MICROWAVE REMOTE SENSING
ACTIVE AND PASSIVE

Volume II

Radar Remote Sensing and Surface Scattering and Emission Theory

Fawwaz T. Ulaby
Richard K. Moore
Adrian K. Fung

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Editor's Foreword

This volume is one of a series on remote sensing subjects which will be issued in the Addison-Wesley Advanced Book Program. The series is designed to cover remote sensing subjects with the breadth and depth required for use by students in graduate level courses and at the same time to serve as general reference texts for remote sensing engineering and applications scientists. The areas to be covered include theory and techniques, modeling, instruments, and applications.

The first volume, by Dr. Philip N. Slater of the Committee on Remote Sensing and Optical Sciences Center at the University of Arizona, dealt with remote sensing optics and optical systems, an area in which Dr. Slater has published extensively and has established international recognition.

The present volume will be one of three on active and passive microwave remote sensing, by Professors Fawwaz T. Ulaby, Richard K. Moore, and Adrian K. Fung of the University of Kansas. These authors have made important contributions to microwave theory, instrumentation, and practical applications from the earliest days of remote sensing in the United States, as these three volumes amply demonstrate.

It is an especial pleasure to acknowledge that each of these authors has been a patient mentor to me, and that I have learned much from them. A large number of the radar remote sensing engineers and applications scientists in the United States and throughout the world have been trained by them. A list of their engineering Ph.D. students now reads like an international Who's Who—from Korea to Thailand, Canada to Chile, Western Europe to Australia, as well as the United States. The scientists who have visited their Remote Sensing Laboratory over the last two decades have quite literally come from all over the world, and the range of their questions and interests has served to stimulate the already catholic research concerns of the group at Kansas. The extent of their teaching interests and experience, and their international experience, is reflected in this volume in the clear exposition of these experienced teachers and scientists. I commend the volumes in this series to you, and look forward to using them with my own students.

DAVID S. SIMONETT

Preface

Over the past two decades, *microwave remote sensing* has evolved into an important tool for monitoring the atmospheres and surfaces of planetary objects, with special emphasis on observations of the planet earth. The term "microwave remote sensing" encompasses the physics of radiowave propagation in and interaction with material media, including surface and volume scattering and emission; the techniques used for designing microwave sensors and processing the data they acquire; and the translation of the measured data into information about the temporal or spatial variation of atmospheric or surface and medium parameters or properties. Sensors usually are divided into two groups according to their modes of operation: *active* sensors are those that provide their own source of illumination and therefore contain a transmitter and a receiver, while *passive* sensors are simply receivers that measure the radiation emanating from the scene under observation. Active microwave sensors include *radar imagers*, *scatterometers*, and *altimeters*, and passive microwave sensors are often referred to as *microwave radiometers*.

Aside from their traditional meteorological and military applications, radars have been used extensively for mapping geological structures and features, particularly in those parts of the world where cloud cover presents a serious problem to optical sensors. Other application areas, some demonstrated and others still in the research phase, include vegetation mapping, discrimination of sea-ice types, measuring ocean wind speed and direction, mapping soil moisture content and snow water content, and land-use evaluations. Microwave radiometers have been used from satellite platforms to retrieve the atmospheric temperature and water vapor density over the oceans, to estimate the liquid-water content of clouds and to discriminate between different types of sea ice as an aid to navigation in arctic waters. Other potential applications which are still in the research phase include the monitoring of the spatial distribution of soil moisture content and snow water content, which are important factors in agriculture, hydrology, and meteorology.

The three components of microwave remote sensing—sensor-scene interaction, sensor design and measurement techniques, and the application of microwave remote sensing in geoscience—are the subject of this book. It should be emphasized, however, that the book is written from the standpoint of the physicist or engineer working in microwave remote sensing, rather than from the standpoint of the ultimate user, such as the geologist or hydrologist. We have attempted to establish the link, based on current knowledge, between the microwave sensor response and scene parameters such as soil moisture content, through intermediary parameters like the physical temperature and dielectric properties of the scene. The next step, which usually involves the incorporation of remotely sensed data into appropriate models, or the use of the data in conjunction with other sources of information, is outside the scope of this book. For example, we shall discuss how radar is used to map linear geological features, but the methodology involving the use of such information by the geologist, as one of several inputs, for delineating mineral and petroleum exploration sites, will not be covered.

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The material covered in this book is divided into three volumes. Volume I, *Microwave Remote Sensing Fundamentals and Radiometry*, starts out with an introductory chapter on the history and applications of active and passive microwave remote sensing, followed by introductory treatments of electromagnetic wave propagation (Chapter 2), antennas (Chapter 3), and microwave interaction with atmospheric constituents (Chapter 5). These three chapters are intended to provide a review of those fundamental aspects of remote sensing that are common to all types of microwave sensors. The major topic of Volume I is microwave radiometry, which is treated in Chapters 4 and 6 and the latter part of Chapter 5. Chapter 4 begins by introducing radiometric concepts and quantities of interest, and then proceeds to treat the radiometric measurement problem for atmospheric and terrestrial sources of natural radiation. Emission by atmospheric gases, clouds, and rain is covered in Chapter 5 using the radiative-transfer formulations developed earlier in Chapter 4. Chapter 6 discusses the operation and performance characteristics of radiometer receivers, with special emphasis given to measurement precision, calibration techniques, and imaging considerations.

Volume II, *Radar Remote Sensing and Surface Scattering and Emission Theory*, consists of Chapters 7–12. The fundamental principles of radar backscattering measurements are covered in Chapter 7, which include measurement statistics, angle, Doppler and pulse discrimination techniques, and associated ambiguity functions. Chapters 8 and 9 describe the operation of real-aperture and synthetic-aperture sidelooking airborne radar systems, respectively, and Chapter 10 focuses on internal and external calibration techniques employed in scattering measurements.

Approaches used for modeling microwave interaction with material media are covered in Chapters 11–13. The primary purpose of Chapter 11 is to help the reader develop a "feel" for the physical mechanisms responsible for the scattering and emission behavior of homogeneous and inhomogeneous media. This is done through discussions of specific factors governing the scattering and emission (such as surface roughness, dielectric properties, penetration depth and dielectric inhomogeneity): and through the presentation of simple semi-empirical models. Theoretical models involving a higher degree of mathematical sophistication are developed in Chapters 12 and 13, with Chapter 12 being limited to treatments of extended surfaces (as for the ocean and bare soil), while Chapter 13 (of Volume III) considers scattering and emission models for the more general case of a layer of volume scatterers (as in a vegetation canopy) over a rough surface.

As suggested by its title, *Volume Scattering and Emission Theory, Advanced Systems, and Applications*, Volume III contains a chapter devoted to volume scattering and emission (Chapter 13), two chapters on the system configurations and applications of scatterometers (Chapter 14) and altimeters (Chapter 15), a chapter on synthetic-aperture radar (SAR) processing techniques (Chapter 16), and five chapters on active and passive microwave remote-sensing applications. In addition, Volume III includes a special appendix containing a summary of the dielectric properties of several types of material media, including fresh and saline water, pure and sea ice, snow, soils, and vegetation.

The three-volume combination is intended as a graduate-level, three-semester course sequence in microwave remote sensing, although the organization of the book is such that, through the appropriate selection of relevant chapters, the book may be narrowed in scope to cover one-semester courses in specific subjects, such as active microwave systems, microwave radiometry, scattering and emission theories, or microwave remote-sensing applications. Additionally, this book is intended to serve

remote-sensing engineers and scientists as a reference guide to those aspects of the remote-sensing process that pertain to the microwave part of the electromagnetic spectrum.

The authors wish to acknowledge the help and support of the many people who have contributed to the development of this book. Thanks are due to the agencies that have supported our research activities, especially the National Aeronautics and Space Administration, the National Science Foundation, and the Department of Defense. We wish to give special thanks to our students, who have suffered through several semesters of having a text in note form and who have provided many suggestions for improving and clarifying the presentation. We are also grateful to Vera Sehon and her colleagues of the Graphic Arts Service at the University of Kansas Center for Research, Inc., for the artwork and photographic processing associated with this book—with special recognition going to Ricky Nigus, who was the primary graphic artist on this project.

Above all, we wish to thank our secretaries, Lee Blackledge, Julie Banhart, and Kathy Brinkman, for typing this manuscript, for polishing its prose and syntax, and for their patience throughout this task.

FAWWAZ T. ULABY
RICHARD K. MOORE
ADRIAN K. FUNG

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Chapter 7

Measurement and Discrimination

In microwave remote sensing the distinction between different subjects sensed, usually areas on the ground, is primarily caused by the difference in the signal strength received by the radar or radiometer. Hence, the measurement of received signal strength is the most important measurement in remote-sensing devices. This characteristic of remote-sensing microwave instruments is different from the typical radar or radiometer used for other purposes, where a measurement of position is often the most important characteristic of the system, and measurement of the amplitude of the signal is unimportant.

Measurements of position represent discrimination for the microwave remote sensor because the amplitudes of the signals received from different areas must be discriminated from each other. The methods to distinguish among different areas on the ground generally amount to measurements of angle, distance, or speed. Speed measurement actually is used in microwave remote sensing as a measurement of distance on the ground. Similarly, angle measurement is used to discriminate a region on the ground in that the angle from the axis of the sensor differs for different points on the ground.

The measurement of amplitude is highly dependent upon the statistics of the received signals. Both for radars and for radiometers, the usual signal has a fading characteristic like that of noise. In the case of the radiometer this comes about because the signal source itself is noiselike. In the case of an airborne radar, it comes about because the Doppler frequency shift associated with each point scatterer on the ground is different. This results in a signal made up of many sine waves of different frequencies—a model often used for noise. The primary difference between the noiselike signals for the radiometer and radar is that the bandwidth of the radiometer signal is very great (tens or hundreds of MHz), whereas the Doppler bandwidth for the radar is much smaller and typically does not exceed a few kHz.

7-1 THE RADAR EQUATION

The fundamental relation between the characteristics of the radar, the target, and the received signal is called the *radar equation*. The geometry of scattering

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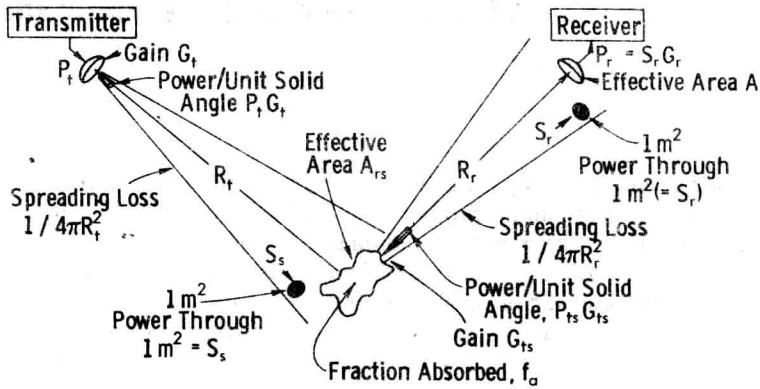

Fig. 7.1 Geometry of and quantities involved in the radar equation.

from an isolated radar target (scatterer) is shown in Fig. 7.1, along with the parameters that are involved in the radar equation.

When a power P_t is transmitted by an antenna with gain G_t, the power per unit solid angle in the direction of the scatterer is P_tG_t, where the value of G_t in that direction is used. At the scatterer,

$$\begin{pmatrix} \text{power/} \\ \text{unit area} \\ \text{incident on} \\ \text{scatterer} \end{pmatrix} = \begin{pmatrix} \text{power} \\ \text{transmitted} \\ \text{toward} \\ \text{scatterer} \end{pmatrix} \begin{pmatrix} \text{spreading} \\ \text{loss} \end{pmatrix}, \qquad S_s = (P_tG_t)\left(\frac{1}{4\pi R^2}\right), \tag{7.1}$$

where S_s is the value of the Poynting vector (power density) at the scatterer. The *spreading loss* $1/4\pi R^2$ is the reduction in power density associated with spreading of the power over a sphere of radius R surrounding the antenna.

To obtain the total power intercepted by the scatterer, the power density must be multiplied by the effective receiving area of the scatterer:

$$\begin{pmatrix} \text{power} \\ \text{intercepted} \\ \text{by} \\ \text{scatterer} \end{pmatrix} = \begin{pmatrix} \text{incident} \\ \text{power/} \\ \text{unit area} \end{pmatrix} \begin{pmatrix} \text{effective} \\ \text{receiving} \\ \text{area of} \\ \text{scatterer} \end{pmatrix}, \qquad P_{rs} = S_sA_{rs}. \tag{7.2}$$

Note that the effective area A_{rs} is not the actual area of the incident beam intercepted by the scatterer, but rather is the *effective* area; i.e., it is that area of the incident beam from which all power would be removed if one assumed that the power going through all the rest of the beam continued uninterrupted. The actual value of A_{rs} depends on the effectiveness of the scatterer as a receiving antenna.

Some of the power received by the scatterer is absorbed in losses in the scatterer unless it is a perfect conductor or a perfect insulator; the rest is reradiated in various directions. The fraction absorbed is f_a, so the fraction reradiated is $1-f_a$, and the total reradiated power is

$$\begin{pmatrix}\text{power}\\ \text{reradiated}\\ \text{by}\\ \text{scatterer}\end{pmatrix} = \begin{pmatrix}\text{power}\\ \text{intercepted}\\ \text{by}\\ \text{scatterer}\end{pmatrix}\begin{pmatrix}\text{fraction of}\\ \text{intercepted}\\ \text{power not}\\ \text{absorbed}\end{pmatrix}, \quad P_{ts} = P_{rs}(1-f_a). \tag{7.3}$$

The conduction and displacement currents that flow in the scatterer result in reradiation that has a pattern (like an antenna pattern); this situation is illustrated in Fig. 7.2. Note that the effective receiving area of the scatterer is a function of its orientation relative to the incoming beam, so that A_{rs} in (7.2) is understood to apply only for the direction of the incoming beam. The reradiation pattern may not be the same as the pattern of A_{rs}, and the gain in the direction of the receiver is the relevant value in the reradiation pattern. Thus,

$$\begin{pmatrix}\text{power/}\\ \text{unit area}\\ \text{at}\\ \text{receiver}\end{pmatrix} = \begin{pmatrix}\text{power}\\ \text{reradiated}\\ \text{by}\\ \text{scatterer}\end{pmatrix}\begin{pmatrix}\text{gain}\\ \text{toward}\\ \text{receiver}\end{pmatrix}\begin{pmatrix}\text{spreading}\\ \text{factor}\end{pmatrix},$$

$$S_r = P_{ts}G_{ts}\frac{1}{4\pi R_r^2}, \tag{7.4}$$

where P_{ts} is the total reradiated power, G_{ts} is the gain of the scatterer in the direction of the receiver, and $1/4\pi R_r^2$ is the spreading factor for the reradiation. Note that a major difference between a communication link and radar scattering is that the communication link has only one spreading factor, whereas the radar has two. Thus, if $R_r = R_t$, the total distance is $2R_t$; for a communication link with this distance, the spreading factor is only $\frac{1}{4}(1/4\pi R_t^2)$.

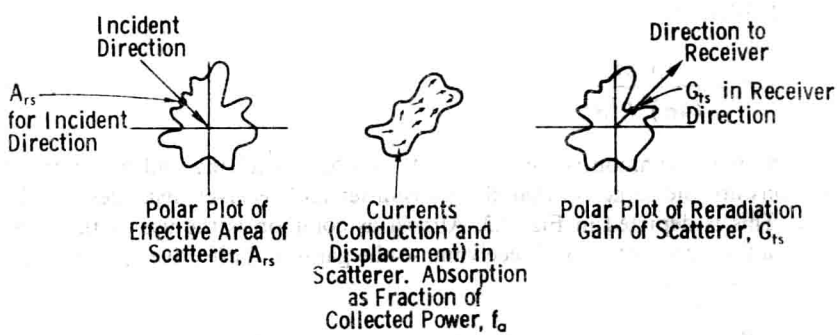

Fig. 7.2 Receiving, absorbing, and reradiating properties of scatterer.

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