

**MICROWAVE REMOTE SENSING**  
**ACTIVE AND PASSIVE**

Volume I

Microwave Remote Sensing  
Fundamentals and Radiometry

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

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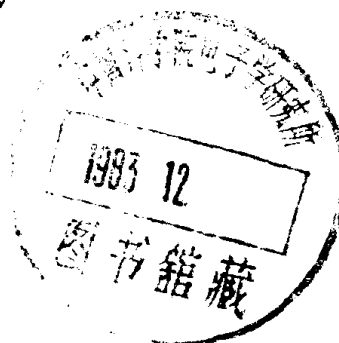
# MICROWAVE REMOTE SENSING ACTIVE AND PASSIVE

Volume I

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**Fawwaz T. Ulaby**  
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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.

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 Schon 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 Debra Shoger, 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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# Introduction

## 1-1 WHY MICROWAVES FOR REMOTE SENSING?

The use of microwaves for remote sensing is fairly new, having been in application only since the early 1960s, whereas aerial photography has been used for over one hundred years and color photography for over forty years. Furthermore, the success of aerial photography, and more recently of Landsat optical images from space, is well known. Why, then, use microwaves?

This question has several answers. Perhaps the most important reasons for using microwaves are their capability to penetrate clouds—and to some extent rain—and their independence of the sun as a source of illumination. Figure 1.1 illustrates the effect of cloud on radio transmission between space and ground. Ice clouds that are dense enough to completely obscure the ground, thus precluding aerial photography, have almost no effect at any microwavelength. Water clouds have a significant effect only when the wavelength gets below 2 cm, and the effect is really strong only for wavelengths below 1 cm. Rain has a greater effect than clouds, but as shown in Fig. 1.2, this effect is negligible below about 4 cm and becomes important only for wavelengths of the order of about 2 cm when the rain is extremely intense. Even at wavelengths of 1 cm, the percentage of the earth covered with rain sufficiently intense to cause a major degradation in the performance of radar is very small indeed.

In the case of the microwave radiometer the effect is more important, and one must consider that the regions shown in Fig. 1.1 and 1.2, for which the transmission is less than about 80 percent, are effectively blocked for radiometric use. Nevertheless, the radiometer at a wavelength of 3 or 4 cm is blocked only a small fraction of the time. In fact, even at the shorter wavelengths of 1.55 and 0.81 cm, which are the respective wavelengths for the electrically scanning microwave radiometer (ESMR) on Nimbus 5 and 6, the effect of clouds is so small that maps of areas such as Greenland and Antarctica (Gloersen et al., 1974) have been produced with almost no cloud effect, whereas mapping such areas in the visible spectrum is much more difficult.

Another reason for the use of microwaves is that they are able to penetrate more deeply into vegetation than optical waves can. A pictorial illustration of

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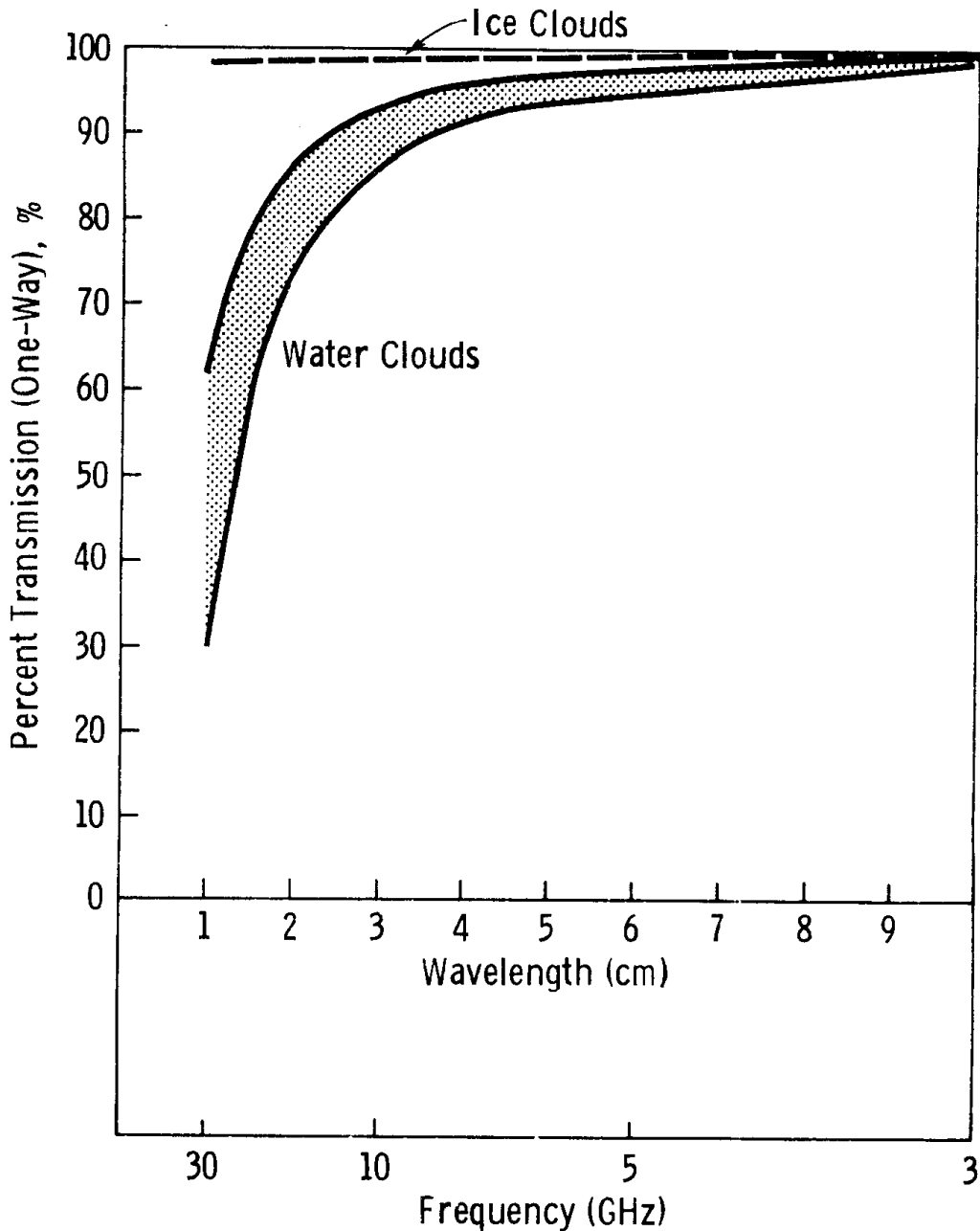


Fig. 1.1 Effect of cloud on radio transmission from space to ground.

the relation between penetration depth and wavelength is shown in Fig. 1.3. The extent of penetration into vegetation depends upon the moisture content and density of the vegetation as well as upon the wavelength of the microwaves. The longer wavelength penetrates much better than the shorter wavelength. Thus, the shorter wavelengths yield information about the upper layers of the vegetation, and the longer wavelengths yield information about the lower layers and the ground beneath. Moreover, microwaves are able to penetrate significantly into the ground itself. Figure 1.4 illustrates the depth at

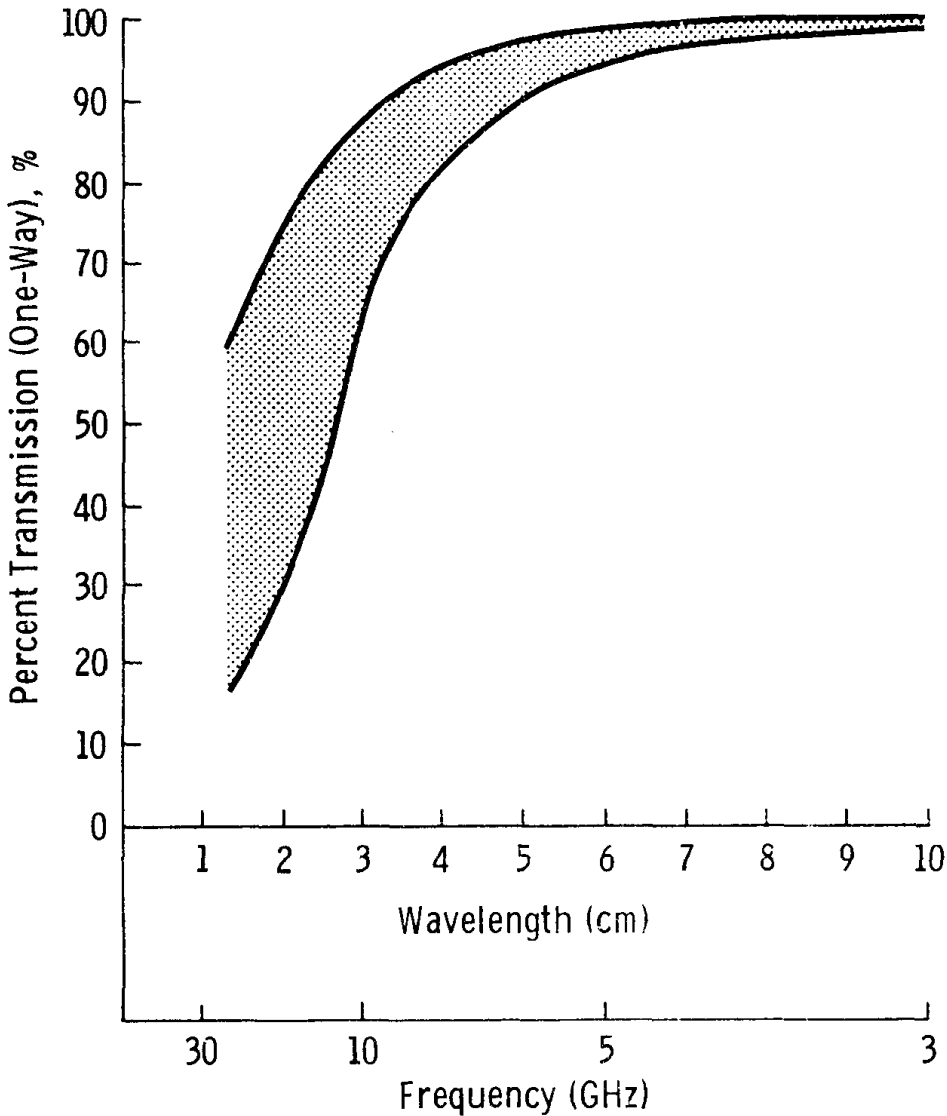
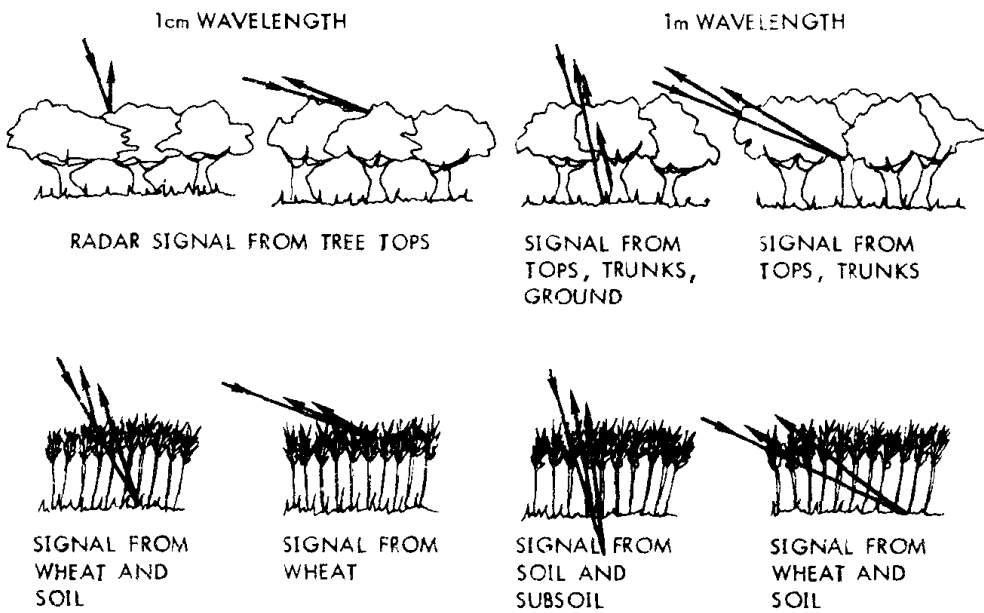


Fig. 1.2 Effect of rain on radio transmission from space to ground.

which the microwave signal decreases by 63 percent for three different frequencies and three different types of soil. Clearly, for dry soil the penetration depth at the lower microwave frequencies is rather substantial, and for wet soil the higher microwave frequencies penetrate only a centimeter or so. Nevertheless, this penetration is larger than that obtainable with visible and infrared radiation.

A third reason for the use of microwaves is simply that the information available from microwaves is different from that available in the visible and infrared regions, so that when conditions are suitable for all three regions, the sensors operating in these regions complement each other. For example, the color observed in the visible and near-infrared region is determined primarily by molecular resonances in the surface layer of the vegetation or soil, whereas



MORE PENETRATION IF VEGETATION IS DRY THAN IF WET

Fig. 1.3 Penetration of radar signals through vegetation.

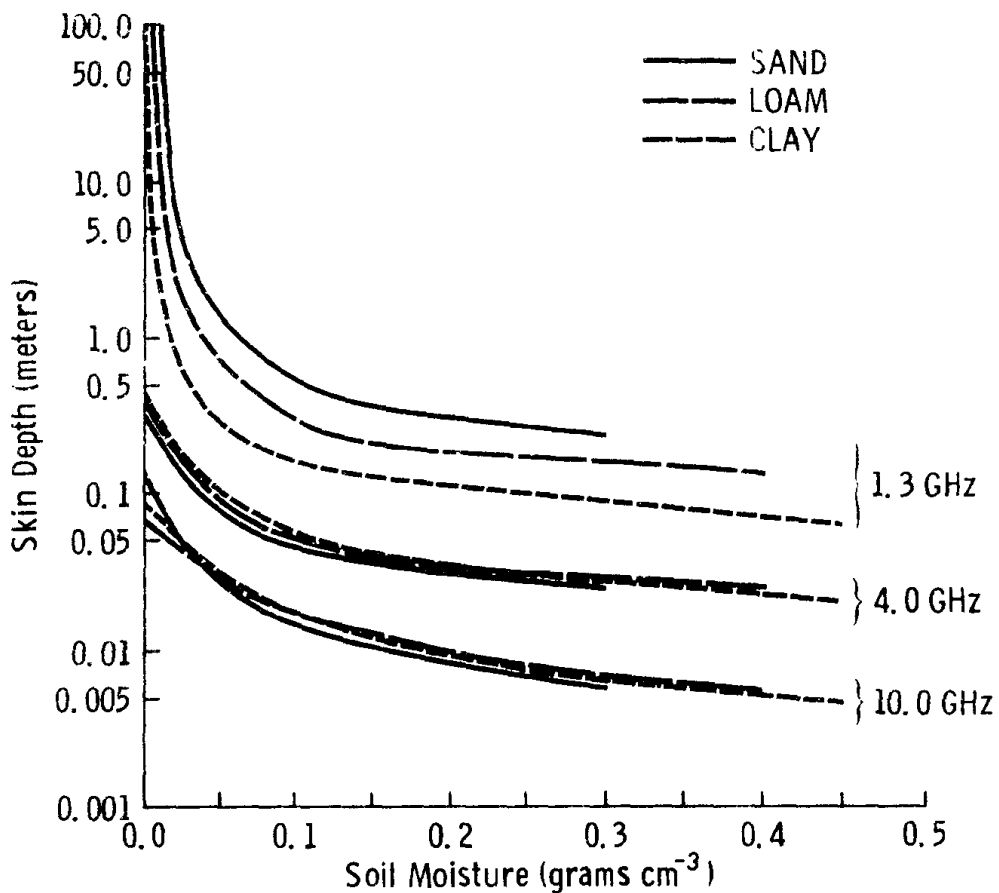


Fig. 1.4 Skin depth as a function of soil volumetric water content, frequency, and soil type (from Cihlar and Ulaby, 1974).



the “color” in the microwave region is a result of geometric and bulk-dielectric properties of the surface or volume studied. Thus, the combined use of microwaves and of visible and infrared radiation allows a study of the geometric, bulk-dielectric, and molecular-resonance properties of a surface, and either one alone is less effective than the combination of the two in delineating all the properties one may wish to sense remotely.

## 1-2 HISTORY OF MICROWAVE SENSING

### 1-2.1 Radars

The very first radio experiment was conducted at a frequency that approached the microwave range. Heinrich Hertz, in 1886, experimentally tested Maxwell’s electromagnetic theory with resonators at a frequency of about 200 MHz, which is close to the microwave spectrum. In his early tests, Hertz demonstrated that reflections could be received from various metallic and nonmetallic objects. The first demonstration of radar as a detector of ships was in 1903 by Hülsmeyer, who obtained a patent for his idea in 1904 (Hülsmeyer, 1904). Marconi (1922) also predicted the use of radio for detection, but did not develop it.

A. H. Taylor and others at the U. S. Naval Research Laboratory were pioneers in the development of radar as a tool for detecting ships and aircraft; the first experiment was conducted with a continuous-wave system in 1922 (Skolnik, 1980). The first pulse radar, however, was used in a series of interesting experiments conducted by Taylor, Breit, and Tuve in 1925 (Breit and Tuve, 1926) to measure the height of the ionosphere. They transmitted pulses from a radio station (not microwave) and, from a location a few miles distant, observed the pulses that were reflected from the ionosphere. This technique was developed further during the late 1920s, but development of pulse radars for detecting objects closer to the earth did not begin until the early 1930s (Taylor et al., 1934).

Although continuous-wave radars were tried at various times in the early 1930s, the experiment at the U. S. Naval Research Laboratory in the spring of 1934 may have been the first to use a pulse radar designed specifically to detect objects (Guerlac, n.d.). This first NRL pulse radar operated at a frequency of 60 MHz, which is not in the microwave band, but is very close to the frequency of the first synthetic-aperture imaging radar developed some 20 years later.

The first *successful* NRL pulse radar was operated in 1936, about the same time as pulse radars were developed in Great Britain under Sir Robert Watson-Watt (1957). By the time of World War II, all the major participants had pulse-radar systems developed for the purpose of locating aircraft and/or ships, although nothing comparable to today’s microwave remote-sensing radars was then in use. The wavelengths were measured in meters or decimeters, not centimeters, and most of the equipment was involved in looking up at aircraft or out at ships. Early in World War II, however, airborne radars were deployed. The first of these also operated at long wavelengths (Rowe, 1948)