Introduction to the Physics and Techniques of Remote Sensing

Second Edition

Charles Elachi
Jakob van Zyl

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The images on the cover show how complimentary information is gained with remote sensing in different parts of the electromagnetic spectrum. Both images are of the Nile River, near the Fourth Cataract in Sudan. The top image is a color infrared photograph taken from Space Shuttle Columbia in November 1995. The bottom image was acquired by the Spaceborne Imaging Radar C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) aboard Space Shuttle Endeavour in April 1994. The thick, white band in the top right of the radar image is an ancient channel of the Nile that is now buried under layers of sand. This channel cannot be seen in the infrared photograph and its existence was not known before this radar image was processed. (Courtesy of NASA/JPL-Caltech)

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To Valerie,
Joanna and Lauren (CE)
and Kalfie and Jorkie (JvZ)

Contents

Preface

The advent of the space age opened a whole new dimension in our ability to observe, study, and monitor planetary (including Earth) surfaces and atmospheres on a global and continuous scale. This led to major developments in the field of remote sensing, both in its scientific and technical aspects. In addition, recent technological developments in detectors and digital electronics opened the whole electromagnetic spectrum to be used for detecting and measuring ever finer details of the emitted and reflected waves that contain the "fingerprints" of the medium with which they interact. Spaceborne imaging spectrometers from the visible to the far infrared are being developed to acquire laboratory quality spectra for each observed surface pixel or atmospheric region, thus allowing direct identification of the surface or atmospheric composition. Multispectral polarimetric and interferometric imaging radars will provide detailed maps of the surface morphology, its motion, and the near-subsurface structure, as well as three-dimensional maps of precipitation regions in the atmosphere. Active microwave sensors are being used to monitor, on a global basis, the dynamics of the ocean: its topography, currents, near-surface wind, and polar ice. Passive and active atmospheric sounders provide detailed profiles of the atmosphere and ionosphere characteristics: temperature, pressure, wind velocity, and electron content. Large-scale multispectral imagers provide repetitive global images of the surface biomass cover and monitor our planet's environmental changes resulting from natural causes as well as from the impact of human civilization.

These capabilities are also being applied more extensively in exploring the planets in our solar system with flyby and orbiting spacecraft. All the major bodies in the solar system, with the exception of Pluto, have been visited and explored. The surface of Venus has been mapped globally by radar, and Mars has been explored with orbiters and rovers. Jupiter and Saturn, as well as their satellites, have been mapped by sophisticated orbiters.

The next decade will also see major advances in our use of spaceborne remote sensing techniques to understand the dynamics of our own planet and its environment. A number of international platforms continuously monitor our planet's surface and atmosphere using multispectral sensors, allowing us to observe long-term global and regional changes. More sophisticated systems will be deployed in the next decade to globally measure ocean salinity, soil moisture, gravity field changes, surface tectonic motion, and so on. These systems will make full use of new developments in technology, information handling, and modeling.

Remote sensing is a maturing discipline that calls on a wide range of specialties and crosses boundaries between traditional scientific and technological disciplines. Its multidisciplinary nature requires its practitioner to have a good basic knowledge in many areas of science and requires interaction with researchers in a wide range of areas such as electromagnetic theory, spectroscopy, applied physics, geology, atmospheric sciences, agronomy, oceanography, plasma physics, electrical engineering, and optical engineering.

The purpose of this text is to provide the basic scientific and engineering background for students and researchers interested in remote sensing and its applications. It addresses (1) the basic physics involved in wave–matter interactions, which is the fundamental element needed to fully interpret the data; (2) the techniques used to collect the data; and (3) the applications to which remote sensing is most successfully applied. This is done keeping in mind the broad educational background of interested readers. The text is self-comprehensive and requires the reader to have the equivalent of a junior level in physics, specifically introductory electromagnetic and quantum theory.

The text is divided into three major parts. After the introduction, Chapter 2 gives the basic properties of electromagnetic waves and their interaction with matter. Chapters 3 through 7 cover the use of remote sensing in solid (including ocean) surface studies. Each chapter covers one major part of the electromagnetic spectrum (visible/near infrared, thermal infrared, passive microwave, and active microwave, respectively). Chapters 8 through 12 cover the use of remote sensing in the study of atmospheres and ionospheres. In each chapter, the basic interaction mechanisms are covered first. This is followed by the techniques used to acquire, measure, and study the information (waves) emanating from the medium under investigation. In most cases, a specific advanced sensor flown or under development is used for illustration.

The text is generously illustrated and includes many examples of data acquired from spaceborne sensors. As a special feature, sixteen of the illustrations presented in the text are reproduced in a separate section of color plates.

This book is based on an upper undergraduate and first-year graduate course that we teach at the California Institute of Technology to a class that consists of students in electrical engineering, applied physics, geology, planetary science, astronomy, and aeronautics. It is intended to be a two-quarter course. This text is also intended to serve engineers and scientists involved in all aspects of remote sensing and its applications.

This book is a result of many years of research, teaching, and learning at Caltech and the Jet Propulsion Laboratory. Through these years, we have collaborated with a large number of scientists, engineers, and students who helped in developing the basis for the material in this book. We would like to acknowledge all of them for creating the most pleasant atmosphere for work and scientific "enjoyment." To name all of them would lead to a very long list. We would also like to acknowledge numerous researchers at JPL who were kind enough to read and provide suggestions on how to improve the text—they include M. Abrams, M. Chahine, J. Curlander, M. Freilich, D. McCleese, J. Waters and H. Nair—as well as all of our students at Caltech, who hopefully became interested enough in this field to carry the banner into the next century.

We also would like to acknowledge the secretaries and artists who typed the text of the First Edition, improved the grammar, and did the artwork, in particular, Clara Sneed, Susan Salas, and Sylvia Munoz. Of course, with the advances in "office technology" we had to type the changes for the Second Edition ourselves.

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JAKOB VAN ZYI

Pasadena, California
May 2005

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Introduction

Remote sensing is defined as the acquisition of information about an object without being in physical contact with it. Information is acquired by detecting and measuring changes that the object imposes on the surrounding field, be it an electromagnetic, acoustic, or potential. This could include an electromagnetic field emitted or reflected by the object, acoustic waves reflected or perturbed by the object, or perturbations of the surrounding gravity or magnetic potential field due to the presence of the object.

The term "remote sensing" is most commonly used in connection with electromagnetic techniques of information acquisition. These techniques cover the whole electromagnetic spectrum from low-frequency radio waves through the microwave, submillimeter, far infrared, near infrared, visible, ultraviolet, x-ray, and gamma-ray regions of the spectrum.

The advent of satellites is allowing the acquisition of global and synoptic detailed information about the planets (including the Earth) and their environments. Sensors on Earth-orbiting satellites provide information about global patterns and dynamics of clouds, surface vegetation cover and its seasonal variations, surface morphologic structures, ocean surface temperature, and near-surface wind. The rapid wide coverage capability of satellite platforms allows monitoring of rapidly changing phenomena, particularly in the atmosphere. The long duration and repetitive capability allows the observation of seasonal, annual, and longer-term changes such as polar ice cover, desert expansion, and tropical deforestation. The wide-scale synoptic coverage allows the observation and study of regional and continental-scale features such as plate boundaries and mountain chains.

Sensors on planetary probes (orbiters, flybys, surface stations, and rovers) are providing similar information about the planets and objects in the solar system. By now, all the planets in the solar system, except for Pluto, have been visited by one or more spacecraft. The comparative study of the properties of the planets is providing new insight into the formation and evolution of the solar system.

Introduction to the Physics and Techniques of Remote Sensing. By C. Elachi and J. van Zyl

1-1 TYPES AND CLASSES OF REMOTE SENSING DATA

The type of remote sensing data acquired is dependent on the type of information being sought, as well as on the size and dynamics of the object or phenomena being studied. The different types of remote sensing data and their characteristics are summarized in Table 1-1. The corresponding sensors and their role in acquiring different types of information are illustrated in Fig. 1-1.

Two-dimensional images and three-dimensional perspectives are usually required when high-resolution spatial information is needed, such as in the case of surface cover and structural mapping (Figs. 1-2, 1-3), or when a global synoptic view is instantaneously required, such as in the case of meteorological and weather observations (Fig. 1-4). Two-dimensional images can be acquired over wide regions of the electromagnetic spectrum (Fig. 1-5) and with a wide selection of spectral bandwidths. Imaging sensors are available in the microwave, infrared (IR), visible, and ultraviolet parts of the spectrum using electronic and photographic detectors. Images are acquired by using active illumination, such as radars or lasers; solar illumination, such as in the ultraviolet, visible, and near infrared;

TABLE 1-1. Types of Remote Sensing Data

Important type of information needed	Type of sensor	Examples of sensors
High spatial resolution and wide coverage	Imaging sensors, cameras	Large-format camera (1984), Seasat imaging radar (1978), Magellan radar mapper (1989), Mars Global Surveyor Camera (1996), Mars Rover Camera (2004)
High spectral resolution over limited areas or along track lines	Spectrometers, spectroradiometers	Shuttle multispectral imaging radiometer (1981), Hyperion (2000)
Limited spectral resolution with high spatial resolution	Multispectral mappers	Landsat multispectral mapper and thematic mapper (1972–1999), SPOT (1986–2002), Galileo NIMS (1989)
High spectral and spatial resolution	Imaging spectrometer	Spaceborne imaging spectrometer (1991), ASTER (1999), Hyperion (2000)
High-accuracy intensity measurement along line tracks or wide swath	Radiometers, scatterometers	Seasat (1978), ERS-1/2 (1991, 1997), NSCAT (1996), QuikSCAT (1999), SeaWinds (2002) scatterometers
High-accuracy intensity measurement with moderate imaging resolution and wide coverage	Imaging radiometers	Electronically scanned microwave radiometer (1975), SMOS (2007)
High-accuracy measurement of location and profile	Altimeters, sounders	Seasat (1978), GEOSAT (1985), TOPEX/Poseidon (1992), and Jason (2001) altimeter, Pioneer Venus orbiter radar (1979), Mars orbiter altimeter (1990)
Three-dimensional topographic mapping	Scanning altimeters and interferometers	Shuttle Radar Topography Mission (2000)

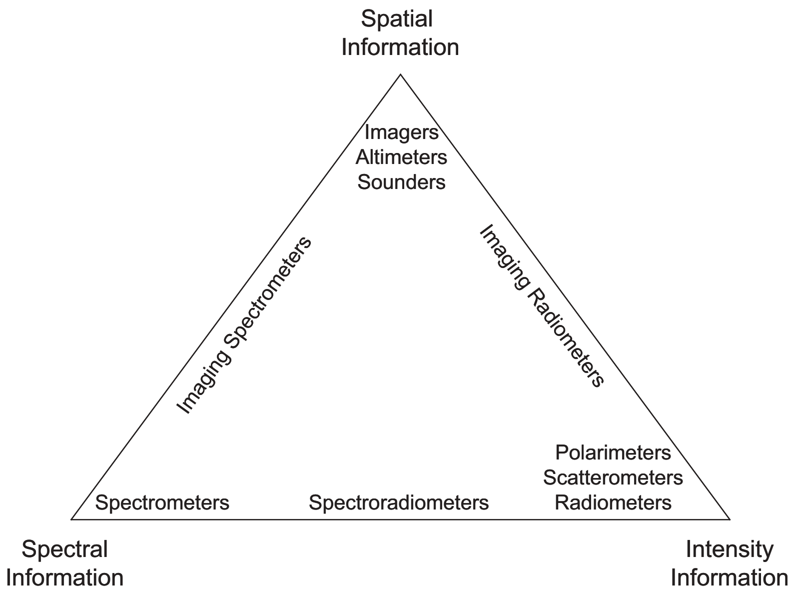

Figure 1-1. Diagram illustrating the different types of information sought after and the type of sensor used to acquire this information. For instance, spectral information is acquired with a spectrometer. Two-dimensional surface spatial information is acquired with an imager such as a camera. An imaging spectrometer also acquires data for each pixel in the image spectral information.

or emission from the surface, such as in thermal infrared, microwave emission (Fig. 1-6), and x and gamma rays.

Spectrometers are used to detect, measure, and chart the spectral content of the incident electromagnetic field (Figs. 1-7, 1-8). This type of information plays a key role in identifying the chemical composition of the object being sensed, be it a planetary surface or atmosphere. In the case of atmospheric studies, the spatial aspect is less critical than the spectral aspect due to the slow spatial variation in the chemical composition. In the case of surface studies, both spatial and spectral information are essential, leading to the need for imaging spectrometers (Figs. 1-9, 1-10). The selection of the number of spectral bands, the bandwidth of each band, the imaging spatial resolution, and the instantaneous field of view leads to trade-offs based on the object being sensed, the sensor data-handling capability, and the detector technological limits.

In a number of applications, both the spectral and spatial aspects are less important, and the information needed is contained mainly in the accurate measurement of the intensity of the electromagnetic wave over a wide spectral region. The corresponding sensors, called radiometers, are used in measuring atmospheric temperature profiles and ocean surface temperature. Imaging radiometers are used to spatially map the variation of these parameters (Fig. 1-11). In active microwave remote sensing, scatterometers are used to accurately measure the backscattered field when the surface is illuminated by a signal with a narrow spectral bandwidth (Fig. 1-12). One special type of radiometer is the polarimeter, in which the key information is embedded in the polarization state of the transmitted, reflected, or scattered wave. The polarization characteristic of reflected or scattered sunlight provides information about the physical properties of planetary atmospheres.

In a number of applications, the information required is strongly related to the three-

Figure 1-2. Landsat MSS visible/near IR image of the Imperial Valley area in California.

dimensional spatial characteristics and location of the object. In this case, altimeters and interferometric radars are used to map the surface topography (Figs. 1-13 to 1-16), and sounders are used to map subsurface structures (Fig. 1-17) or to map atmospheric parameters (such as temperature, composition, or pressure) as a function of altitude (Fig. 1-18).

1-2 BRIEF HISTORY OF REMOTE SENSING

The early development of remote sensing as a scientific field is closely tied to developments in photography. The first photographs were reportedly taken by Daguerre and Niepce in 1839. The following year, Arago, Director of the Paris Observatory, advocated the use of photography for topographic purposes. In 1849, Colonel Aimé Laussedat, an officer in the French Corps of Engineers, embarked on an exhaustive program to use photography in topographic mapping. By 1858, balloons were being used to make photographs of large areas. This was followed by the use of kites in the 1880s and pigeons in the early 1900s to carry cameras to many hundred meters of altitude. The advent of the

Figure 1-3. Folded mountains in the Sierra Madre region, Mexico (Landsat MSS).

airplane made aerial photography a very useful tool because acquisition of data over specific areas and under controlled conditions became possible. The first recorded aerial photographs were taken from an airplane piloted by Wilbur Wright in 1909 over Centocelli, Italy.

Color photography became available in the mid-1930s. At the same time, work was continuing on the development of films that were sensitive to near-infrared radiation. Near-infrared photography was particularly useful for haze penetration. During World War II, research was conducted on the spectral reflectance properties of natural terrain and the availability of photographic emulsions for aerial color infrared photography. The main incentive was to develop techniques for camouflage detection.

In 1956, Colwell performed some of the early experiments on the use of special-purpose aerial photography for the classification and recognition of vegetation types and the detection of diseased and damaged vegetation. Beginning in the mid-1960s, a large number of studies of the application of color infrared and multispectral photography were undertaken under the sponsorship of NASA, leading to the launch of multispectral imagers on the Landsat satellites in the 1970s.

At the long-wavelength end of the spectrum, active microwave systems have been used since the early twentieth century and particularly after World War II to detect and track moving objects such as ships and, later, planes. More recently, active microwave sensors have been developed that provide two-dimensional images that look very similar to regular photography, except that the image brightness is a reflection of the scat-

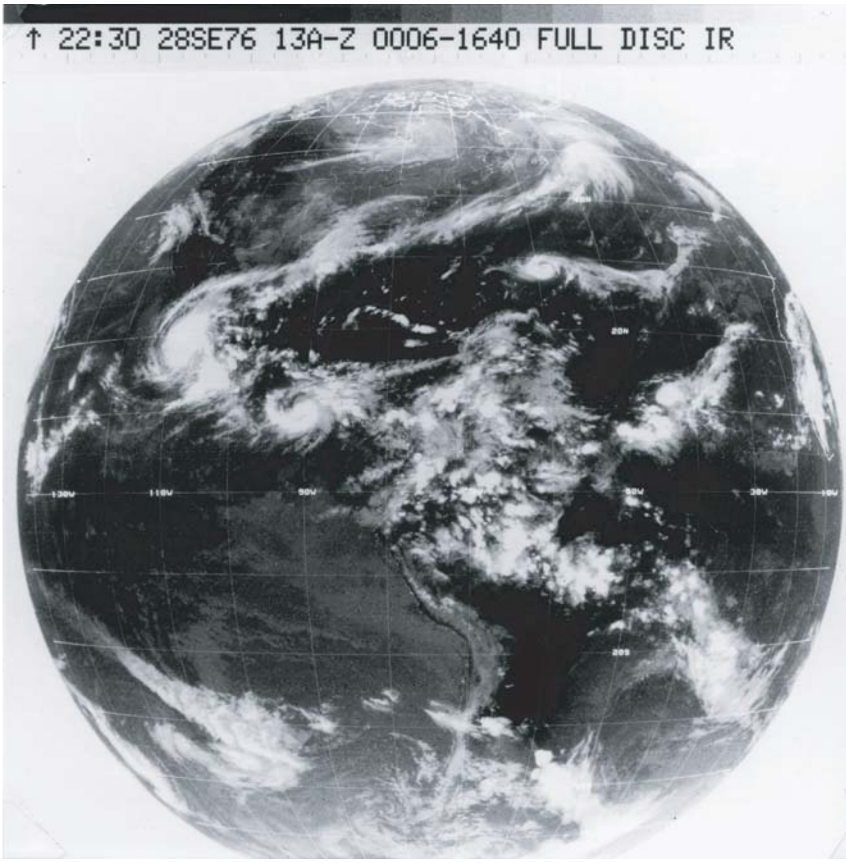

Figure 1-4. Infrared image of the western hemisphere acquired from a meterological satellite.

tering properties of the surface in the microwave region. Passive microwave sensors were also developed to provide "photographs" of the microwave emission of natural objects.

The tracking and ranging capabilities of radio systems were known as early as 1889, when Heinrich Hertz showed that solid objects reflected radio waves. In the first quarter of the twentieth century, a number of investigations were conducted in the use of radar systems for the detection and tracking of ships and planes and for the study of the ionosphere.

Radar work expanded dramatically during World War II. Today, the diversity of applications for radar is truly startling. It is being used to study ocean surface features, lower- and upper-atmospheric phenomena, subsurface and surface land structures, and surface cover. Radar sensors exist in many different configurations. These include altimeters to provide topographic measurements, scatterometers to measure surface roughness, and polarimetric and interferometric imagers.

In the mid-1950s, extensive work took place in the development of real-aperture airborne imaging radars. At about the same time, work was ongoing in developing synthetic-aperture imaging radars (SAR), which use coherent signals to achieve high-reso-

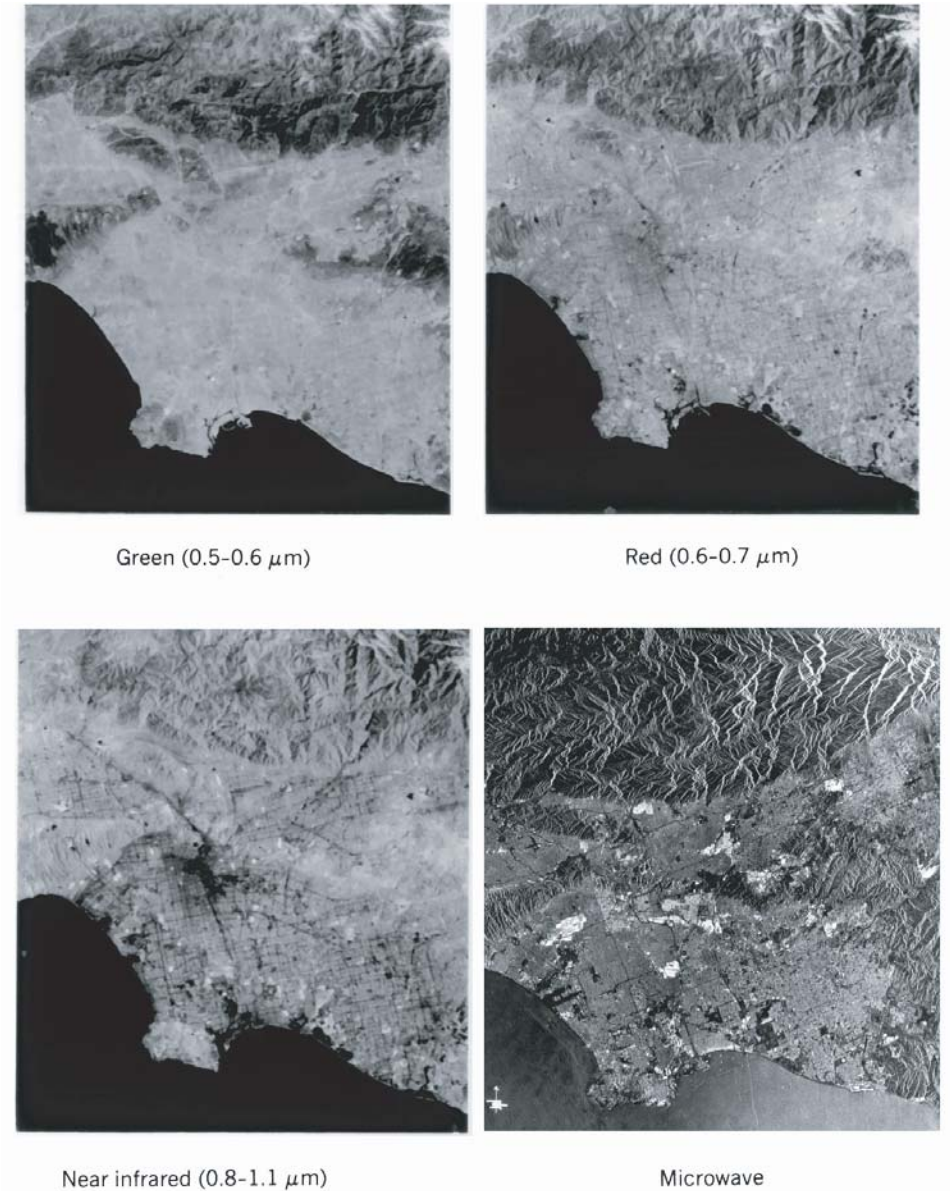

Figure 1-5. Multispectral satellite images of the Los Angeles basin acquired in the visible, infrared, and microwave regions of the spectrum. See color section.

lution capability from high-flying aircraft. These systems became available to the scientific community in the mid-1960s. Since then, work has continued at a number of institutions to develop the capability of radar sensors to study natural surfaces. This work led to the orbital flight around the Earth of the Seasat SAR (1978) and the Shuttle Imaging Radar (1981, 1984). Since then, several countries have flown orbital SAR systems.

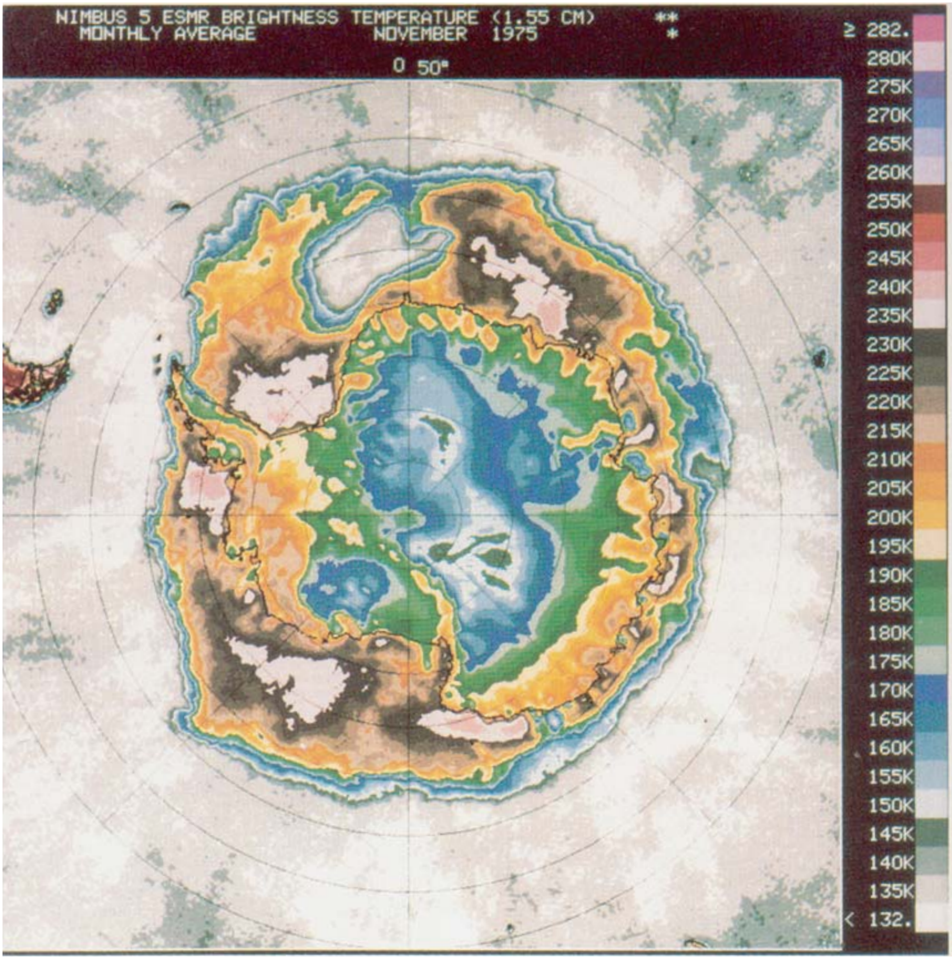

Figure 1-6. Passive microwave image of Antarctic ice cover acquired with a spaceborne radiometer. The color chart corresponds to the surface brightness temperature. See color section.

The most recently introduced remote sensing instrument is the laser, which was first developed in 1960. It is mainly being used for atmospheric studies, topographic mapping, and surface studies by fluorescence.

There has been great progress in spaceborne remote sensing over the past three decades. Most of the early remote sensing satellites were developed exclusively by government agencies in a small number of countries. Now nearly 20 countries are either developing or flying remote sensing satellites, and many of these satellites are developed, launched and operated by commercial firms. In some cases, these commercial firms have completely replaced government developers, and the original developers in the governments now are simply the customers of the commercial firms.

The capabilities of remote sensing satellites have also dramatically increased over the past two decades. The number of spectral channels available has grown from a few to more than 200 in the case of the Hyperion instrument. Resolutions of a few meters or less are now available from commercial vendors. Synthetic-aperture radars are now ca-

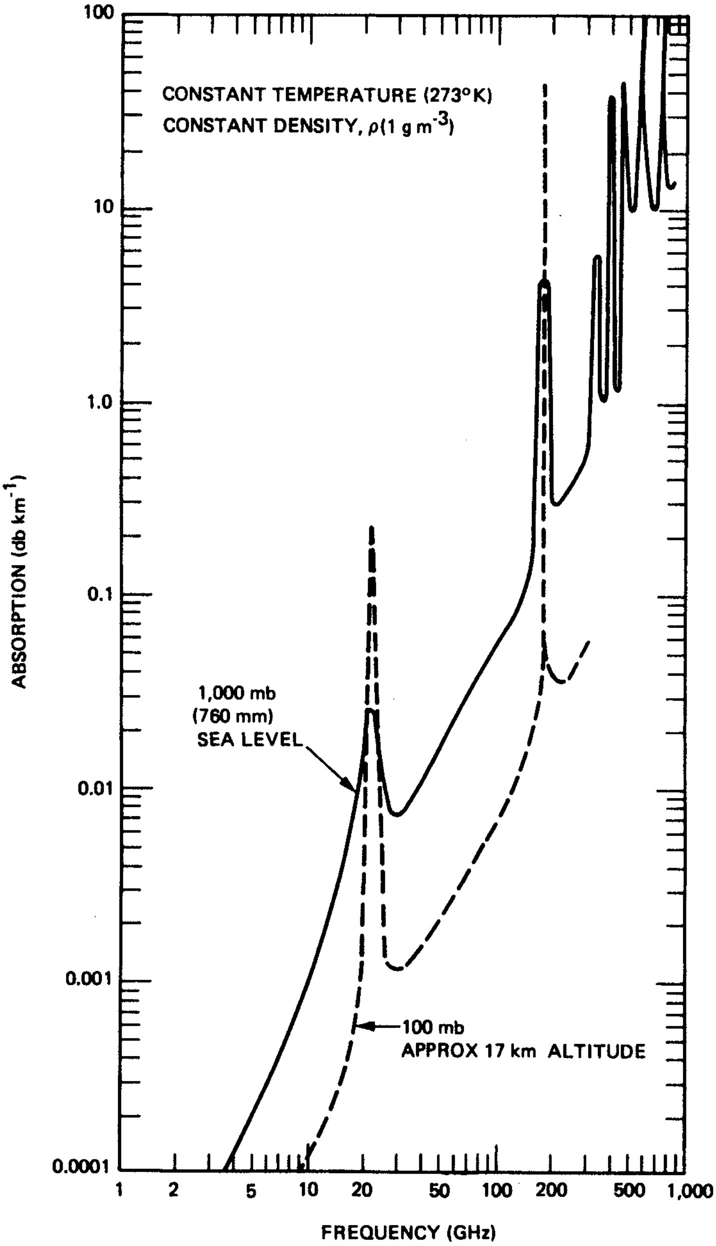

Figure 1-7. Absorption spectrum of H_2O for two pressures (100 mbars and 1000 mbars), at constant temperature of 273° K. (From Chahine et al., 1983.)

pable of collecting images on demand in many different modes. Satellites are now acquiring images of other planets in more spectral channels and with better resolutions than what was available for the Earth two decades ago. And as the remote sensing data have become more available, the number of applications has grown. In many cases, the limitation now has shifted from the technology that acquires the data to the techniques

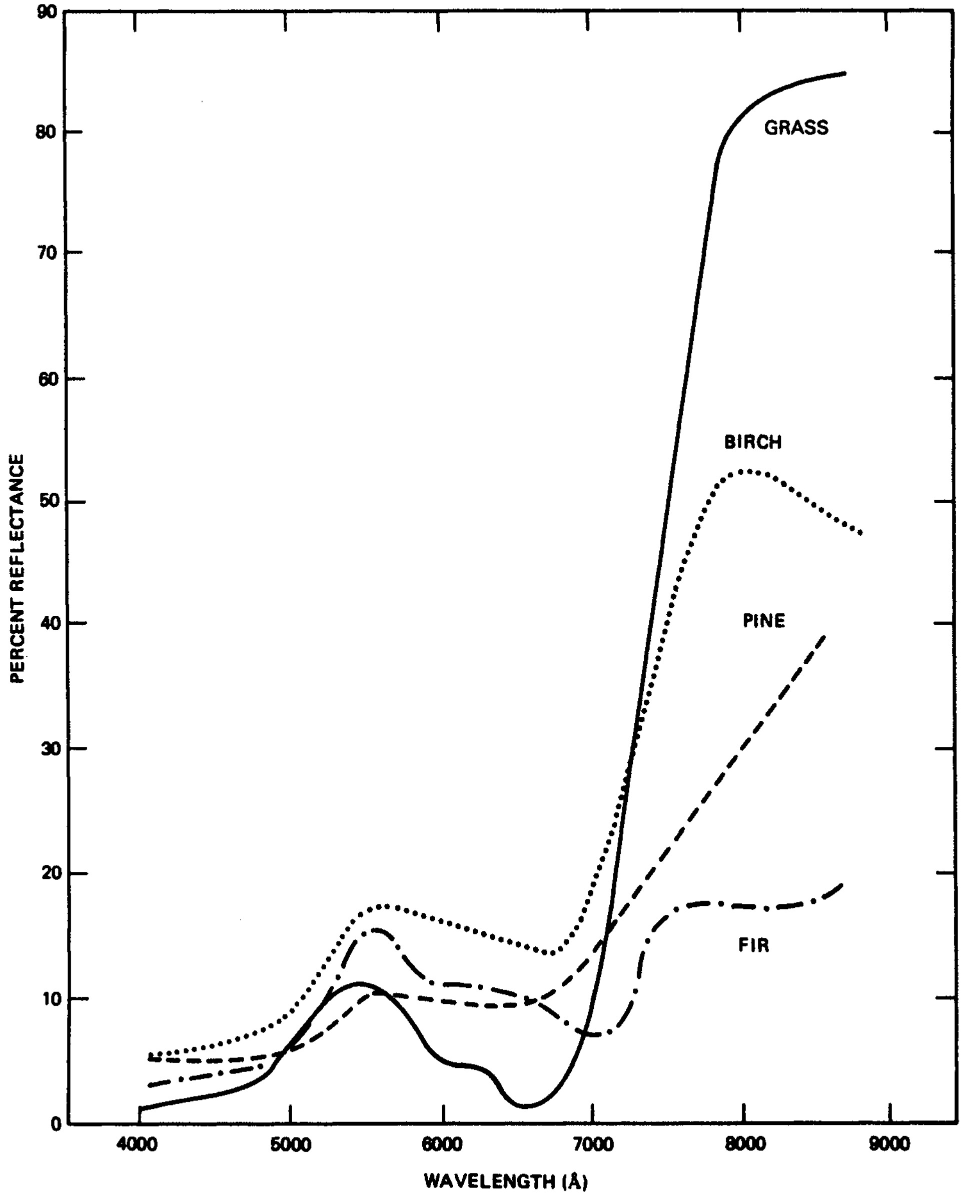

Figure 1-8. Spectral signature of some vegetation types. (From Brooks, 1972.)

and training needed to optimally exploit the information embedded in the remote sensing data.

1-3 REMOTE SENSING SPACE PLATFORMS

Up until 1946, remote sensing data were mainly acquired from airplanes or balloons. In 1946, pictures were taken from V-2 rockets. The sounding rocket photographs proved