figure 5-6 gives the theoretical polarization dependence of σ^0 (generally verified by experiment) as a function of grazing angle for a moderately smooth surface, which tends to occur at lower frequencies. The critical angle, θ_C, occurs at different grazing angles for the two polarizations due to multipath effects so that at lower angles the difference between clutter reflectivity at vertical and horizontal polarizations can be quite large. However, for higher angles and frequencies, the horizontal polarization reflectivity is usually only a few dB lower than the vertical polarization reflectivity. Although these polarization trends on average are valid, for specific clutter patches the occasional presence of natural diplanes can result in widely varying polarization returns.

5.2.2.2 Temporal and Spatial Dependencies

Temporal and spatial variations occur due to either the motion of scatterers within the radar cell (usually due to wind) or the nature of scatterers changing as the radar cell moves in range or azimuth. Such statistical variation is described in terms of probability distributions with simple mathematical equations to facilitate modeling. Coherent receiver noise has a complex normal (Gaussian) amplitude distribution before detection and a Rayleigh distribution after detection, assuming a linear (voltage) detector, or an exponential distribution if a square law (power) detector is used. Clutter amplitudes can also appear Gaussian or Rayleigh distributed for the low-resolution case where there are a large number of scatterers within the radar cell. However, as the resolution improves, the radar cell may contain only a few clutter scatterers, resulting in a non-Gaussian or Rayleigh distribution. Also, shadowing at low grazing angles can result in hiding large scatterers some of the time. The resulting distributions are said to have long "tails" because the probability of observing large values of the clutter amplitude is greater than with Rayleigh statistics.

A commonly used family of distributions for describing clutter power is the Weibull, which is illustrated in Figure 5-7. One form of the equation for the general Weibull distribution is [6]

$$p_\sigma(\sigma) = \begin{cases} \dfrac{b\sigma^{b-1}}{\alpha} \exp\left(-\dfrac{\sigma^b}{\alpha}\right), & \sigma \geq 0 \\ 0, & \sigma < 0 \end{cases} \tag{5.18}$$

where $\alpha = \sigma_m^b / \ln 2$, and σ_m is the median of the distribution. The parameter $a = 1/b$ is called the *width* parameter; b itself is called the *shape parameter*. The parameter $\alpha^{1/b}$ is

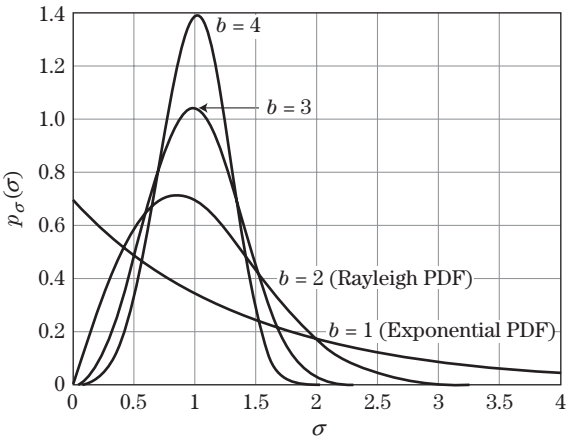

FIGURE 5-7 ■ Weibull distributions for $\sigma_m = 1$ and several values of b.

called the *scale* parameter. For a given σ_m or α, the higher the value of a and thus the lower the value of b and the longer the high value "tails" of the distribution. Figure 5-7 illustrates this for $\sigma_m = 1$. When $a = 1$ (and thus $b = 1$), the Weibull distribution reduces to the exponential PDF, while for $a = {}^1\!/_2$ ($b = 2$) it reduces to the Rayleigh PDF.

Because the Weibull is, in general, a two-parameter (b and σ_m) distribution, it can be adjusted to fit both the mean and variance of experimental data. Experimenters express the variation of clutter by choosing values of b and σ_m to best fit a Weibull distribution to their data.

Other experimenters prefer to use the log-normal distribution, another two-parameter function. The log-normal distribution is simply a distribution in which the logarithm of the return is normally distributed. It is given by [6]

$$p_\sigma(\sigma) = \frac{1}{\sigma s\sqrt{2\pi}} \exp\left(-\frac{(\ln\sigma - \bar{\sigma})^2}{2s^2}\right) \tag{5.19}$$

where $\bar{\sigma}$ is the mean RCS, and s^2 is the variance of σ.

This distribution is often used when modeling radars using a logarithmic receiver. The logarithmic receiver increases dynamic range by compressing large values of returns relative to smaller returns. An advantage of the log-normal distribution is that it models even higher "tails" than the Weibull, so it may provide a better fit to severe clutter data. Figure 5-8 gives several samples of the log-normal family, all with $\sigma_m = 1$ as in Figure 5-7.

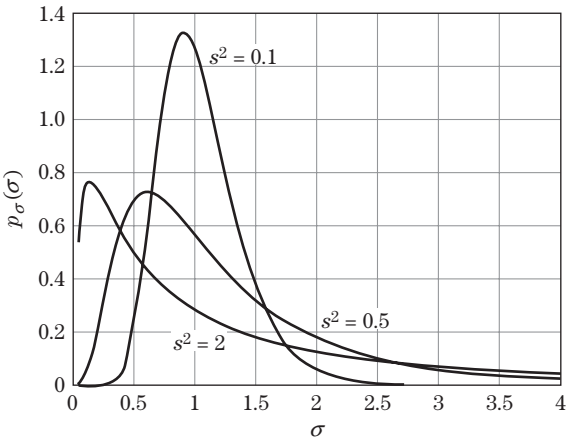

FIGURE 5-8 ■ Log-normal distributions for $\sigma_m = 1$ and several values of s^2.

When compared with Figure 5-7, it is obvious that log-normal-distributed data will exhibit a larger percentage of high values than Weibull-distributed data with the same median.

Some authors simply express the variation of clutter data in terms of the mean (or median) and the variance (or standard deviation, the square root of variance) without specifying an associated PDF. This approach is adequate for comparing the general strength and variability of different types of clutter for various conditions but does not provide enough information for analysis of radar detection performance.

5.2.2.3 Average Value Data

An extensive body of definitive experiments has been performed in the last 40 years to characterize radar clutter. Some of the key studies are as follows:

- Rain backscatter measurements from 10 to 100 GHz performed jointly by the U.S. Army Ballistic Research Laboratory (BRL) and the Georgia Tech Research Institute (GTRI) in the mid 1970s [7,8].
- Measurement of frozen precipitation by the U.S. Army Harry Diamond Laboratory millimeter waves in the late 1980s [9].
- University of Kansas measurements on terrain at high angles in the 1980s [10].
- Measurement of land clutter at low grazing angles by the Massachusetts Institute of Technology Lincoln Laboratories (MIT/LL) in the 1980s and 1990s [11].
- Naval Research Laboratory (NRL) four frequency sea clutter measurements at high grazing angles [12].
- Georgia Tech measurements of sea clutter at low grazing angles [13,14].
- The "SNOWMAN" MMW measurements performed jointly by the U.S. Army MICOM and GTRI on snow-covered ground [15].

Countless other measurement programs have been conducted in the United States and Europe. This section will attempt to summarize data from these and many other experimental programs, but the interested reader is urged to also review the references at the end of the chapter.

Land Reflectivity

Dependence on Grazing Angle Figure 5-9 shows the backscatter reflectivity of crops and short grass at X-band compiled from three data sources. The data are reported as a function

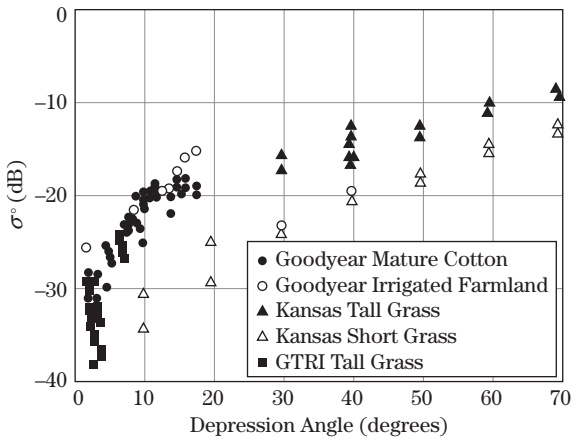

FIGURE 5-9 ■ σ^0 data for grass and crops from several sources at X-band. (Data from [16–18]. With permission.)

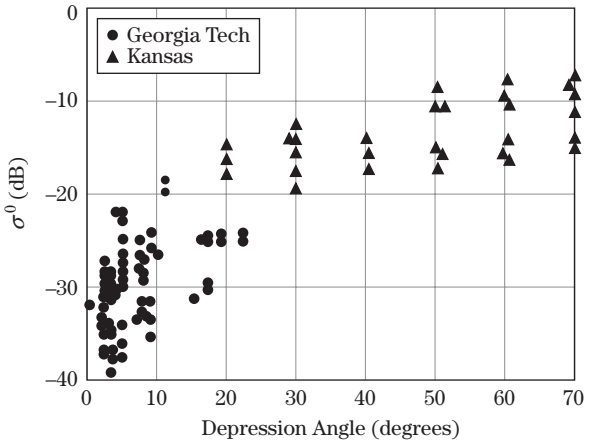

FIGURE 5-10 ■ σ^0 data for trees from two sources for X-band. (Data from [16,18]. With permission.)

of depression angle [16–18]. The data consist of time averages of individual spatial samples and exhibit the expected characteristic dependence on grazing angle shown in Figure 5-6, being relatively independent of angle above 10 degrees while rapidly decreasing in value at angles below 10 degrees. The greater spread in the data at very low depression angles is most likely due to shadowing effects.

Figure 5-10 presents backscatter reflectivity data from trees over the same angular regime as Figure 5-8. Again, the data represent time averages of spatial samples. A similar dependence is exhibited for the angular dependence as for grass and crops; however, the values for σ^0 are several dB higher, and the spatial variation is greater.

Dependence on Frequency Band Figures 5-11 through 5-14 present plots of averaged reflectivity data for five frequency bands compiled by Nathanson [15]. The data consist of σ^0 values at 0–1.5°, 3°, 10°, 30°, and 60°. Figure 5-11 gives data for relatively flat desert for L-band through X-band as a function of grazing angle. The spread in the data over the frequency range is approximately 10 dB, and the spread over 0 to 60° depression angle is more than 30 dB. Data from other sources including bare hills at L-band have yielded extremely high values for the reflectivity ($\sigma^0 > 0$ dB with corresponding RCS values of +40 dBsm) when viewing the sides of the hills at essentially 0° depression angle [16].

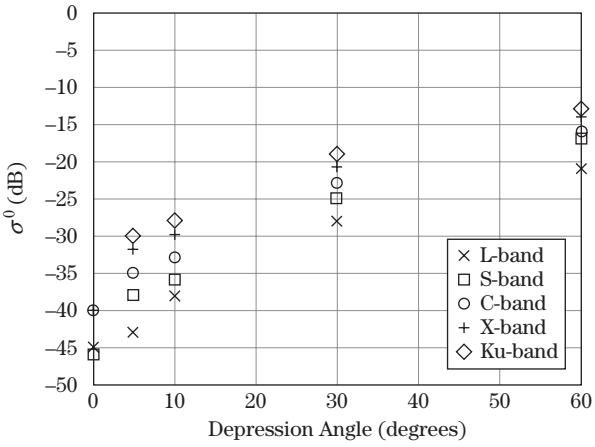

FIGURE 5-11 ■ Averaged reflectivity data for desert terrain as a function of frequency. (Adapted from Nathanson [15]. With permission.)

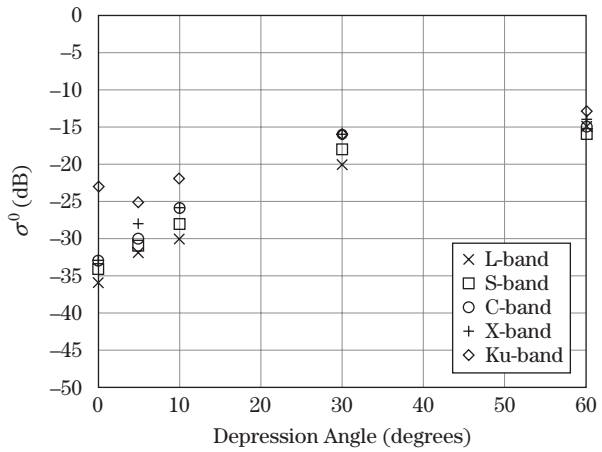

FIGURE 5-12 ■ Averaged reflectivity data for rural farmland as a function of frequency. (Adapted from Nathanson [15]. With permission.)

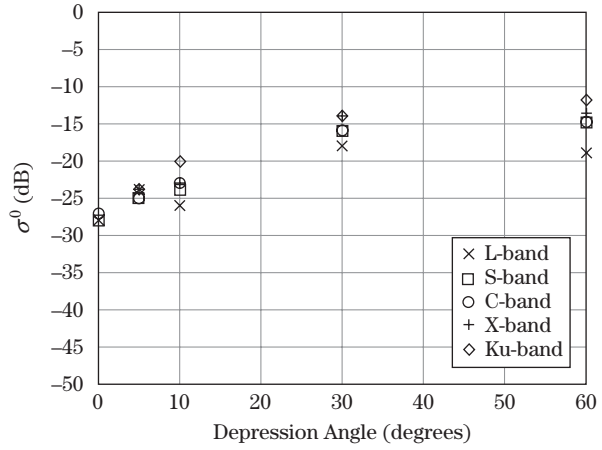

FIGURE 5-13 ■ Plot of averaged reflectivity data for heavy vegetation/jungle as a function of frequency. (Adapted from Nathanson [15]. Used with permission.)

Figure 5-12 shows averaged data for rural farmland. The spread in the data with frequency is lower than for the desert terrain, being approximately 6 dB. Also, the variation with depression angle is somewhat less, being approximately 25 dB. Figure 5-13 gives averaged data for heavy vegetation and jungle. The spread in the data with frequency is again approximately 6 dB with a similar angular variation as Figure 5-12.

Figure 5-14 gives averaged data for urban environments. The spread in the data with frequency band is lower than the previous plots, but the data are high in value as might be expected since presumably many man-made targets are included. Also, the dependence on depression angle is less than for the previous figures.

Very low angle clutter returns are of particular concern as such returns can significantly affect the detection of low flying objects such as missiles. The MIT Lincoln Laboratory performed extensive measurements in the 1980s to characterize low angle clutter over many terrain types [11]. Figure 5-15 gives σ^0 data collected by the MIT/LL for very low depression angles (0.4 to 1°) and for several frequency bands from UHF to X-band, including both vertical and horizontal polarizations. As can be seen from the figure, σ^0 appears to be at a maximum in the UHF band, decreasing at the higher frequencies, presumably due to absorption of the energy. Also, little difference is seen between

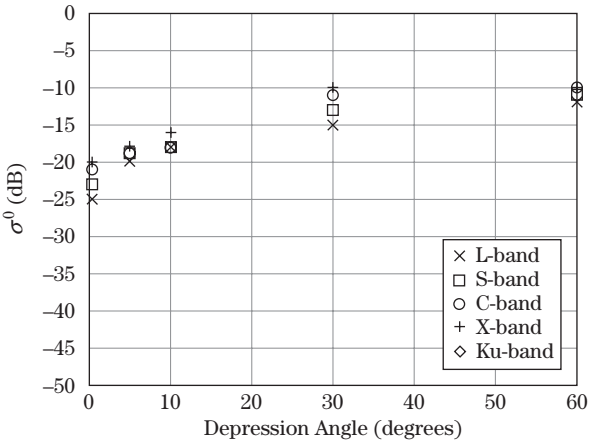

FIGURE 5-14 ■ Plot of averaged reflectivity data for urban terrains as a function of frequency. (Adapted from Nathanson [15]. With permission.)

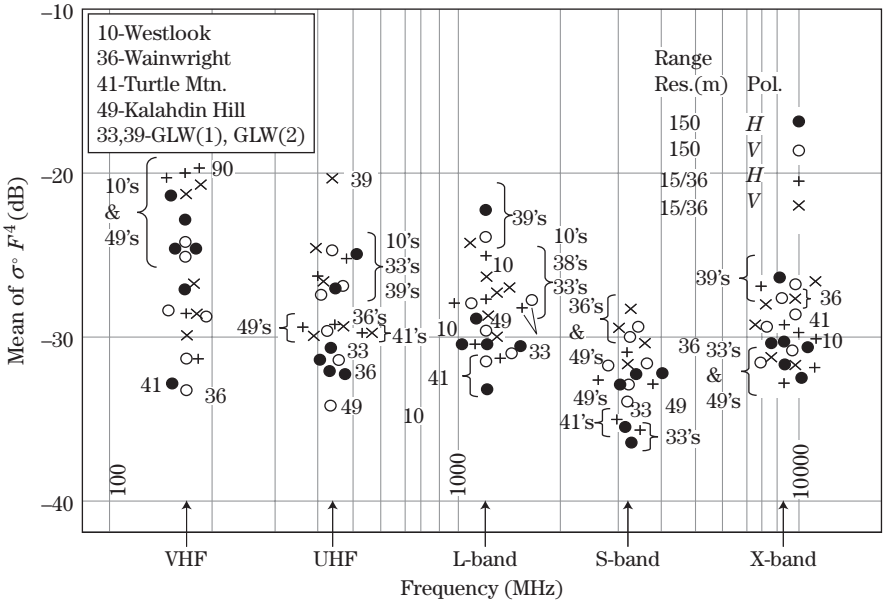

FIGURE 5-15 ■ σ^0 data for several forest/low-relief terrains at low (0.4–1°) depressions angles as a function of frequency. (From Billingsley [11]. With permission)

horizontal and vertical polarizations. Figure 5-16 gives data on mountain terrains for several frequency bands. As can be seen, the reflectivity decreases rapidly with increasing frequency, presumably caused by vegetation attenuating the returns from bare rock and ground at the higher frequencies. Note that σ^0 values of nearly 0 dB are reported at the lowest-frequency bands. Such values can often overwhelm radar MTI processors, leading to false alarms.

Sea Reflectivity The sea surface is composed of salty water with a reflection coefficient of almost −1 at microwave frequencies for small grazing angles. Thus, a smooth sea appears like an infinite flat conductive plate that scatters all of the energy impacting the surface in a forward direction so no backscatter occurs. As the wave height starts to increase, the sea begins to appear like a rough surface, and as the wave height continues to grow, organized

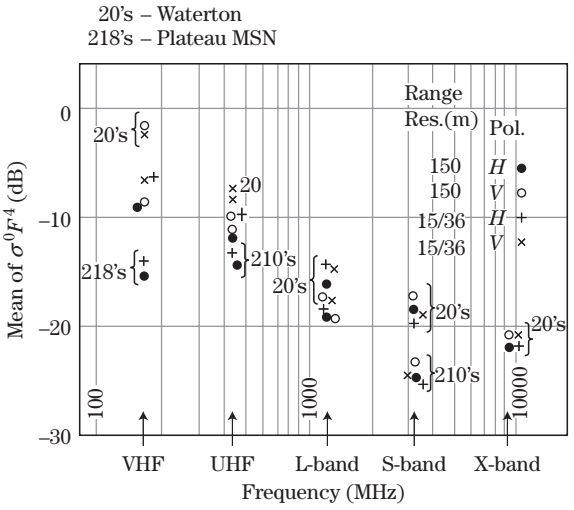

FIGURE 5-16 ■ σ^0 data for two mountain terrains at low (1.2°) depressions angles as a function of frequency. (From Billingsley [11]. With permission.)

TABLE 5-2 ■ Parameters Affecting Sea Return

PARAMETER	COMMENTS
Wave height	Strong proportional dependence
Wind speed	Dependence increases with increasing frequency
Wind/wave look direction	Significant difference between up-wave and down-wave
Polarization	Dependence decreases with increasing frequency
Grazing angle	Strong dependence at low angles, weaker dependence in the plateau region
Frequency band	Proportional to frequency in the microwave region

wavefronts occur that provide a strong directional dependence to the scattering. Table 5-2 gives the primary physical parameters that can affect sea return.

As can be seen from Table 5-2, wave height is one of the major physical parameters affecting sea return. Unfortunately, wave height is often difficult to measure during experiments. In addition, wave height is irregular. The wave height is considered to be the "significant wave height," which is an estimate of the average peak-to-trough height of the largest one-third of the observed waves.

Since it is easier to estimate a range of wave heights than a specific wave height, sea return data are often give in terms of *sea state*. The Douglas sea number [6] is a specific, widely used scale of sea states, correlated wind speeds, and subjective descriptions in which each defined sea state represents a range of wave heights as given in Table 5-3.[2] Note that sea states are defined only for a fully developed sea, that is, a sea over which a constant wind has been blowing long enough to build waves to their maximum height and the distance over which the wind has been blowing (called the *fetch*) is far enough to build waves to their maximum value.

[2]Other sea scales exist, such as the Beaufort scale and the World Meteorological Organization (WMO) scale. The WMO scale generally adopts the Douglas sea-scale definitions.

TABLE 5-3 ■ Douglas Sea State versus Wave Height and Wind Speed for a Fully Developed Sea

Sea State	Significant Wave Height (ft)	Wind Speed (Kts)
0	0 to 0.5	0 to 2
1	0.5 to 1	2 to 7
2	1 to 3	7 to 12
3	3 to 5	12 to 16
4	5 to 8	16 to 20
5	8 to 12	20 to 25
6	12 to 20	25 to 32
7	20 to 40	32 to 45
8	40+	45+

Source: Adapted from Long [6] (with permission).

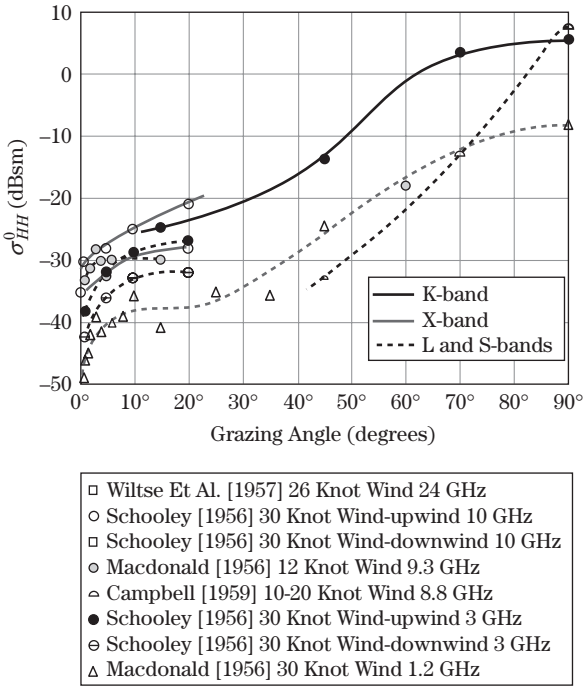

FIGURE 5-17 ■ Sea return as a function of grazing angle for four radar bands. (From Long [6]. With permission.)

Angular and Frequency Dependencies Figure 5-17 gives horizontally polarized sea return data from several original sources for four radar bands as a function of grazing angle, wind speeds corresponding to high sea states, and upwind versus downwind directions. The data illustrate strong angular, frequency, and look direction dependence. Note that very high values of σ^0 (above 0 dB) are seen at nadir. This suggests that sea clutter could be a significant limitation when searching for a small, slow-moving target on the sea surface. In addition to high backscatter, shadowing and sea Doppler accentuate the detection problem.

Figure 5-18 presents a plot of averaged data for sea clutter from Nathanson [15] for five radar bands as a function of depression angle for sea state 1. For this low sea state, σ^0 is relatively small, particularly for low depression angles. Note that there is much more

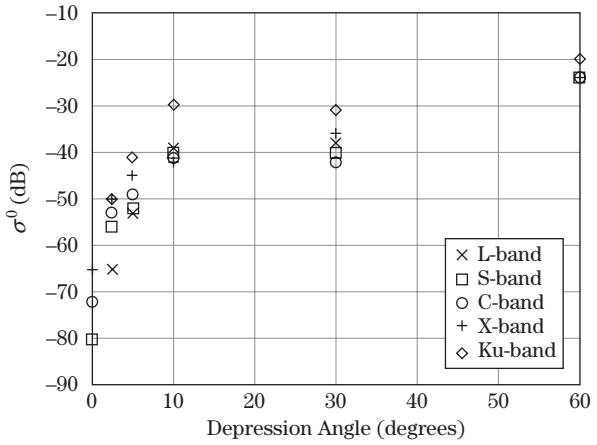

FIGURE 5-18 ■ Averaged sea return as a function of depression angle and radar band, sea state 1, VV polarization. (Adapted from Nathanson [15]. With permission.)

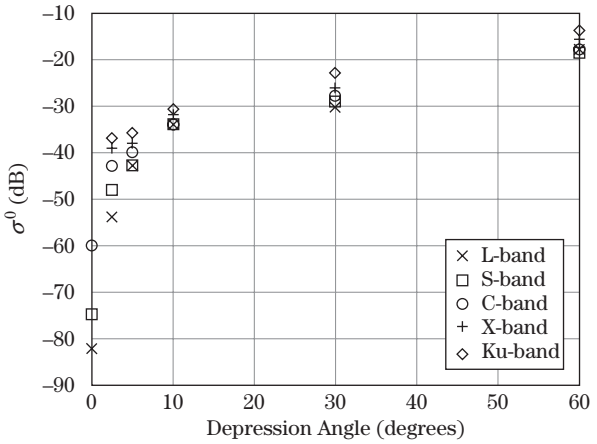

FIGURE 5-19 ■ Averaged sea return as a function of depression angle and radar band, sea state 3, VV polarization. (Adapted from Nathanson [15]. With permission.)

variation with frequency at the lower depression angles. Figure 5-19 gives averaged sea return data for sea state 3. These data are almost 10 dB higher than for sea state 1. The frequency dependencies appear to be similar to those for Figure 5-18.

Figure 5-20 compares values of σ^0 for vertical and horizontal polarized returns from sea clutter at L- and X-bands. As was discussed previously, there is a much greater difference between the vertical and horizontal values of σ^0 at L-band than there is at X-band.

One important parameter for sea return is the range fall-off of sea clutter echo power. As range increases, the grazing angle δ at which the sea surface is viewed decreases. When δ falls below the critical angle, θ_C, the surface becomes "smooth" by the Rayleigh criterion of equation (5.15). Figure 5-21 gives the measured sea data as a function of range dependence for two regions: above and below the critical angle; and low and high wave heights [19]. Note that the range for the critical angle moves in (higher depression angle), and the wave height (and thus, the rms surface roughness) increases as predicted by equation (5.16). These data show that, below the critical angle, the R^{-3} range dependence of pulse-limited sea clutter return transitions to approximately an R^{-7} dependence so that the clutter return rapidly becomes insignificant. In addition, the critical angle often appears near the first multipath null angle, further enhancing the clutter roll-off with range. (See Chapter 4 for a discussion of multipath.)

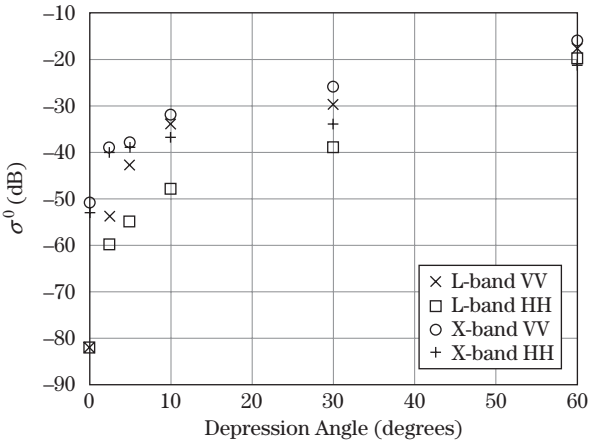

FIGURE 5-20 ■ Sea return as a function of depression angle for VV and HH polarizations, land X-bands, sea state 3. (Adapted from Nathanson [15]. With permission.)

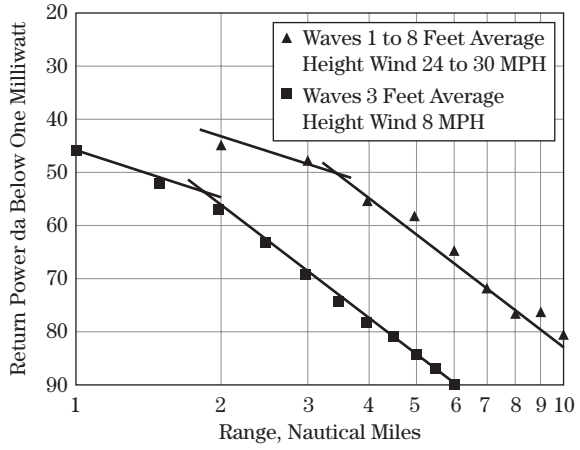

FIGURE 5-21 ■ Range dependence of sea return for two wave conditions, X-band, HH polarization. (From Dyer and Currie [19]. With permission.)

Ducting Because the sea surface has a strong reflection coefficient and water vapor is always present near the surface, conditions can occur such that a high water concentration and thus a reflective layer occur over some region above the water. When this happens, the high water concentration layer and the sea surface act like a two-dimensional waveguide, trapping the radiofrequency (RF) energy and extending the range of sea return detection. The reflection coefficient of the sea determines the duct shape and transmission efficiency. Figure 5-22 shows two sets of sea return data as a function of grazing angle taken with the same radar, the only difference being the lapse of several hours in time. The morning data show much less dependence on angle than the afternoon data. Apparently, ducting conditions were present in the morning but were absent in the afternoon. These data were collected in February in Wildwood, New Jersey, showing that ducting can occur in cold as well as tropical conditions.

Figure 5-23 gives a summary of range dependence measurements above and below the critical angle performed in Boca Raton, Florida, over a period of several years at X-band. Range dependencies quite different from the expected R^{-3} for a pulse-limited radar occurred a significant portion of the time, indicating both ducting conditions and possibly variations in the multipath field from time to time.

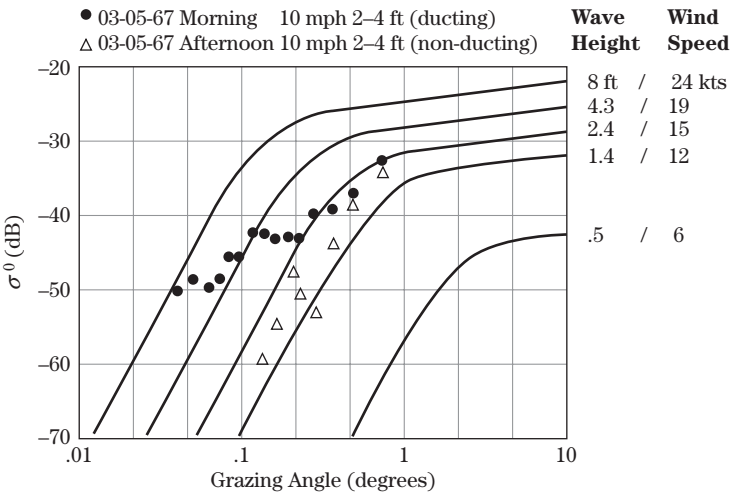

FIGURE 5-22 ■ Comparison of sea return achieved under ducting and nonducting conditions, X-band, HH polarization. (From Dyer and Currie [19]. With permission.)

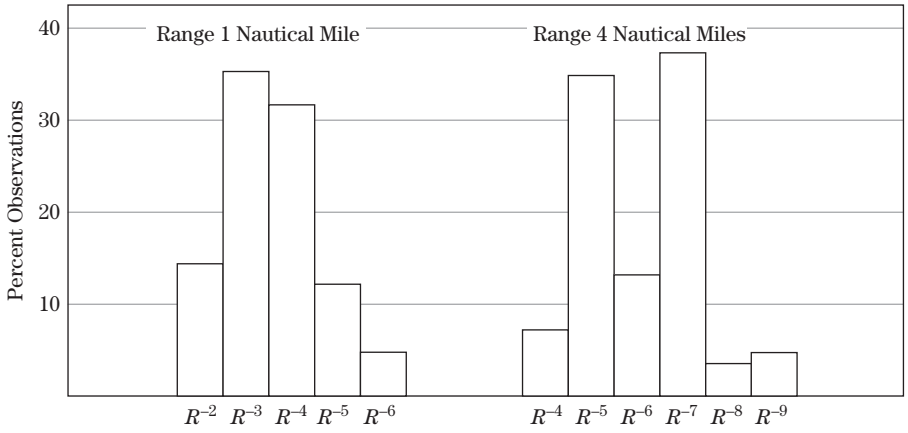

FIGURE 5-23 ■ Measured range dependencies above and below the critical grazing angle as a percentage of total measurements. (From Dyer and Currie [19]. With permission.)

5.2.2.4 Clutter Variability Properties

In the previous section average values for surface clutter were discussed, but the variability of clutter reflectivity with time and or space is as least as important, if not more so. These topics are addressed in this section.

Land Clutter Variations

Temporal Variations Land clutter generally contains some vegetation. Consequently, land clutter returns will vary with time due to wind-blown motion of leaves, needles, branches, and stalks. Since such motion makes detection more difficult, it must be described and allowances made for it when calculating the probability of detection for a target in clutter. The probability density function, $p_\sigma(\sigma)$, and the cumulative distribution function (CDF), $P_\sigma(\sigma)$, are used to describe the variation in RCS or power. Figure 5-24 illustrates an estimated unnormalized probability density function obtained as the histogram of the measured data, which is just a plot of the number of independent clutter samples that fall within a series of narrow power intervals. If the histogram is normalized by dividing the sample counts by the total number of samples times the width of an amplitude bin, an estimate of the PDF is obtained.

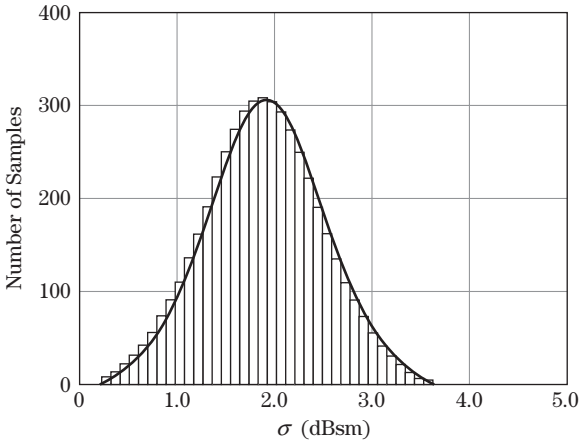

FIGURE 5-24 ■ A histogram provides an estimate of an unnormalized probability density function.

The CDF is the integral of the PDF,

$$P_\sigma(\sigma) = \int_{-\infty}^{\sigma} P_\sigma(v)\, dv \tag{5.20}$$

Values of the CDF increase monotonically from zero to one. If the area under the normalized histogram from the lowest value to some value σ is calculated, an estimate of the CDF is obtained. Cumulative distributions are quite useful because some key parameters are easily read from a plot of the CDF. For instance, the median value is the 50% point ($P_\sigma(\sigma) = 0.5$) on the curve. Rivers [20] observed that for log-normal and Weibull distributions with parameters appropriate for modeling measured sea clutter, the mean value of the power, $\bar{\sigma}$, can be estimated from the value corresponding to the 90% point on the CDF, $\sigma_{0.9}$, to be 3.5 dB below the 90% point by the relation

$$\bar{\sigma} = (\sigma_{0.9} - 3.5 \text{ dB}) \pm 0.5 \text{ dB} \tag{5.21}$$

Newer land clutter data observed by Billingsley [11] is spikier than that used by Rivers, suggesting that the ±0.5 dB tolerance in equation (5.21) should be wider [6]. As another example of the usefulness of CDFs, the standard deviation in dB of a log-normal distribution is $\sigma_{0.84} - \sigma_{0.16}$.

Figure 5-25 gives a measured CDF for wind-blown trees at X-band. The dotted line approximates the CDF corresponding to an exponential PDF in this plot format. The data in Figure 5-25 appear approximately exponential in their general shape, but their distribution is seen to be wider than exponential. For example, the 90% mark on the CDF occurs at about –39 dB for the exponential distribution, but not until the larger value of –30 dB for the X-band tree data. Variable clutter complicates detection in two ways. First, since the return is changing with time, part of the time the reflectivity will be larger than the average value. Second, the rate of fluctuation can limit the effectiveness of Doppler processing.

Table 5-4 gives the standard deviations (square root of the variance) measured for wind-blown vegetation as a function of frequency and polarization. The standard deviation for an exponential distribution, converted to a decibel scale, is approximately 5.7 dB [6]. Thus, at 9 GHz the distributions appear narrower than exponential, but at 95 GHz and higher they are wider than exponential.

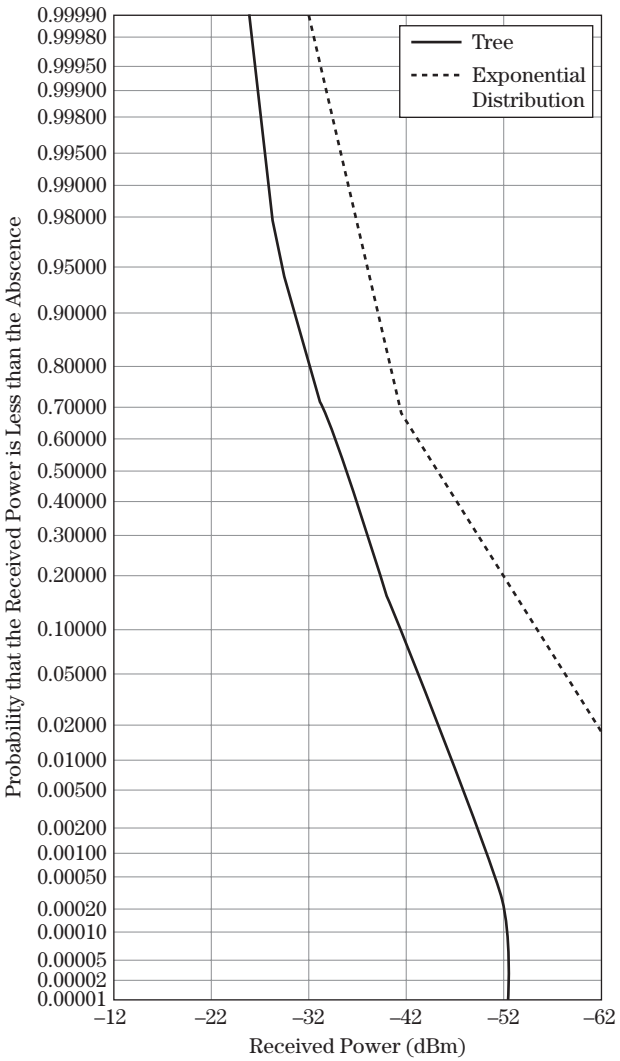

FIGURE 5-25 ■ Cumulative probability distribution for deciduous trees at X-band, 4.1°depression angle. (From Currie et al. [21]. With permission.)

Decorrelation Time An important metric of clutter temporal properties is the decorrelation time. The decorrelation time, τ_0, is defined as the time lag required for the autocorrelation function of a set of clutter samples to decay to some defined fraction, usually 0.5 or $1/e = 0.367$ of its peak value at zero lag. The autocorrelation function $\phi_{cc}(\tau)$ of the time-varying clutter return, $c(t)$, measures how similar successive data samples are to a first sample as the delay time between samples increases. The power spectral density function is the Fourier transform of $\phi_{cc}(\tau)$,

$$S_{cc}(f) = \int_{-\infty}^{+\infty} \phi_{cc}(\tau)\, e^{-j2\pi f \tau} d\tau \tag{5.22}$$

where τ is the autocorrelation lag time.

If the clutter power spectrum is "white" (constant) over the receiver bandwidth B, then the decorrelation time equals $1/B$. This is the same as the case for random noise.

TABLE 5-4 ■ Measured Standard Deviations of Temporal Variations for Trees

Frequency Clutter Type	Polarization	Average Value of Standard Deviation (dB)			
		9.5 GHz	16.5 GHz	35 GHz	95 GHz
Deciduous trees, summer	Vertical	3.9	—	4.7	—
	Horizontal	4.0	—	4.0	5.4
	Average	4.0	—	4.3	5.4
Deciduous trees, fall	Vertical	3.9	4.2	4.4	6.4
	Horizontal	3.9	4.3	4.3	5.3
	Average	3.9	4.2	4.3	5.0
Pine trees	Vertical	3.5	3.7	3.7	6.8
	Horizontal	3.3	3.8	4.2	6.3
	Average	3.4	3.7	3.9	6.5
Mixed trees, summer	Vertical	3.3	—	4.0	—
	Horizontal	4.6	—	4.2	—
	Average	4.4	—	4.1	—
Mixed trees, fall	Vertical	4.1	4.1	4.7	6.3
	Horizontal	4.5	4.3	4.6	5.0
	Average	4.4	4.2	4.6	5.4
Field, tall grass	Vertical	1.5	—	1.7	2.0
	Horizontal	1.0	1.2	1.3	—
	Average	1.3	1.2	1.4	2.0
Rocky area	Vertical	1.1	2.2	1.8	1.6
	Horizontal	1.2	1.7	1.7	1.7
	Average	1.1	1.9	1.8	1.7
10-in. corner reflector located in grassy field		1.0	1.0	1.2	1.2

Source: From Currie et al. [21] (with permission).

Because the receiver bandwidth also determines the Nyquist rate of its output, the received signal output will normally be sampled at a rate of about $1/B$ samples per second (see Chapter 14). Since the samples are spaced by the decorrelation time, the sampled data will appear uncorrelated with a white power spectrum. If the clutter instead has a decorrelation time greater than $1/B$ seconds, then the sampled clutter data will not appear white and will have some degree of correlation from one sample to the next.

The decorrelation time is important for detection analysis because it determines the number of uncorrelated samples, N_i, available for integration for signal-to-clutter improvement according to

$$N_i = \begin{cases} \dfrac{N_t PRI}{\tau_0}, & PRI \le \tau_0 \\ N_t, & PRI \ge \tau_0 \end{cases} \tag{5.23}$$

where N_t is the total number of clutter samples and PRI is the time between samples. As will be seen in Chapter 15, coherent or noncoherent integration of radar data can improve the detectability of targets in the presence of interference, provided that the interference samples are uncorrelated so they can be made to "average out" while the target signal is reinforced. Thus, if the total sample collection time $N_t PRI$ is shorter than the decorrelation time, no uncorrelated clutter samples are obtained, and no improvement in target detectability is gained by integration of successive samples.

If the clutter does decorrelate during the collection time, then some improvement in target detectability is possible by integrating multiple samples. In coherent integration, the complex (in-phase [I] and quadrature [Q]) data are integrated (added) to cause the target component of the samples to add in phase, whereas the uncorrelated clutter and noise components do not add in phase. In this case, the signal-to-clutter ratio (SCR) and signal-to-noise ratio (SNR) (and thus signal-to-interference ratio [SIR]) are increased, significantly improving target detectability. In noncoherent integration, the magnitude or magnitude squared of the complex receiver output data is taken and then integrated. Discarding the phase information eliminates the possibility of a gain in SCR. Nonetheless, an improvement in target detectability is still achieved, though less than in the coherent integration case. Chapter 15 discusses the effects of coherent and noncoherent integration on target detection in white interference in greater detail.

Figure 5-26 presents the autocorrelation functions for windblown trees in conditions described as a "windy day," while Table 5-5 gives the 50% ($\tau_{1/2}$) and $1/e$ ($\tau_{1/e}$) decorrelation times in seconds. As can be seen, essentially no integration improvement could be achieved at the lower frequency bands, and only limited improvement could be achieved at X-band.

Figure 5-27 gives measured decorrelation times for higher frequencies (10 GHz through 95 GHz) as a function of wind speed. As can be seen, at the higher frequencies much shorter decorrelation times are observed, an advantage for obtaining better noncoherent integration efficiency.

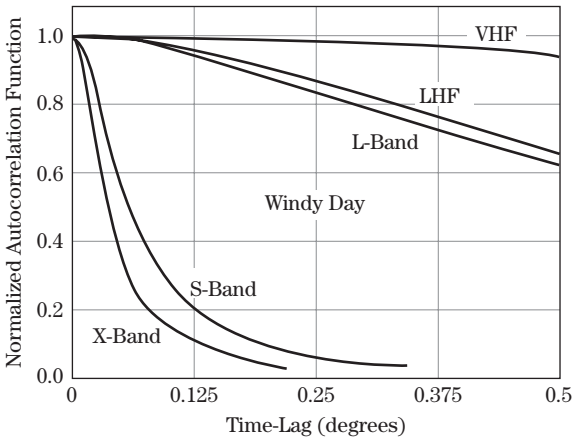

FIGURE 5-26 ■ Autocorrelation functions of the returns from windblown trees for several frequency bands on a windy day. (From Billingsley [11]. With permission.)

TABLE 5-5 ■ Measured Decorrelation Times at Five Frequency Bands

Frequency Band	Correlation Time(s)	
	$\tau_{1/2}$	$\tau_{1/e}$
VHF	4.01*	5.04*
UHF	0.69	0.94
L-Band	0.67	0.95
S-Band	0.062	0.081
X-Band	0.033	0.049

Note: * = extrapolated estimate
Source: From Billingsley [11] (with permission).

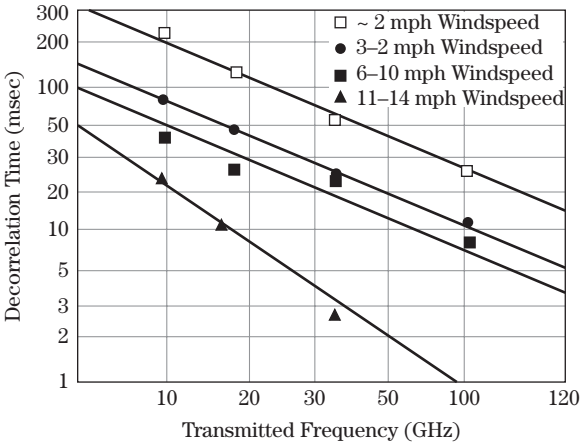

FIGURE 5-27 ■ Decorrelation time for windblown trees as a function of wind speed. (From Currie et al. [21]. With permission.)

Clutter Frequency Spectra A second way to look at temporal variations in clutter returns is in terms of clutter power spectra. Power spectra tell us how rapidly a return is varying. This is of interest since many radars use Doppler processing to improve target detection in heavy clutter. Clutter spectra are of interest for two situations: (1) very slow-moving targets such as ground vehicles or boats; and 2) high-speed targets that may be affected by aliasing ("foldover") of the clutter spectra around the pulse repetition frequency (PRF). (See Chapter 8 for a discussion of Doppler foldover.)

Theoretical formulations of clutter spectra yield Gaussian-shaped spectra, yet a number of actual clutter measurements have yielded power law-shaped spectra. These differences are of concern since power law spectral shapes roll off more gradually with frequency than Gaussian spectra. This problem was first identified by Fishbein et al. [22] when attempting to develop models for the spectral data on trees at X-band shown in Figure 5-28 [22]. They found that a Gaussian curve fit rolled off much too rapidly. A much better fit was obtained with a power law curve of the form

$$S_{cc}(f) = \sigma_{DC}\left(\frac{1}{1+\left(\frac{f}{f_c}\right)^n}\right) \tag{5.24}$$

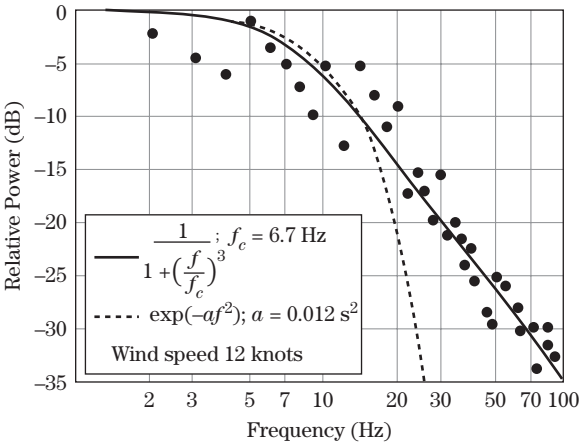

FIGURE 5-28 ■ Spectral data from trees at X-band with Gaussian and power function curve fits. (From Fishbein et al. [22]. With permission.)

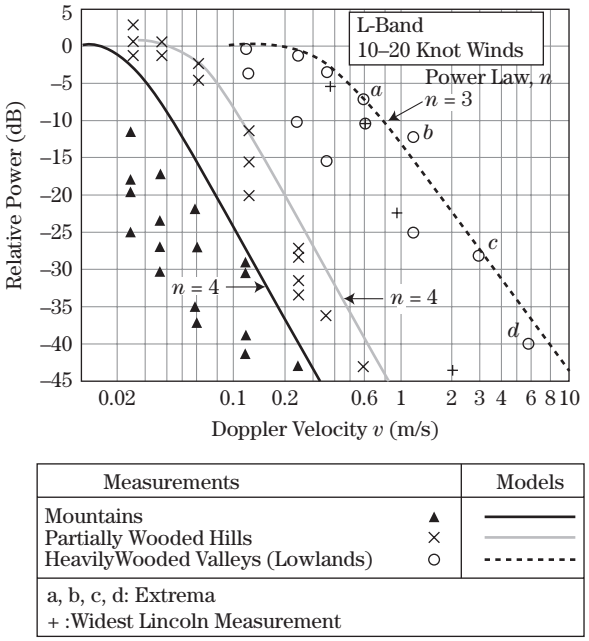

FIGURE 5-29 ■ L-band spectral data with various power law curve fits. (From Simpkins et al. [23]. With permission.)

where σ_{DC} is the DC clutter power return, f_c is the 3 dB cutoff frequency for the power spectrum, and n is an integer selected to best fit the data. Fishbein et al. found that a value of $n = 3$ fit the data best. Other experimenters have also measured power law dependencies. Figure 5-29 presents power spectral data at L-band for woods and wooded hills measured by the U.S. Air Force's Rome Air Development Center (RADC) [23]. For these data, the best power law fits were obtained with $n = 3$ or 4.

Table 5-6 presents the cutoff and power law exponents determined for wind-blown tree data at 10 GHz though 95 GHz for both logarithmic and linear receiver transfer functions. The exponent seems to lessen with increasing frequency, implying a slower roll-off, while the logarithmic receiver provides a steeper roll-off than the linear case.

To date, theorists have not been able to determine a theoretical basis for power law frequency dependence, yet experimenters continue to observe them in measured data. One possibility is that Doppler spectra can be significantly affected by radar system imperfections such as nonlinearities, dynamic range limits, and oscillator phase noise. Recently, Billingsley [11] measured tree data with a high-quality coherent instrumentation radar having high linearity over a wide dynamic range, stabilized oscillators, and low-sidelobe narrow Doppler filters. He obtained clutter power spectra that were well modeled by a

TABLE 5-6 ■ Corner Frequencies and Power Exponents for Tree Return Spectra

Power Function Parameter	Frequency			
	9.5 GHz	16 GHz	35 GHz	95 GHz
n (linear)	3	3	2.5	2
n (log)	4	3	3	3
f_c (Hz), 6–15 mph wind speed	9	16	21	35

Source: From Currie et al. [21] (with permission).

two-sided exponential roll-off. This spectrum has a rate of decay that falls between the Gaussian and power law models.

These observations suggest that equipment imperfections may be a significant contributor to the slower decay of data that are well modeled by power law spectra. However, many fielded systems will suffer these limitations, so a practical approach to performance assessments could use both Gaussian and power law clutter power spectrum models to establish upper and lower bounds on performance in the presence of clutter.

Spatial Variations As discussed earlier, when the radar scans across the surface, the number and types of scatterers within the radar beam change, resulting in a changing return. These variations are described using the same tools as for temporal variations (i.e., amplitude distributions and spatial correlation functions).

Spatial amplitude distributions can be much wider than temporal distributions, particularly at lower grazing angles where shadowing and multipath come into play. Most experimenters resort to Weibull distributions to describe the variations. A key finding of experimenters is that at higher grazing angles, spatial distributions tend to appear exponential (Weibull width parameter $a \approx 1$) while at low grazing angles the width parameter increases greatly. The calculated spatial distributions by Booth [24] for cultivated land at X-band in Figure 5-30 illustrate this effect. They are approximately exponential-distributed (width parameter $a \approx 1$) at a grazing angle of 5° but become much wider at lower angles.

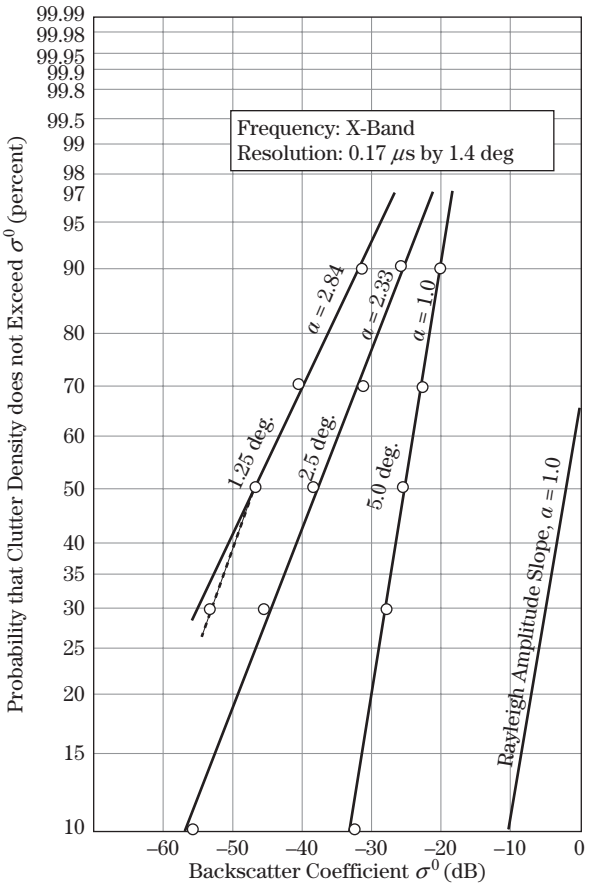

FIGURE 5-30 ■ Spatial distributions of cultivated land as function of grazing angle X-band. (From Booth [24]. With permission.)

TABLE 5-7 ■ Spatial Statistical Attributes for X-Band Ground Clutter

Terrain Type	Depression Angle (deg)	Weibull Parameters			Ensemble Mean Clutter Strength σ^0 (dB)	Percent of Samples above Radar Noise Floor	Number of Patches
		a	σ_m (dB)	σ_w^0 (dB)			
Rural/	0.00–0.25	4.8	−60	−33	−32.0	36	413
Low-Relief	0.25–0.50	4.1	−53	−32	−30.7	46	448
	0.50–0.75	3.7	−50	−32	−29.9	55	223
	0.75–1.00	3.4	−46	−31	−28.5	62	128
	1.00–1.25	3.2	−44	−30	−28.5	66	92
	1.25–1.50	2.8	−40	−29	−27.0	69	48
	1.50–4.00	2.2	−34	−27	−25.6	75	75
Rural/	0–1	2.7	−39	−28	−26.7	58	176
High-Relief	1–2	2.4	−35	−26	−25.9	61	107
	2–3	2.2	−32	−25	−24.1	70	44
	3–4	1.9	−29	−23	−23.3	66	31
	4–5	1.7	−26	−21	−22.2	74	16
	5–6	1.4	−25	−21	−21.5	78	9
	6–8	1.3	−22	−19	−19.1	86	8
Urban	0.00–0.25	5.6	−54	−20	−18.7	57	25
	0.25–0.70	4.3	−42	−19	−17.0	69	31
	0.70–4.00	3.3	−37	−22	−24.0	73	53

σ_m = median reflectivity
σ_w^0 = mean reflectivity
F = propagation factor (see Chapter 4)
Source: Adapted from Billingsley [11] (with permission).

The effect of grazing angle on the PDF is further illustrated by Table 5-7, which gives spatial statistics for rural and urban settings as a function of grazing angle for very low angles. For rural settings, and angles above 5 degrees, the Weibull width parameter a indicates an approximately exponential power PDF ($a \approx 1$), while the PDF becomes much wider for lower angles. As might be expected, the urban setting exhibits larger width parameters and thus distributions wider than exponential even at 4°. Thus, in general, exponential power statistics are expected in the plateau regions for all but urban clutter, but much wider distributions are seen for low grazing angles. For urban settings, wide distributions may be observed even in the plateau region because of the height of man-made structures that cause shadowing even at higher grazing angles.

Sea Clutter Variation The return from the sea varies in time due to the effects of the wind on sea waves. These effects are of several types: waves created by the wind blowing for a period of time over a given "fetch" of water, ripples that appear on the surface due directly to the wind, white caps created when the tops of waves break over the front of the waves, and airborne spray that results from ripples and white caps.

Initially, amplitude (voltage) statistics from a fixed range-azimuth cell were assumed to be Rayleigh. This model fit measured data for low-resolution radars well. However, as finer-resolution radars came into use over time, non-Rayleigh statistics were encountered. The current view is that wind-produced ripples on the sea surface produce noise-like variations in sea return or "speckle" that are approximately Rayleigh distributed in amplitude but that the large-scale moving structure of the sea swells changes the local slope of the

rippled surface, imposing a time-varying change in the mean of the Rayeigh PDF in a give spatial cell. The resulting amplitude statistics of the return are non-Rayleigh, implying a non-Gaussian model of the complex I/Q data.

In general, the amplitude statistics are observed to become "spikier" with decreasing grazing angle and decreasing radar footprint area, possibly due to a decreasing average or median clutter value while the strength of the sea clutter spikes remains relatively constant. Also, horizontal polarization tends to present spikier clutter than does vertical polarization, particularly at low grazing angles. Sea clutter statistics also vary with the radar-wind/wave look direction.

Experimenters have used Weibull, log-normal, and K distributions to model sea statistics. In particular, Ward et al. [25] and Ward [26] performed extensive modeling of sea return using the K distribution, a two-parameter distribution that can be related to the Weibull and the log-normal. It is given by [6]

$$p_\xi(\xi) = \begin{cases} \dfrac{2b}{\Gamma(v)} \left(\dfrac{b\xi}{2}\right)^v K_{v-1}(b\xi), & \xi > 0 \\ 0, & \xi < 0 \end{cases} \tag{5.25}$$

where

$\xi = \sqrt{\sigma}$ is the clutter amplitude.
v is the "shape factor."
b is a scale factor.
$\Gamma(\cdot)$ is the gamma function.
K_n is the modified Bessel function of the third kind and order n.

Ward showed that this distribution describes the statistics of the product of two random variables, one described by a Rayleigh PDF and the other by a chi or gamma PDF [26]. Thus, the Rayleigh component can be used to model the speckle portion of the sea return, while the chi component can be used to model the time-varying mean of the local Rayleigh PDF due to large-scale sea structure, as discussed previously. The K distribution is believed to provide a better fit to sea clutter data, particularly for high resolution radars. See [25–27] for more information.

Temporal Variations

Correlation Properties Work on calculating autocorrelation functions for sea returns has demonstrated that there are three mechanisms involved: (1) return from sea spray and white caps; (2) specular returns (spikes) from wavefronts; and (3) Bragg scattering [28]. The return from sea spray and Bragg scattering decorrelates very rapidly, while the specular return from the wavefront is highly correlated in time. Figure 5-31 illustrates this effect. The figure shows the autocorrelation function for sea return at K_u-band on two time scales. The upper scale indicates that almost 600 ms are required for the return to decorrelate to 50% of the ACF peak. The lower scale shows that the return drops from a normalized correlation of 1 to 0.85 in approximately one ms. The initial 15% decorrelation is due to the rapidly moving sea spray, while the longer 50% decorrelation time is due to the much slower motion of the wavefronts. Attempts have been made to use frequency agility to decorrelate sea return, but only the decorrelation due to sea spray and speckle is affected. Thus, sea waves tend to be highly correlated over many milliseconds, so that only scan-to-scan integration will be effective in increasing target detectability.

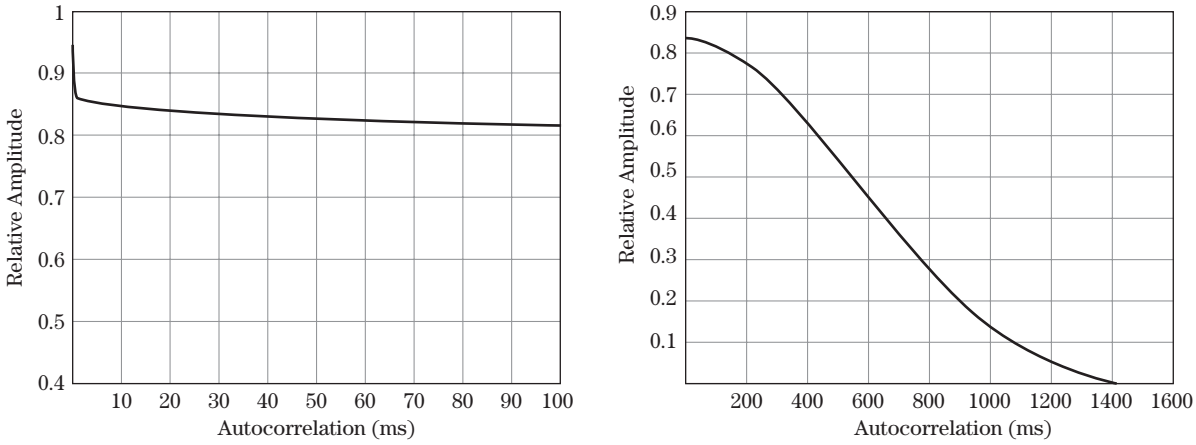

FIGURE 5-31 ■ Autocorrelation function of sea return at K_u-band. 3.9° depression angle, and downwind/down-wave look direction. (From Ward et al. [25]. With permission.)

Spectral Properties The spectrum for sea clutter differs from that of land since sea waves can move physically toward or away from the radar. Thus, sea clutter can have a nonzero average Doppler frequency, unlike land clutter where moving scatterers are anchored in place. The Doppler frequency at which the motion of scatterers at a radial velocity, v, appears is given by the equation

$$f_d = \frac{2v}{\lambda} \tag{5.26}$$

Consequently, the width, Δf_d, of the Doppler spectrum is related to the width, Δv, of the velocity spectrum according to

$$\Delta v = \frac{\lambda}{2}\Delta f_d \tag{5.27}$$

Figure 5-32 gives an example of the coherent spectrum at L-band, indicating the spectrum width for various amplitude levels [29]. At higher frequencies the center frequency and spectral width would be expected to scale proportional to the transmitted frequency in accordance with equations (5.26) and (5.27). While the spectra in this figure are approximately symmetric and Gaussian in shape, sea clutter spectra, especially at fine resolution and low grazing angle, are often distinctly asymmetric; see [28] for a number of examples.

Sea Spikes *Sea spikes* are strong returns from highly localized points or regions on the sea surface. The region generating the spike is usually, but not always, much smaller than the resolution cell area. Spikes are a problem for radar detection because they can exceed the signal level of small targets and can last for many seconds. Explanations of the causes for such returns are disputed by various researchers and have included returns from white caps, to sea spray, to returns from particular facets located on the wavefronts. Most likely all are responsible. Some general properties of sea spikes from the radar point of view reported by Werle [30] are as follows:

- Spikes occur significantly more often for horizontal than for vertical polarization.
- Spike intensity is usually greater for horizontal than for vertical polarization.
- HH/VV polarization ratios of greater than 10 dB were observed.

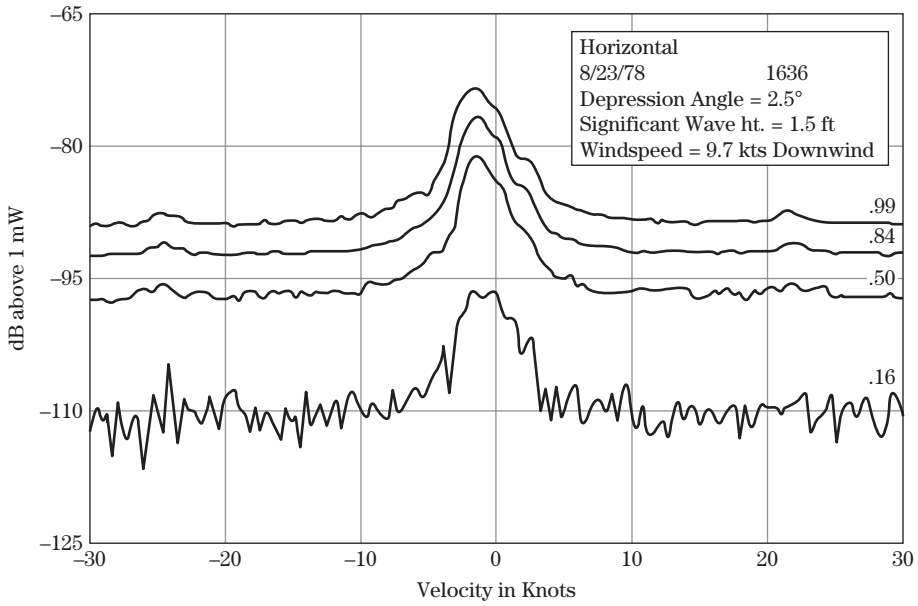

FIGURE 5-32 ■ Percentile of Doppler spectra at L-band. (From Plummer et al. [29]. With permission.)

- Spikes at both HH and VV occurred much less often than for HH alone.
- Rarely was a VV spike seen without a concurrent HH spike.

Walker [28] sates that the HH/VV intensity difference holds for the specular and Bragg scattering components but that the white cap component has roughly equal HH and VV backscatter. Given these properties, use of a dual-polarized radar and analysis of measured HH/VV polarization ratios may be one technique for recognizing and removing spikes from clutter data.

Spatial Variations Sea clutter returns are due to moving scatterers: the wind-driven spray and the gross and fine shape of the moving waves. Consequently the temporal and spatial variations of sea clutter are correlated. The only major difference between the two is due to wind-wave look direction. Generally, upwind/up-wave provides the highest radar return while downwind/down-wave provides the lowest return. This occurs because waves lean away from the wind so that the more vertical wavefronts are exposed in the upwind/up-wave direction, while the sloping backs are exposed in the downwind/down-wave direction.

5.2.3 Atmospheric Clutter

Atmospheric clutter primarily consists of hydrometeors, of which rain is the primary case of interest. Other atmospheric phenomena such as *angels* (clear air returns of unknown origin) can be of concern but will not be covered here. Frozen precipitation is also of interest, but primarily at millimeter wave frequencies because of the lower reflectivity of ice compared with water in the microwave bands. Experiments to determine average reflectivity as well as the spectral properties of rain are discussed in the following sections.

5.2.3.1 Average Value Data

Rain Reflectivity Average Values Raindrops can be modeled as dielectric spheres of differing sizes that are contained within the radar resolution cell. The radar return from the rain is, thus, the sum of the reflectivity of all the drops. As a result, the drop-size distribution is critical to the resultant reflectivity. The variability between most rain clutter

TABLE 5-8 ■ Average Rain Reflectivity versus Frequency Band

		η, dB m^{-1} Transmit frequency, GHz						
Z, dBz	Radar band: Type	S 3.0	C 5.6	X 9.3	K_u 15.0	K_a 35	W 95	mm 140
−12	Heavy stratus clouds				−100	−85	−69	−62
14	Drizzle, 0.25 mm/h	−102	−91	−81	−71	−58	−45*	−50*
23	Light rain, 1 mm/h	−92	−81.5	−72	−62	−49	−43*	−39*
32	Moderate rain, 4 mm/h	−83	−72	−62	−53	−41	−38*	−38*
41	Heavy rain, 16 mm/h	−73	−62	−53	−45	−33	−35*	−37*

* Approximate
Source: From Nathanson [15] (with permission).

models is due to differences in the drop-size distribution selected. Referring to Figure 5-5, recall that the reflectivity of a sphere is a strong function of the ratio of the circumference to the wavelength in the Rayleigh scattering region, so that rain reflectivity depends strongly on the percentage of large drops and will increase with increasing frequency until the resonance region is encountered.

Of course, every rainstorm has a different drop-size distribution, and distributions often change in differing parts of the same storm. Thus, a great deal of variation in the return with both time and space can be expected. Consequently, when discussing average values for reflectivity, it should be understood that considerable variation will be encountered in a realistic situation.

Table 5-8 gives average rain backscatter from several sources for S-band through W-band for several rain situations. As can be seen, the backscatter coefficient increases with increasing frequency (at least up to 35 GHz) and increasing rain rate. Observers of rainstorms have noted that rain drop size increases with increasing rain rate, which accounts for the direct dependence of reflectivity on rain rate. Attenuation has been eliminated from the rain data, so the apparent backscatter can be less for heavy rain rates.[3]

Table 5-8 includes a column listing an alternative scale for rain reflectivity denoted with the symbol Z. This scale, common in meteorological applications, is also called volume reflectivity. It relates radar reflectivity to the distribution of drop sizes, which is more useful for estimating rain rates. It is usually expressed in decibel units and denoted dBz. The relationship between η and Z is [31]

$$\eta = \frac{\pi^5 |K|^2}{\lambda^4} Z \tag{5.28}$$

where K is the complex index of refraction and Z is in units of $m^6/m^3 = m^3$. While K depends on temperature and wavelength, for most weather conditions $|K|^2 \approx 0.93$ for liquid scatterers (e.g., rain, fog) and 0.197 for frozen scatterers (e.g., snow, hail).

For use in meteorology, Z is converted to units of mm^6/m^3 (which requires multiplication of Z in m^3 by 10^{18}) and then to a decibel scale denoted dBz. Thus,

$$Z\ (\text{dBz}) = 10 \log_{10}(10^{18} Z) = 10 \log_{10}(Z) + 180 \tag{5.29}$$

The calculations of equations (5.28) and (5.29) were used to obtain the dBz values in Table 5-8.

[3]Of course, the target echo signal strength is reduced by rain attenuation as well.

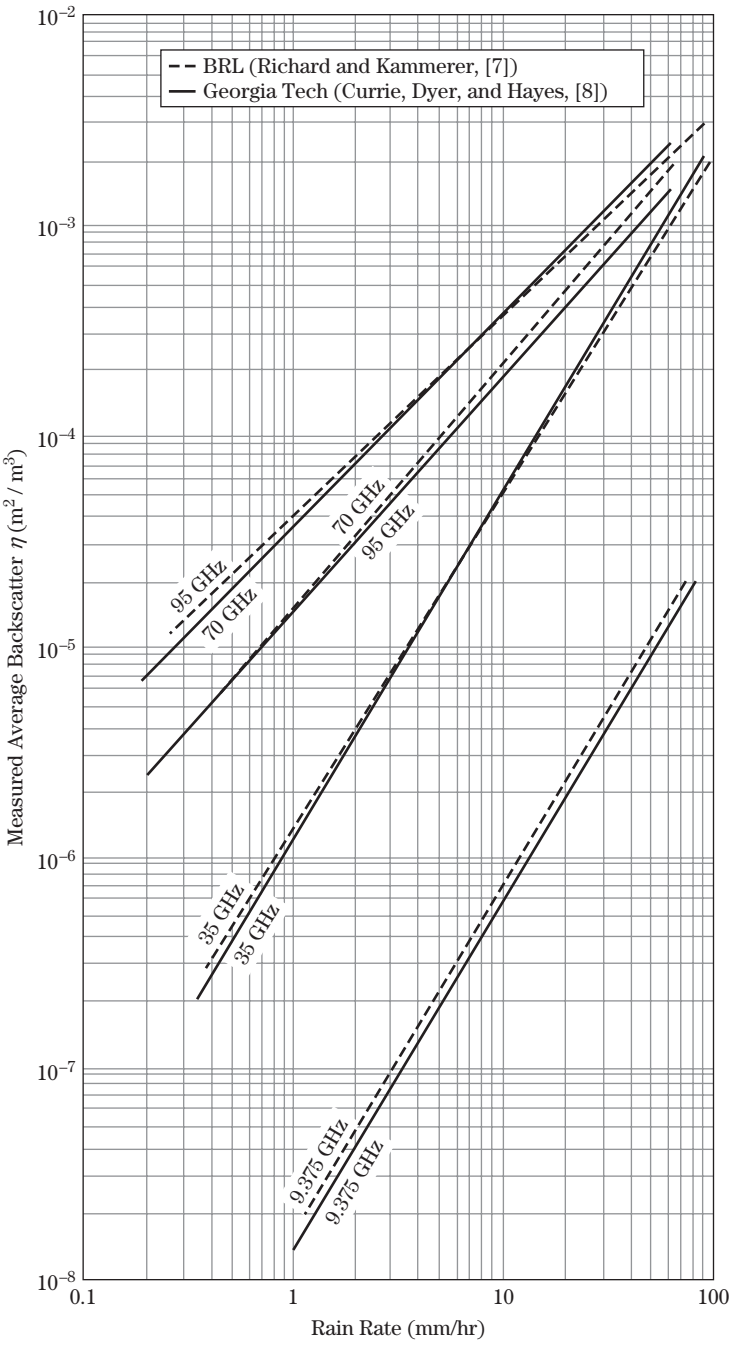

FIGURE 5-33 ■ Least squares fit to rain data at four frequency bands. (From Currie [32]. With permission.)

Figure 5-33 gives least square fit curves to rain data obtained from thunderstorms in a joint experiment between the U.S. Army BRL and GTRI in Orlando, Florida, in the 1970s [32]. Thunderstorms are known for producing large drops, so the wide variation in reflectivity with rain rate is not surprising. One interesting factor is the flattening of the curves at 70 and 95 GHz. This may indicate that the ratio of drop circumference to wavelength is approaching the resonance or optical regions, resulting in a lessened

dependence on drop size. BRL and GTRI each separately analyzed the data, getting slightly different results as shown. However, the overall spread in the data dwarfs these small differences.

Frozen Precipitation As indicated earlier, the reflectivity of frozen precipitation such as snow is generally ignored at microwave frequencies. However, at higher frequencies snow reflectivity can be significant. Figure 5-34 presents data on snow reflectivity at 95,

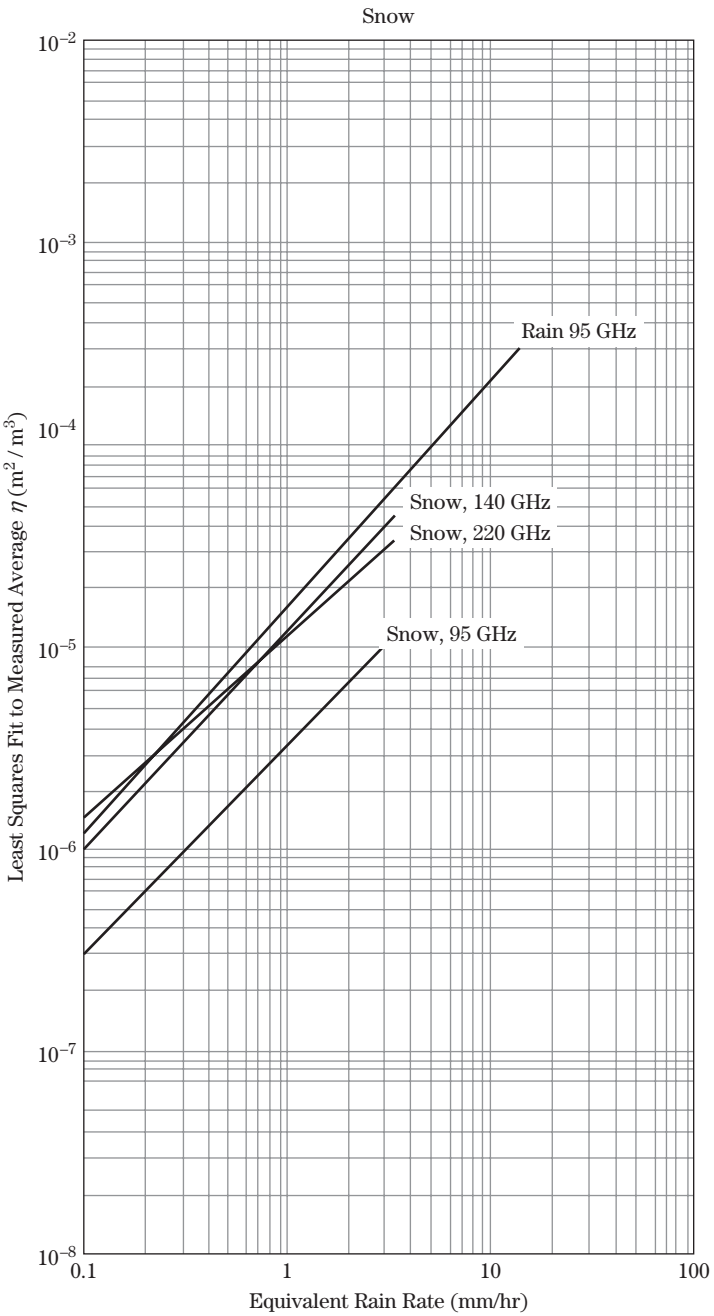

FIGURE 5-34 ■ Least squares fit to snow data at two frequency bands compared with rain data. (From Currie et al. [34]. With permission.)

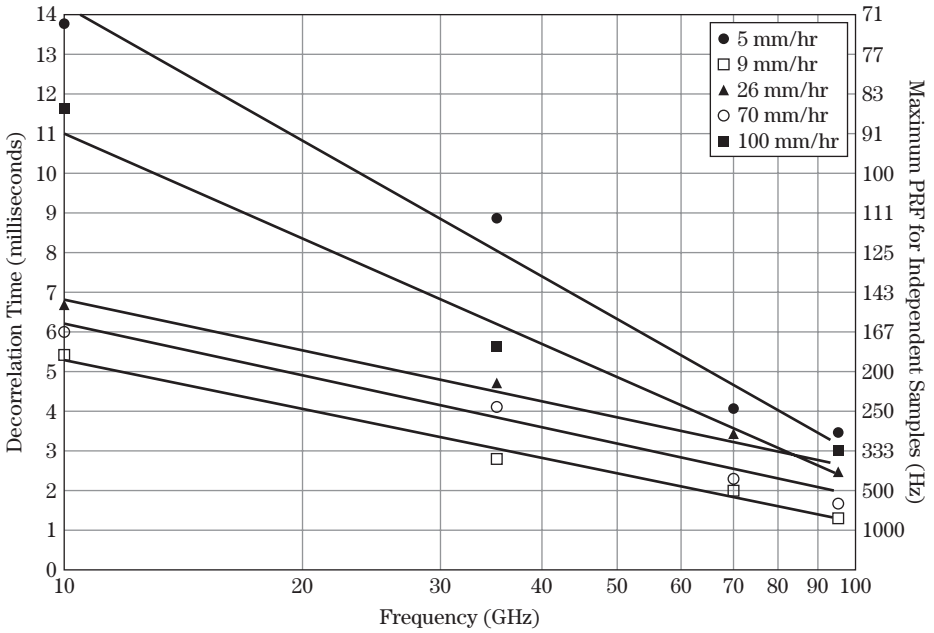

FIGURE 5-35 ■ Decorrelation time for rain backscatter as a function of frequency. (From Currie et al. [8]. With permission.)

140, and 220 GHz measured by Nemarich et al. [33,34] at the U.S. Army Harry Diamond Laboratory compared with the Georgia Tech 95 GHz rain data from Figure 5-33 The snow data are plotted versus equivalent rain rate based on snow water content. While the snow return is much lower at 95 GHz than the rain return, the snow returns at higher frequencies are comparable to the rain return for 95 GHz.

5.2.3.2 Temporal Spectra

Figure 5-35 presents data on the decorrelation time for rain return at 10 through 95 GHz. The maximum PRF for independent samples, calculated as the inverse of the decorrelation time as discussed in Section 5.2.2.4, is given on the right side. Note that for 5 mm/hr rain rate and 10 GHz, the maximum PRF for independent samples is only 71 Hz. At higher rain rates and higher frequencies, the maximum PRF increases significantly.

Figure 5-36 shows the spectral response at 10 through 95 GHz measured during the experiment displayed in Figure 5-33 [35]. Also shown is the Doppler shift for a slow-moving target at 3 mph. The spectral curves were matched to power law functions of the form of equation (5.24) in a manner similar to the data for trees discussed earlier. The figure shows that the rain return frequency spectra would be approximately 15 dB down from the peak (constant power level) at the Doppler frequency for a 3 mph target. This implies that the SCR could be improved by up to 15 dB through the use of careful Doppler processing.

Other important factors related to rain clutter are the spatial extent of a storm (both horizontal and vertical) and its Doppler characteristics, which are affected by prevailing winds, rain rates, and atmospheric turbulence. Attenuation due to rain is extremely important and was discussed in Chapter 4.

5.2.4 Millimeter Wave Clutter

The only difference between millimeter waves and microwaves is the wavelength. However, because of the change in the reflectivity properties of spheres and cylinders as the

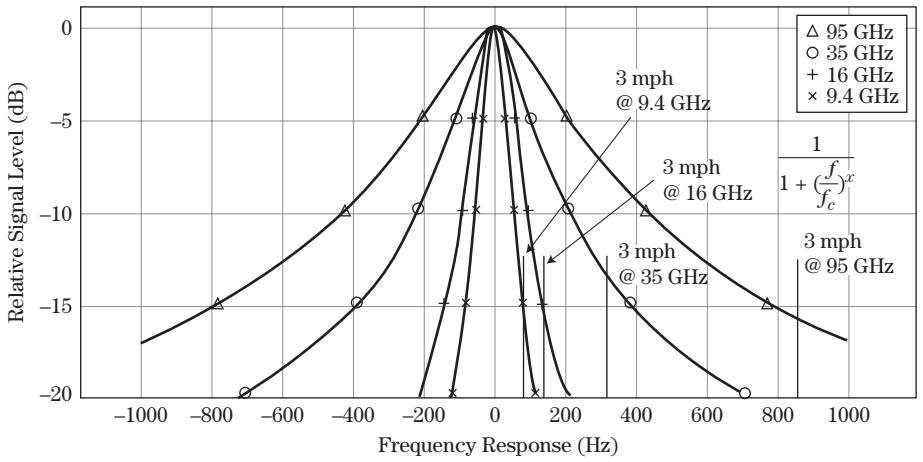

FIGURE 5-36 ■ Rain spectral response for four frequencies compared with a 3 mph moving target. (From Hayes [35]. With permission.)

circumference-to-wavelength ratio approaches unity, significant differences in reflectivity can be observed at higher frequencies. The dependence of rain reflectivity on rain rate at 70 and 95 GHz in Figure 5-33 is one example.

Table 5-9 compares the circumference-to-wavelength ratios of different natural and man-made objects at 35 through 300 GHz. As the ratio approaches 1 or larger unusual reflectivity effects will be observed. From the table it can be seen that this can occur for many types of common scatterers.

As an example of unusual effects at millimeter waves, Figure 5-37 shows the radar reflectivity of snow-covered ground at 35 GHz as a function of time of day. The air temperature was below freezing at the start of the measurement but rose above freezing between 8 a.m. and 8:15 a.m. As can be seen, the reflectivity of the snow dropped about 10 dB in 45 minutes. The temperature continued to hover around freezing, and the reflectivity varied depending on whether the temperature fell below or rose above freezing. This phenomenon has been observed at lower frequencies, but the effect was much smaller. The current theory is that when snow melts and refreezes, large resonant crystals form that reflect RF energy back to the radar, whereas, when melting occurs, surface water prevents

TABLE 5-9 ■ Comparison of the Circumference in Wavelengths of Different Natural and Man-made Items

		Ratio of Diameter to Wavelength (a/λ)			
Scatterer	Diameter (mm)	35 GHz	95 GHz	140 GHz	300 GHz
Raindrops	0.2–6	0.02–0.7	0.6–2	0.09–2.8	0.2–6
Sea Spray	0.2–10	0.02–1.15	0.6–3.3	0.09–4.7	0.2–6
Pine Needles	0.5–1.5	0.057–0.171	0.167–0.5	0.23–0.7	0.5–1.5
Screw Heads	1.5-25	0.17–2.9	0.5–8.3	0.7–11.7	1.5–25
Rivets	10	1.15	3.3	4.7	10
Grass Blades	2–8	0.23–0.92	0.7–2.7	0.93–3.7	2–8
Deciduous Leaves	6–20	0.7–2.31	2.0–6.7	2.8–9.4	6–20
Branches	5–76	0.7–8.78	2.0–25	2.8–35.5	6–76
Snow Crystals	5–50	0.58–5.77	1.7–16	2.3–23.3	5–50
Hail	1–10	0.12–1.15	0.3–3.3	0.47–4.7	1–10

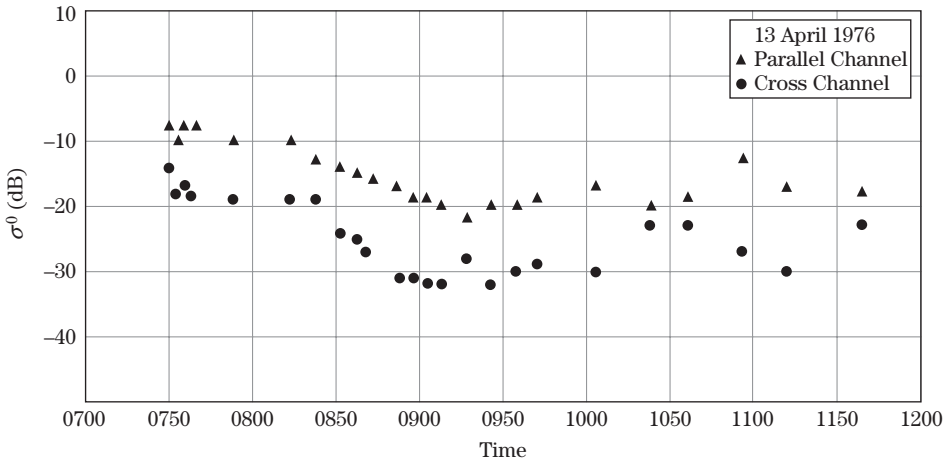

FIGURE 5-37 ■ Snow-covered ground reflectivity at 35 GHz as a function of time of day. (From Currie et al. [36]. With permission.)

penetration into the snow layers to forward scatter more of the energy. The key point of this discussion is that the radar designer must be aware of possible unusual scattering effects as the frequency increases into the millimeter wave region.

5.3 CLUTTER MODELING

5.3.1 General Approaches for Estimating Detection Performance in Clutter

Although a great deal of effort has been expended in developing theoretical models for clutter, most of these models have severe limitations because of the complexity of the real world. As a result, most radar designers either develop their own empirical models from clutter data or use models from the literature to estimate radar performance in clutter. For readers interested in pursuing theoretical modeling, several references are presented at the end of this chapter. The remainder of this section presents some empirical models that have been proven to be of use over the years.

5.3.2 Clutter Models

5.3.2.1 Surface Clutter

In the late 1970's GTRI developed an open literature empirical model for the reflectivity σ^0 of varying types of land clutter for grazing angles in the low angle and plateau regions [36]. In the 1980s this model was extended to higher frequencies, and additional data were used to refine the model [37]. The model takes into account wavelength, rms surface roughness, and grazing angle and has the form

$$\sigma^0 = A(\delta + C)^B \exp\left[\frac{-D}{1 + \dfrac{0.1\sigma_h}{\lambda}}\right] \tag{5.30}$$

TABLE 5-10 ■ Coefficients for GTRI Empirical Model

Constant	Frequency	Soil/ Sand	Grass	Tall Grass Crops	Trees	Urban	Wet Snow	Dry Snow
	3	0.0045	0.0071	0.0071	0.00054	0.362	—	—
	5	0.0096	0.015	0.015	0.0012	0.779	—	—
A	10	0.25	0.023	0.006	0.002	2.0	0.0246	0.195
	15	0.05	0.079	0.079	0.019	2.0	—	—
	35	—	0.125	0.301	0.036	—	0.195	2.45
	95	—	—	—	3.6	—	1.138	3.6
	3	0.83	1.5	1.5	0.64	1.8	—	—
	5	0.83	1.5	1.5	0.64	1.8	—	—
B	10	0.83	1.5	1.5	0.64	1.8	1.7	1.7
	15	0.83	1.5	1.5	0.64	1.8	—	—
	35	—	1.5	1.5	0.64	—	1.7	1.7
	95	—	1.5	1.5	0.64	—	0.83	0.83
	3	0.0013	0.012	0.012	0.002	0.015	—	—
	5	0.0013	0.012	0.012	0.002	0.015	—	—
C	10	0.0013	0.012	0.012	0.002	0.015	0.0016	0.0016
	15	0.0013	0.012	0.012	0.002	0.015	—	—
	35	—	0.012	0.012	0.012	—	0.008	0.0016
	95	—	0.012	0.012	0.012	—	0.008	0.0016
	3	2.3	0.0	0.0	0.0	0.0	—	—
	5	2.3	0.0	0.0	0.0	0.0	—	—
D	10	2.3	0.0	0.0	0.0	0.0	0.0	0.0
	15	2.3	0.0	0.0	0.0	0.0	—	—
	35	—	0.0	0.0	0.0	—	0.0	0.0
	95	—	0.0	0.0	0.0	—	0.0	0.0

Source: From Currie [32] (with permission).

where δ is the grazing angle in radians, σ_h is the rms surface roughness, and A, B, C, and D are empirically derived constants.

Table 5-10 gives the values for A, B, C, and D for frequencies of 3 through 95 GHz for several types of clutter. Figure 5-38 shows the model output for trees at X-band plotted against some GTRI data on tree reflectivity. Note that the model prediction appears a little high when compared to the data since the model attempts to predict an average of both temporal and spatial variations. This model has not been updated to reflect the low angle data reported by Billingsley [11].

Although several empirical models have been developed for sea return, the GTRI model has been one of the more popular ones used, particularly for low angles. The model is based on many years of radar data collection at a test site near Boca Raton, Florida. The model predicts average sea clutter values as a function of polarization, wavelength, grazing angle, radar boresight-wind direction, average wave height, and wind speed. Table 5-11 summarizes the equations for the model.

The definitions of variables are as follows:

- λ is the radar wavelength.
- δ is the grazing angle.

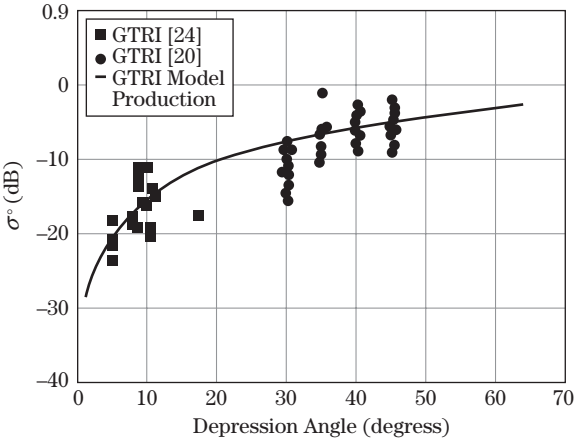

FIGURE 5-38 ■ Comparison of GTRI model output with data for deciduous trees at X-band. (From Currie [32]. With permission.)

- ϕ is the angle between radar boresight and wind direction.
- h_{av} is the average wave height.
- A_i is the "interference factor," which takes into account rms surface roughness and multipath.
- A_u is the upwind/downwind factor.
- A_w is the wind speed factor.

Figure 5-39 gives a sample output of the model. Shown is the value of σ^0 as a function of bore sight-upwind direction for three frequencies. (The model assumes that the wind and waves are proceeding in the same direction.) Note that after the original 1 to 10 GHz sea clutter model was developed, a second model was developed for 10 to 100 GHz [38].

TABLE 5-11 ■ GTRI Sea Clutter Model Equations

$\sigma^0_{HH} = 10\log[3.9 \times 10^{-6}\lambda\delta^{0.4}A_i A_u A_w]$
For 1 to 3 GHz $\sigma^0_{VV} = \sigma^0_{HH} - 1.73\ln(h_{av} + 0.015) + 3.76\ln(\lambda) + 2.46\ln(\delta + 0.0001) + 222$
For 3 to 10 GHz $\sigma^0_{VV} = \sigma^0_{HH} - 1.05\ln(h_{av} + 0.015) + 1.09\ln(\lambda) + 1.27\ln(\delta + 0.0001) + 9.70$
$\sigma_\phi = (14.4\lambda + 5.5)\delta h_{av}/\lambda$
$A_i = \sigma_\phi^4\left(1 + \sigma_\phi^4\right)$
$A_u = \exp\left[0.2\cos\phi(1 - 2.8\delta)(\lambda + 0.015)^{-0.4}\right]$
$qw = 1.1/(\lambda + 0.015)^{-0.4}$
$V_w = 8.67h_{av}^{0.4}$
$A_w = [1.94V_w/(1 + V_w/15.4)]^{qw}$

Note: Values for h_{av} and λ are given in meters, δ and ϕ are in radians.
Source: From Horst et al. [39] (with permission).

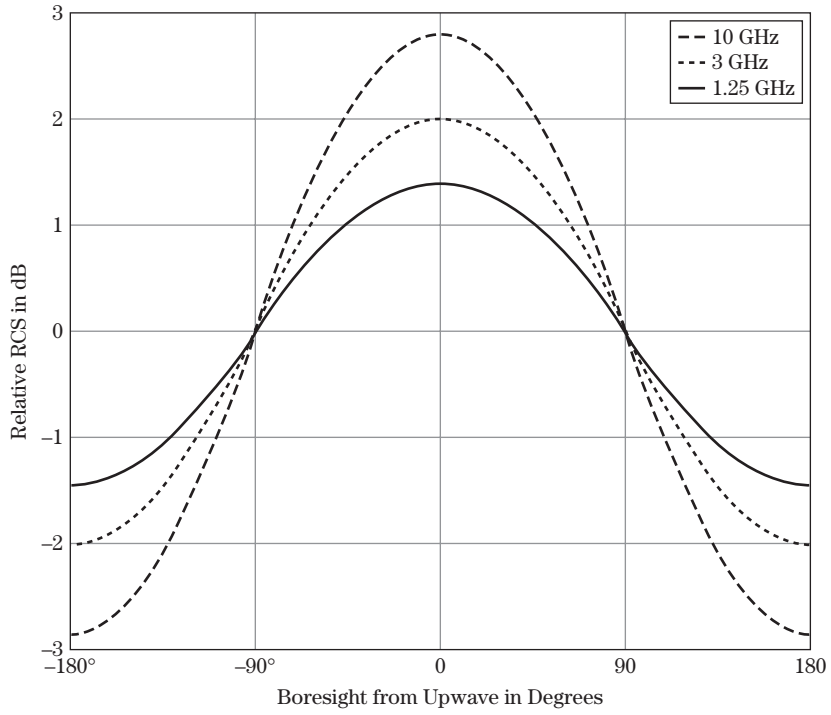

FIGURE 5-39 ■ GTRI sea clutter model output for three frequencies at 1° grazing angle. (From Long [6]. With permission.)

Unfortunately, the experimenters used a different X-band data set from that used for the original model development so that the results of the two models do not agree at 10 GHz. Some users that need to model sea return over the entire frequency range average the results from the two models at 10 GHz.

5.3.2.2 Atmospheric Clutter Models

The equations for the least squares fit to rain data presented in Figure 5-33 are presented in Table 5-12. The equations have the form

$$\eta = AR^B \text{ m}^{-1} \tag{5.31}$$

where η is the radar cross section per unit volume, and A and B are constants given in Table 5-12. Note that significant variability in the data occurred around the calculated least squares fits.

TABLE 5-12 ■ Model Coefficients for Rain

Frequency (GHz)	A	B
9.4	1.3×10^{-8}	1.6
35	1.2×10^{-6}	1.6
70	4.2×10^{-5}	1.1
95	1.5×10^{-5}	1.0

Source: From Currie et al. [34] (with permission).

5.4 CONCLUDING REMARKS

This chapter defined the required terminology for dealing with radar clutter; discussed the average, temporal, and spatial properties of clutter; and introduced some empirical models for clutter. In no way should this discussion be considered as comprehensive in nature. Dozens of books have been written on this topic from both theoretical and empirical points of view. Some of these books are listed in Section 5.4.2. The next section provides a summary of average clutter data taken from the sources discussed previously.

5.4.1 Reflectivity Summary

Table 5-13 gives some average values for land clutter as a function of aspect angle that are plotted in Figures 5-13 through 5-16, which were adapted from Nathanson [15]. Table 5-14 summarizes average values for sea clutter as a function of polarization and depression angle which were plotted in Figures 5-20 through 5-22, again adapted from Nathanson. These data reflect the general trends discussed previously but omit any dependence on wind direction, a weakness corrected by the GTRI model of Table 5-11.

Table 5-8 given previously summarizes average values for rain return as a function of frequency and rain rate, again, taken from Nathanson [15].

The temporal and spatial variations of land clutter were best represented by Weibull distributions. The width parameters (standard deviation or Weibull width parameter) for land clutter were given in Tables 5-4 and 5-7. Spectral bandwidth and roll-off characteristics for wind-blown trees were presented in Table 5-6. Rain spectral constants were presented in Figure 5-35.

TABLE 5-13 ■ Summary of Averaged Land Reflectivity (σ^0 in db)

		Grazing Angle (Deg.)			
Clutter Type	Frequency Band	1.5	10	30	60
Desert	L	−45	−38	−28	−21
	S	−46	−36	−25	−17
	C	−40	−33	−23	−16
	X	−40	−30	−21	−14
	K_u		−28	−19	−13
Farmland	L	−36	−30	−20	−15
	S	−34	−28	−18	−16
	C	−33	−26	−16	−15
	X	−33	−26	−16	−14
	K_u	−23	−22	−16	−13
Woods	L	−28	−26	−18	−19
	S	−28	−24	−16	−15
	C	−27	−23	−16	−15
	X	−26	−23	−14	−14
	K_u	−13	−20	−14	−12
Urban	L	−25	−18	−15	−12
	S	−23	−18	−13	−11
	C	−21	−18	−11	−10
	X	−20	−16	−10	−10
	K_u				

TABLE 5-14 ■ Summary of Averaged Sea Reflectivity (σ^0 in db)

			Grazing Angle (Deg.)			
Sea State	Frequency Band	Polarization	0.1	10	30	60
1	L	VV		−39	−38	−22
	L	HH		−56	−46	−24
	S	VV	−80	−40	−40	−24
	S	HH	−80			−25
	C	VV	−72	−41	−42	−24
	C	HH	−75	−53	−48	−26
	X	VV	−65	−42	−36	−24
	X	HH	−71	−51	−44	−24
	K_u	VV		−40	−31	−20
	K_u	HH			−38	−20
3	L	VV	−82	−34	−30	−18
	L	HH	−82	−48	−39	−20
	S	VV	−75	−34	−29	−19
	S	HH	−68	−46	−38	−20
	C	VV	−60	−34	−28	−18
	C	HH	−69	−40	−37	−20
	X	VV	−51	−32	−26	−16
	X	HH	−53	−37	−34	−21
	K_u	VV		−31	−23	−14
	K_u	HH		−32	−28	−16

5.4.2 Clutter Effect on Detection

This chapter has summarized the clutter characteristics and provided clutter data and modeling for simulating clutter. Clutter limits detection of targets due to its competing signal, which interferes with the target signal. Methods for dealing with these problems using Doppler processing are discussed in Chapter 17.

5.5 FURTHER READING

Perhaps the two best comprehensive references for understanding radar clutter are the texts by Long [6] and Ulaby and Dobson [10]. Both combine in-depth discussion of clutter phenomenology and modeling with extensive summaries of real-world clutter measurements. Ward et al. concentrate on sea clutter measurements and modeling with the K-distribution in [25].

More extensive theoretical analyses are given for sea clutter by Ward et al. in [25] and for various clutter sources in [40–43]. An in-depth analysis of land clutter data is given by Billingsley [11]. Other good reviews of land and sea clutter data can be found in [15,40–43].

Most of the preceding sources are concerned with radar clutter at microwave frequencies. Additional discussion of millimeter-wave clutter data is available in the publications by Currie and various colleagues [34,44,45].

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5.7 PROBLEMS

1. A radar has a pulse length of $\tau = 10\ \mu$s, an azimuth beamwidth $\theta_3 = 3^\circ$, and an elevation beamwidth $\phi_3 = 3^\circ$. At what grazing angle δ does the transition occur between the pulse-limited and beam-limited ground clutter cases when the nominal range to the ground is $R = 10$ km? Repeat for $R = 50$ km.

2. For the same radar used in problem 1, what is the volume V in cubic meters of a volume clutter resolution cell at $R = 10$ km? Repeat for $R = 50$ km.

3. A radar is attempting to detect a point target in the presence of ground clutter. The parameters of the radar and its environment are such that the SNR at a range of $R_0 = 10$ km is 30 dB, while the SCR at the same range is 20 dB. The detection performance at this range is "clutter limited" because the clutter is the dominant interference. Assuming pulse-limited clutter interference, at what range will the SNR and SCR be equal? (At ranges longer than this, the detection performance for this target will be "noise limited.")

4. Consider two radar targets with polarization scattering matrices $\mathbf{S}_1$ and $\mathbf{S}_2$ as follows:

$$\mathbf{S}_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{S}_2 = \begin{bmatrix} 1 & j \\ -j & -1 \end{bmatrix}$$

where $j = \sqrt{-1}$. Compute the parallel/cross-polarization ratio and the vertical/horizontal polarization ratio for each target. Which ratio could be used to discriminate between the two targets?

5. Compute the critical grazing angle for an X-band (10 GHz) radar when the surface roughness σ_h is 1.0 cm, and again when $\sigma_h = 10.0$ cm. Repeat for an L-band (1 GHz) radar and a K-band (35 GHz) radar.

6. Compute the diameter of a conducting sphere at the boundary between the Rayleigh and resonance regions at a radar frequency of 5 GHz (C-band). Repeat for the boundary between the resonance and optics regions.

7. Show that the Weibull distribution reduces to the exponential distribution when $b = 1$, and to the Rayleigh distribution when $b = 2$.

8. A radar collects $N_t = 30$ samples of clutter data having a decorrelation time τ_0 of 1 ms. What is the number of uncorrelated samples N_i if the PRF is 1 kHz? Repeat for PRF = 5 kHz and 40 kHz.

9. Consider the GTRI model for land clutter reflectivity given by equation (5.30). Show that the model predicts that σ^0 becomes independent of surface roughness when $\sigma_h \ll 10\lambda$.

10. Use equations (5.28) and (5.29) to confirm that a reflectivity $\eta = -92$ dB corresponds to a meteorological reflectivity of 23 dBz at S-band (3 GHz) as shown in Table 5-8.

Index

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Raleigh, North Carolina
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ISBN 978-1891121-52-4
9 781891 121524