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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 field. 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 the 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, solid surface motion, and subsidence 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 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.

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 Figure 1.1.

Two-dimensional images are usually required when high-resolution spatial information is needed, such as in the case of surface cover and structural mapping (Figs. 1.2 and 1.3), or when

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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 and 2014), Cassini Camera (2006)
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)
Surface displacement mapping	Radar interferometer	Sentinel (2012, 2016), SkyMed (2007), ALOS (2006), TANDEMX (2010), ALOS-2 (2014)

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; 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 and 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 and 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.

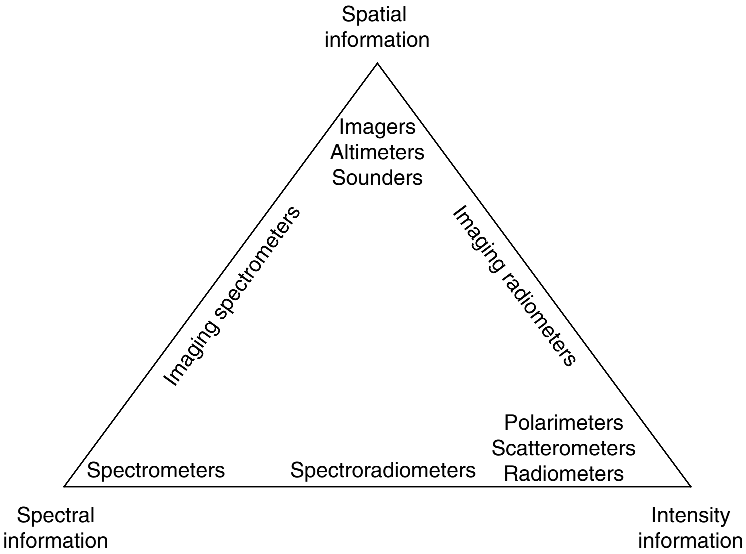


Figure 1.1 Diagram illustrating the different types of information sought after and the type of sensor used to acquire this information. For instance, spectral information is acquired with a spectrometer. Two-dimensional surface spatial information is acquired with an imager such as a camera. An imaging spectrometer also acquires for each pixel in the image the spectral information.

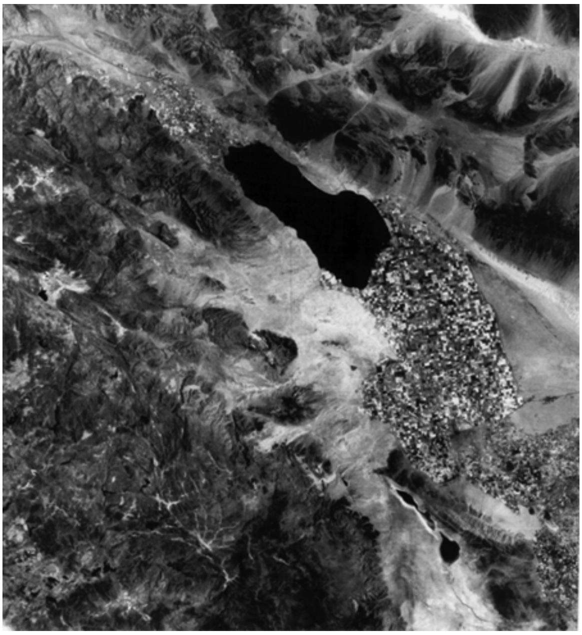


Figure 1.2 Landsat MSS visible/near IR image of the Imperial Valley area in California.

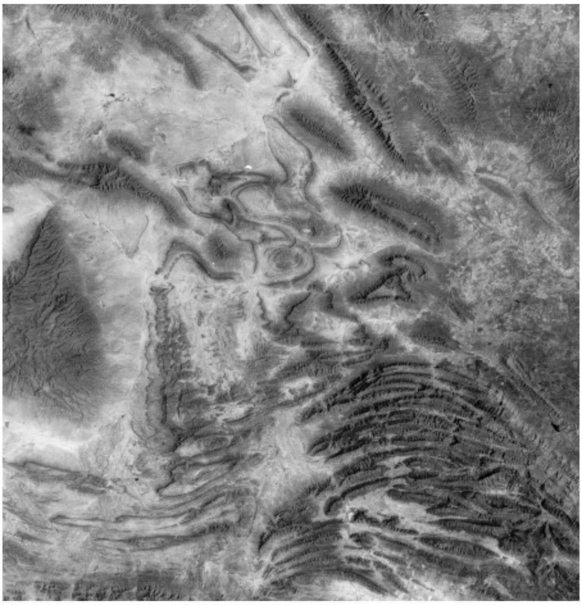


Figure 1.3 Folded mountains in the Sierra Madre region, Mexico (Landsat MSS).

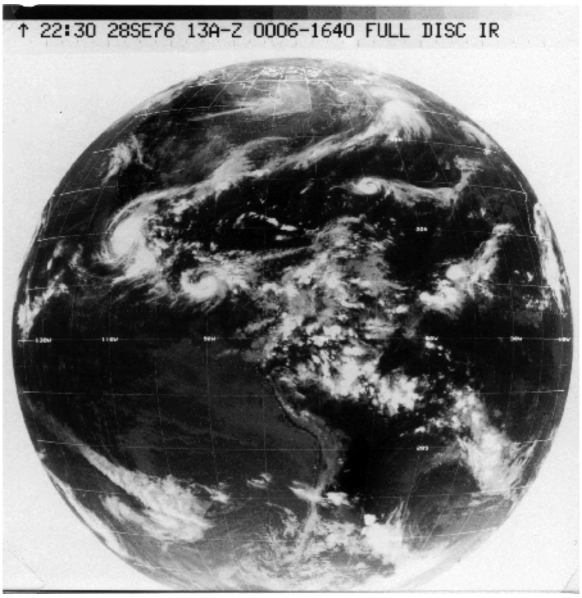
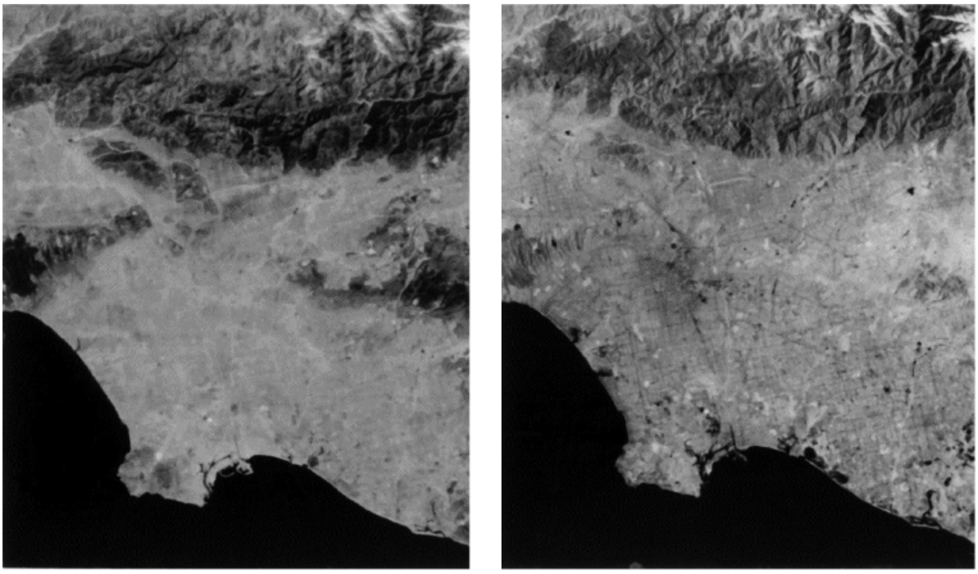


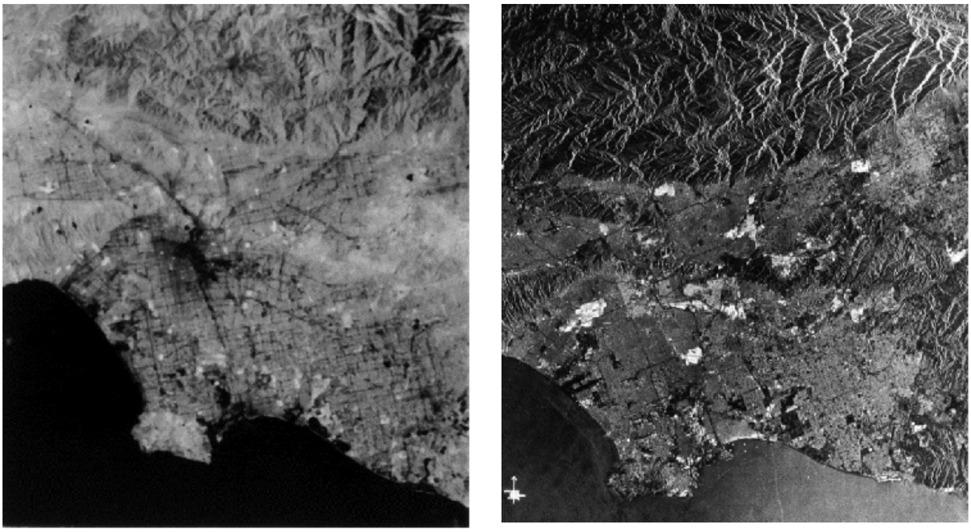
Figure 1.4 Infrared image of the western hemisphere acquired from a meteorological satellite.

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



Green (0.5–0.6 μm)

Red (0.6–0.7 μm)



Near infrared (0.8–1.1 μm)

Microwave

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.

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, or scatterometer, 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.

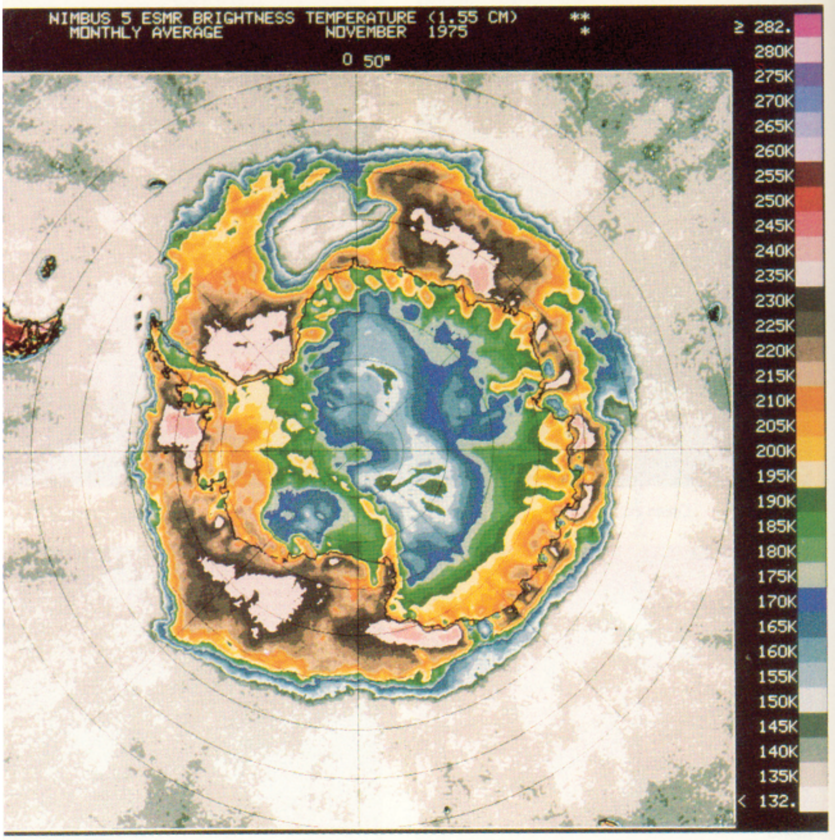


Figure 1.6 Passive microwave image of Antarctic ice cover acquired with a spaceborne radiometer. The color chart corresponds to the surface brightness temperature. See color section.

In a number of applications, the information required is strongly related to the three-dimensional spatial characteristics and location of the object. In this case, stereo imagers, altimeters, and interferometric radars are used to map the surface topography (Figs. 1.13–1.16), and sounders are used to map subsurface structures (Fig. 1.17) or to map atmospheric parameters (such as temperature, composition, and 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 was 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 acquire photography 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 airplane made aerial photography a very useful tool because acquisition of data

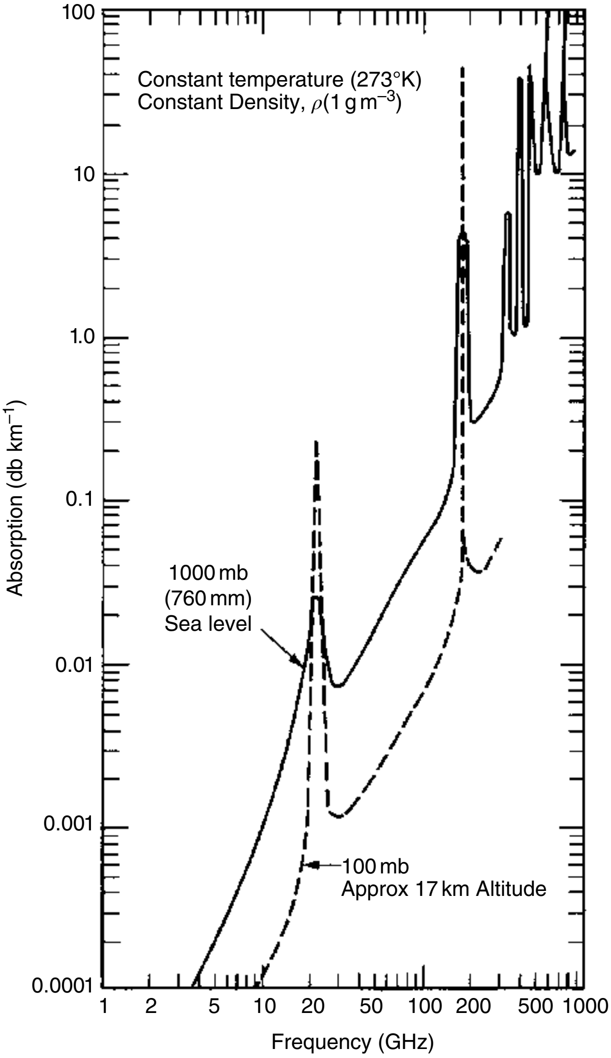


Figure 1.7 Absorption spectrum of H_2O for two pressures (100 and 1000 mbars), at a constant temperature of 273 ° K. *Source:* Chahine et al. (1983). © 1983, American Society of Photogrammetry.

over specific areas and under controlled conditions became possible. The first recorded 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,

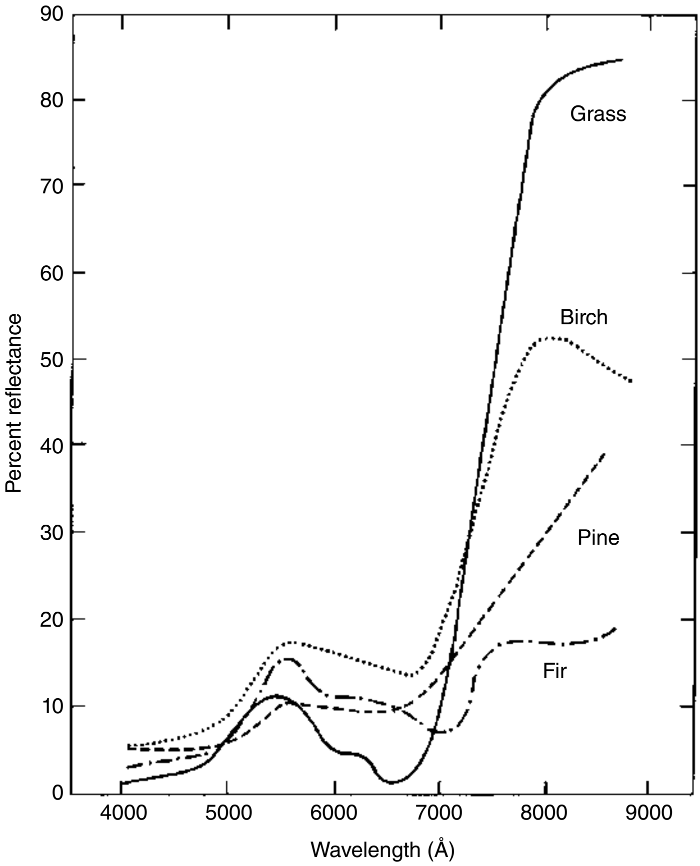


Figure 1.8 Spectral signature of some vegetation types. *Source:* From Brooks (1972).

leading to the launch of multispectral imagers on the Landsat satellites in the 1970s. A major breakthrough was the advent of electronic detectors particularly in large arrays and across many spectral regions.

At the long wavelength end of the spectrum, active microwave systems have been used since early this 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 providing two-dimensional images that look very similar to regular photography, except the image brightness is a reflection of the scattering 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 this 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.

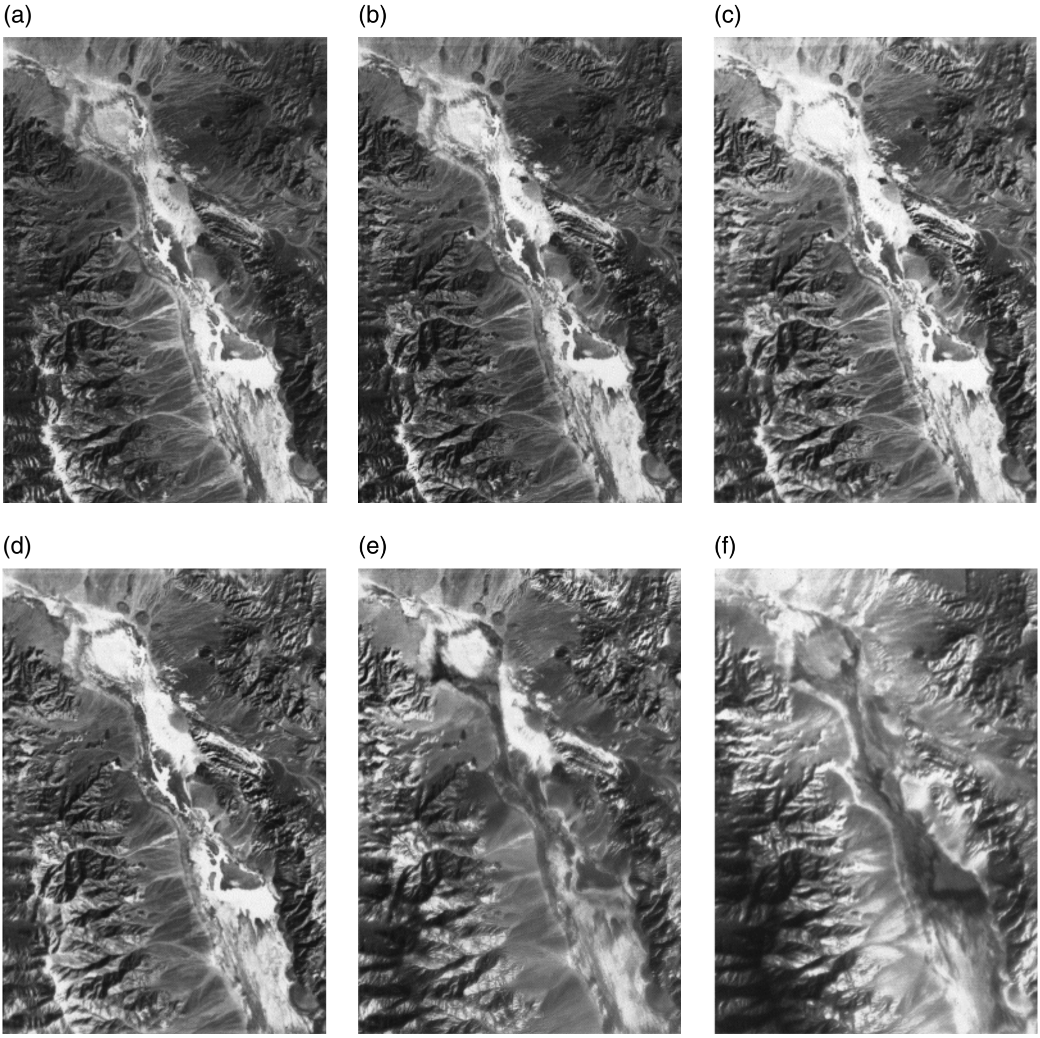


Figure 1.9 Landsat TM images of Death Valley acquired at 0.48 μm (a), 0.56 μm (b), 0.66 μm (c), 0.83 μm (d), 1.65 μm (e), and 11.5 μm (f).

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-resolution 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.

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

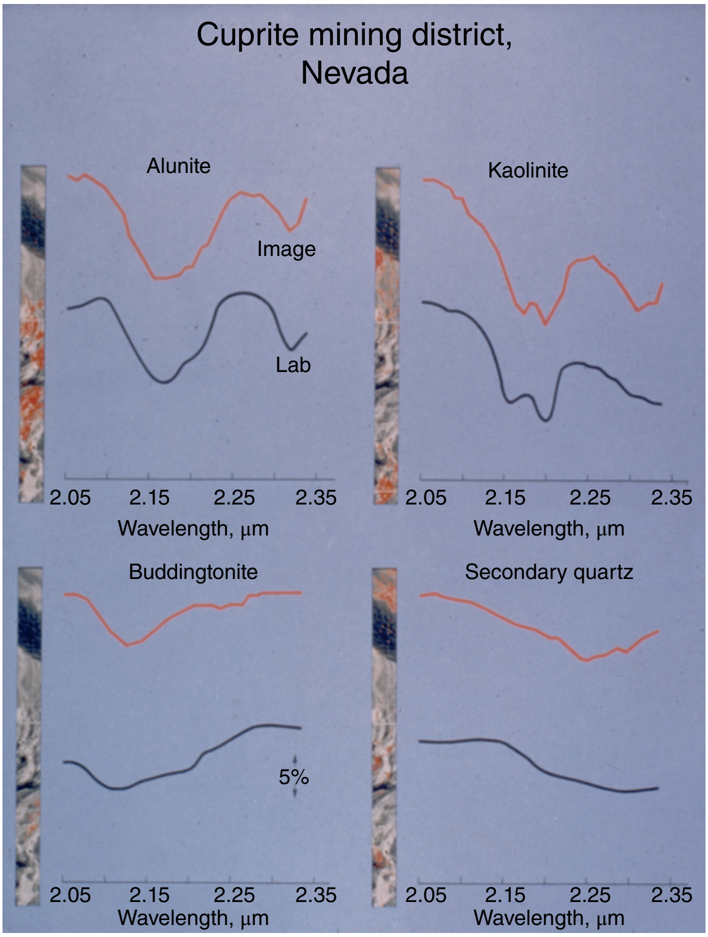


Figure 1.10 Images of an area near Cuprite, Nevada, acquired with an airborne imaging spectrometer. The image is shown to the left. The spectral curves derived from the image data are compared to the spectral curves measured in the laboratory using samples from the same area. *Source:* Courtesy of JPL. See color section.

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 developments, 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 three 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 capable 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 and training to optimally exploit the information embedded in the remote sensing data.

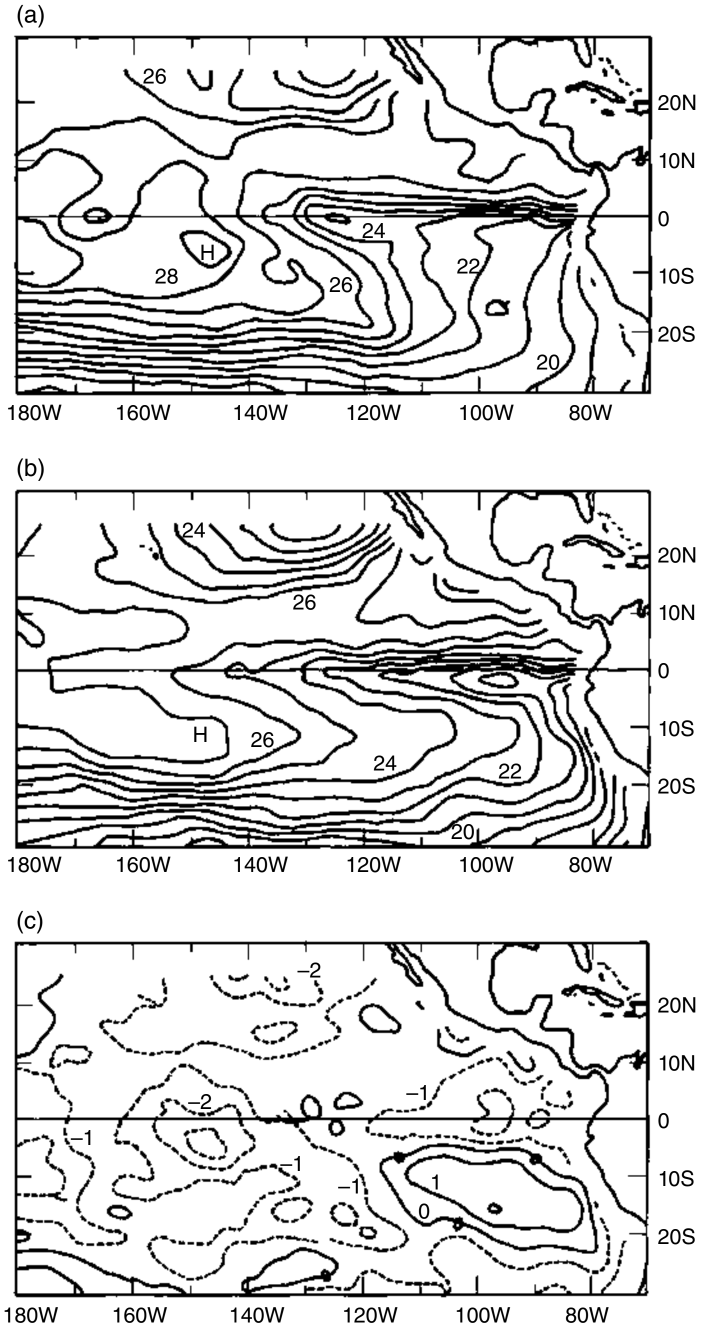


Figure 1.11 Sea surface temperature derived from ship observations (a) and from the Seasat Multispectral Microwave Radiometer (b). (c) shows the difference. *Source:* From Liu (1983). © 1983, John Wiley & Sons.

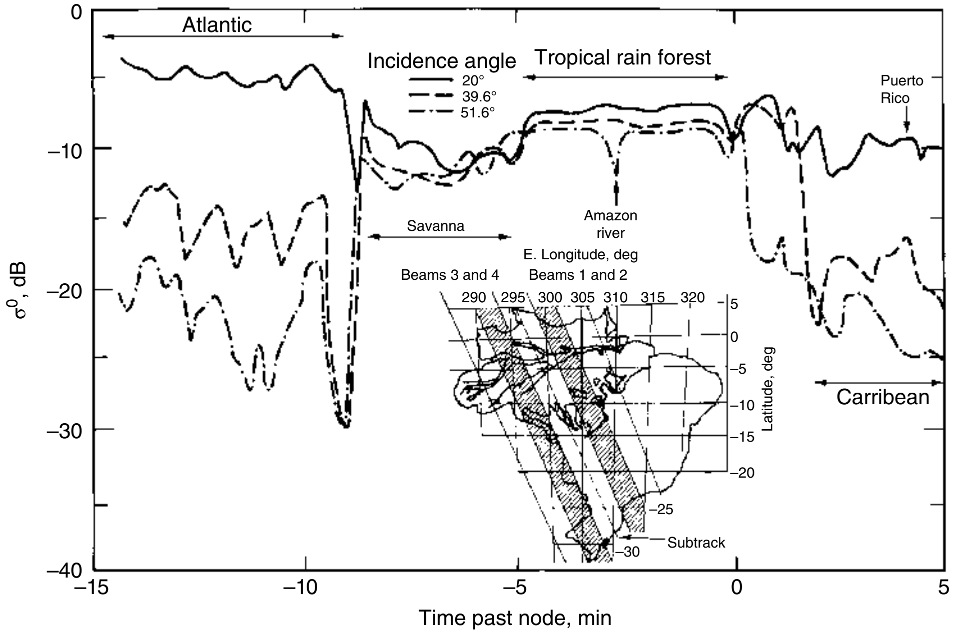


Figure 1.12 Backscatter data acquired over the Amazon region (insert). The different curves correspond to different incidence angles. Data were acquired by the Seasat Scatterometer at 14.6 GHz and at VV polarization. *Source:* Bracalante et al. (1980). © 1980, IEEE.

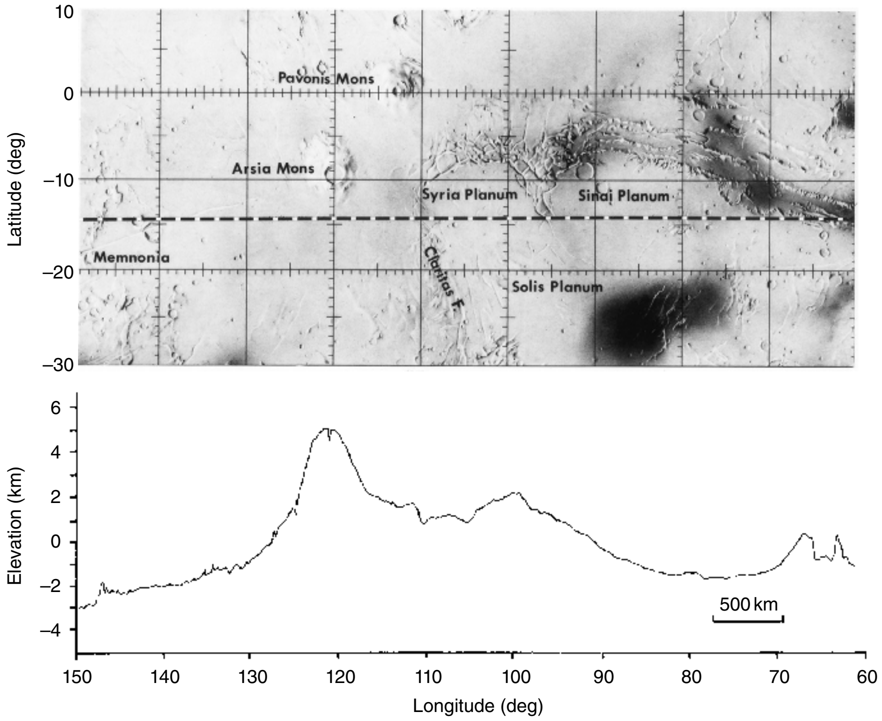


Figure 1.13 Profile of Tharsis region (Mars) acquired with Earth-based radar.

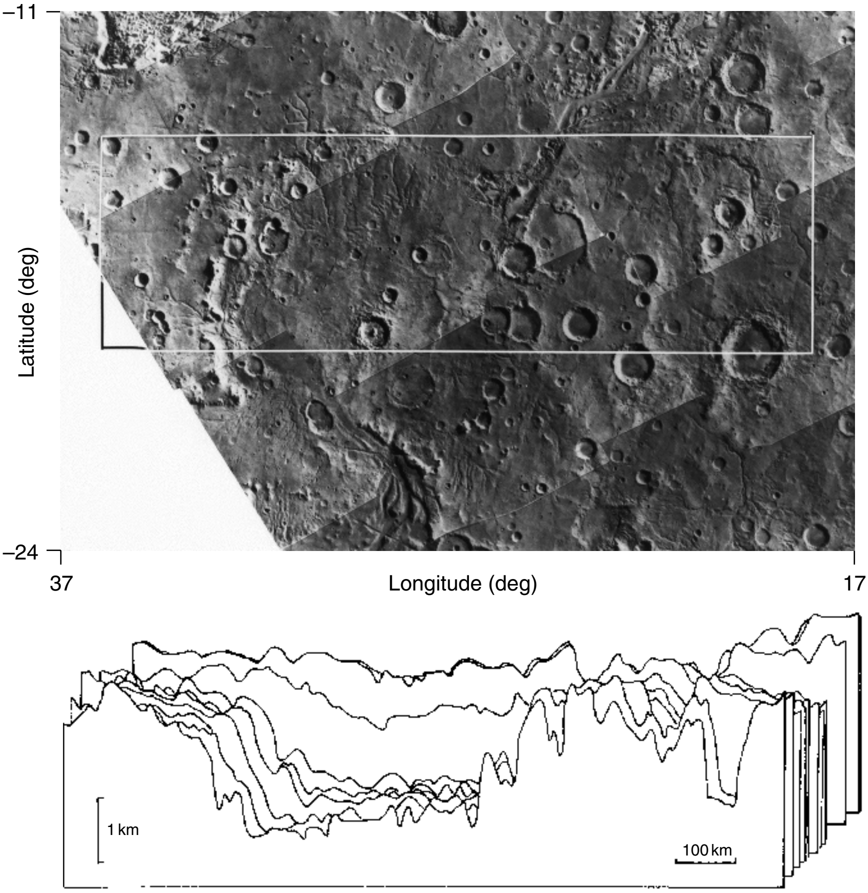


Figure 1.14 Profiles of an unnamed impact basin on Mars using Earth-based radar. The set of profiles shown correspond to the box overlay on the figure.

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 invaluable in illustrating the potential value of photography from orbital altitudes. Systematic orbital observations of the Earth began in 1960 with the launch of Tiros I, the first meteorological satellite, using a low-resolution imaging system. Each Tiros spacecraft carried a narrow-angle TV, five-channel scanning radiometer, and a bolometer.

In 1961, orbital color photography was acquired by an automatic camera in the unmanned MA-4 Mercury spacecraft. This was followed by photography acquired during the Mercury, Gemini, Apollo, and Skylab missions. On Apollo 9, the first multispectral images were acquired to assess their use for Earth resources observation. This was followed by the launch in 1972 of the first Earth Resources Technology Satellite (ERTS-1, later renamed Landsat-1), which was one of the major milestones in the field of Earth remote sensing. ERTS-1 was followed by the series of Landsat missions.

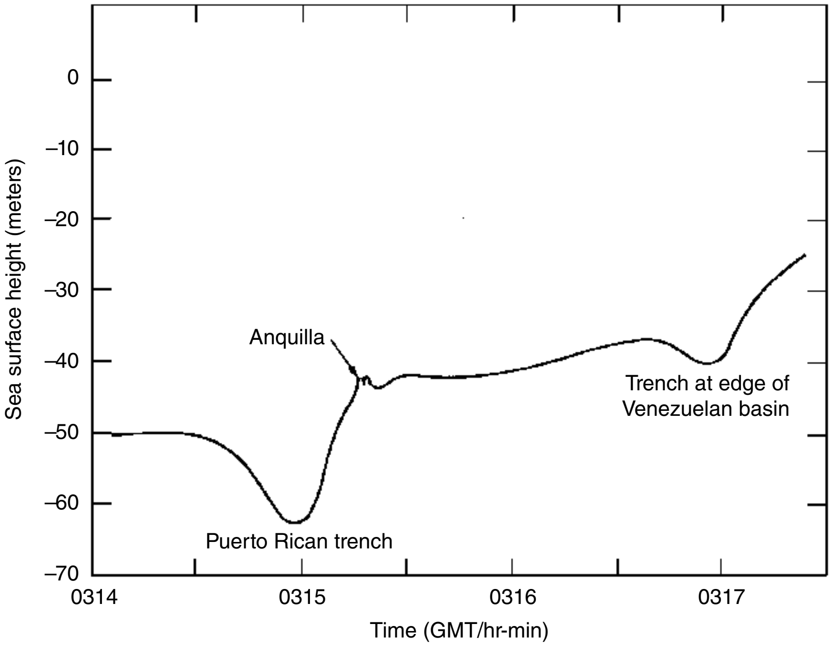


Figure 1.15 Sea surface height over two trenches in the Caribbean acquired with the Seasat altimeter. *Source*: Townsend (1980). © 1980, IEEE.

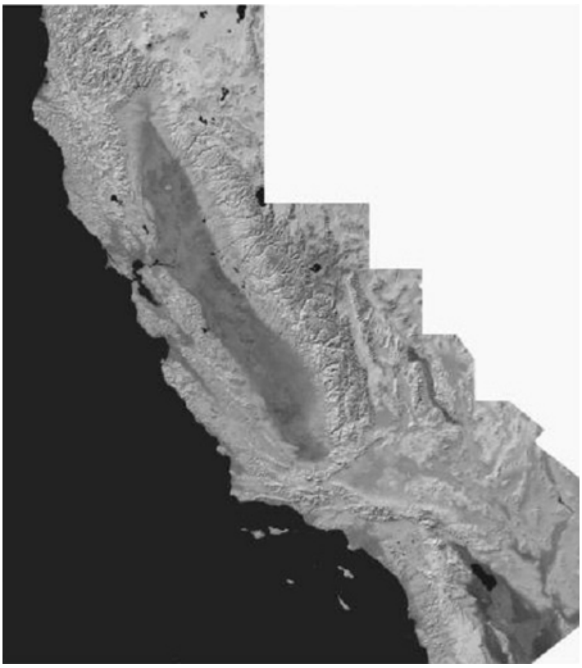


Figure 1.16 Shaded relief display of the topography of California measured by Shuttle Radar Topography Mission using an interferometric SAR.

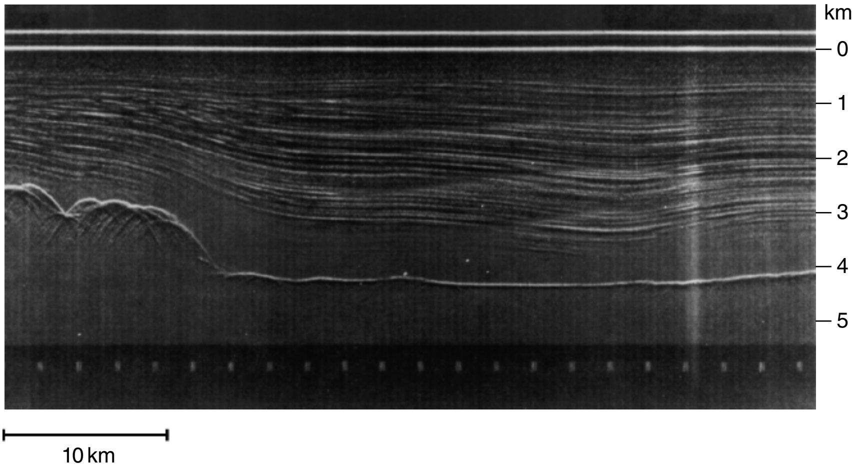


Figure 1.17 Subsurface layering in the ice cover and bedrock profile acquired with an airborne electromagnetic sounder over a part of the Antarctic ice sheet.

Earth orbital spacecraft were also used to acquire remote sensing data other than regular photography. To name just a few, the Nimbus spacecraft carry passive microwave radiometers, infrared spectrometers, and infrared radiometers. The Synchronous Meteorological Satellite (SMS) carried visible and IR spin-scan cameras. Skylab (1972) carried a radiometer and a radar scatterometer. Seasat (1978) carried an imaging radar, a scatterometer, and an altimeter.

In the 1980s and 1990s, the Space Shuttle provided an additional platform for remote sensing. A number of shuttle flights carried imaging radar systems. In particular, the Shuttle Radar Topography Mission, flown on the Space Shuttle in 2000, allowed global mapping of the Earth's topography.

Remote sensing activity was also expanding dramatically using planetary spacecraft. Images were acquired of the surfaces of the Moon, Mercury, Venus, Mars, the Jovian and Saturnian satellites, Pluto, numerous Asteroids and comets, and of the atmospheres of Venus, Jupiter, Saturn Uranus, and Neptune. Other types of remote sensors, such as radar altimeters, sounders, gamma-ray detectors, infrared radiometers, and spectrometers were used on a number of planetary missions.

The use of orbiting spacecraft is becoming a necessity in a number of geophysical disciplines because they allow the acquisition of global and synoptic coverage with a relatively short repetitive period. These features are essential for observing dynamic atmospheric, oceanic, and biologic phenomena. The global coverage capability is also essential in a number of geologic applications where large-scale structures are being investigated. In addition, planetary rovers are using remote sensing instruments to conduct close-up analysis of planetary surfaces. Over the last decade, with the advances in detectors, light optics, microwave technology, antennas, materials, spacecraft technology and data systems, there has been a great expansion in the development, deployment, and utilization of remote sensors. These will be discussed throughout this textbook.

1.4 Transmission Through the Earth and Planetary Atmospheres

The presence of an atmosphere puts limitations on the spectral regions that can be used to observe the underlying surface. This is a result of wave interactions with atmospheric and ionospheric constituents leading to absorption or scattering in specific spectral regions (Figure 1.19).

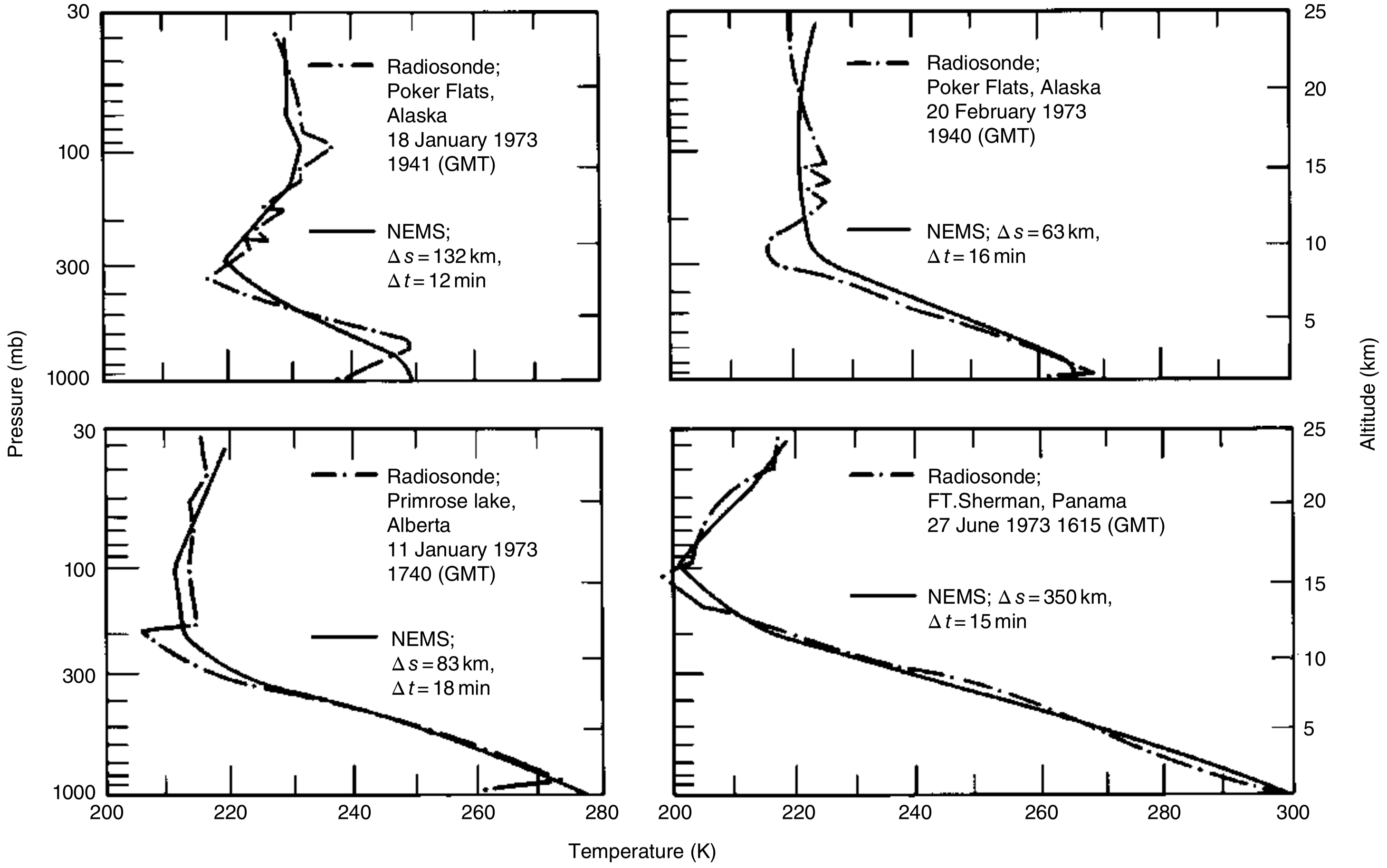


Figure 1.18 Comparison of temperature profiles acquired with a microwave sounder (NEMS) and radiosonde. The spatial and temporal differences, Δs and Δt, between the two measurements are indicated. *Source*: Waters et al. (1975). © 1975, American Meteorological Society.

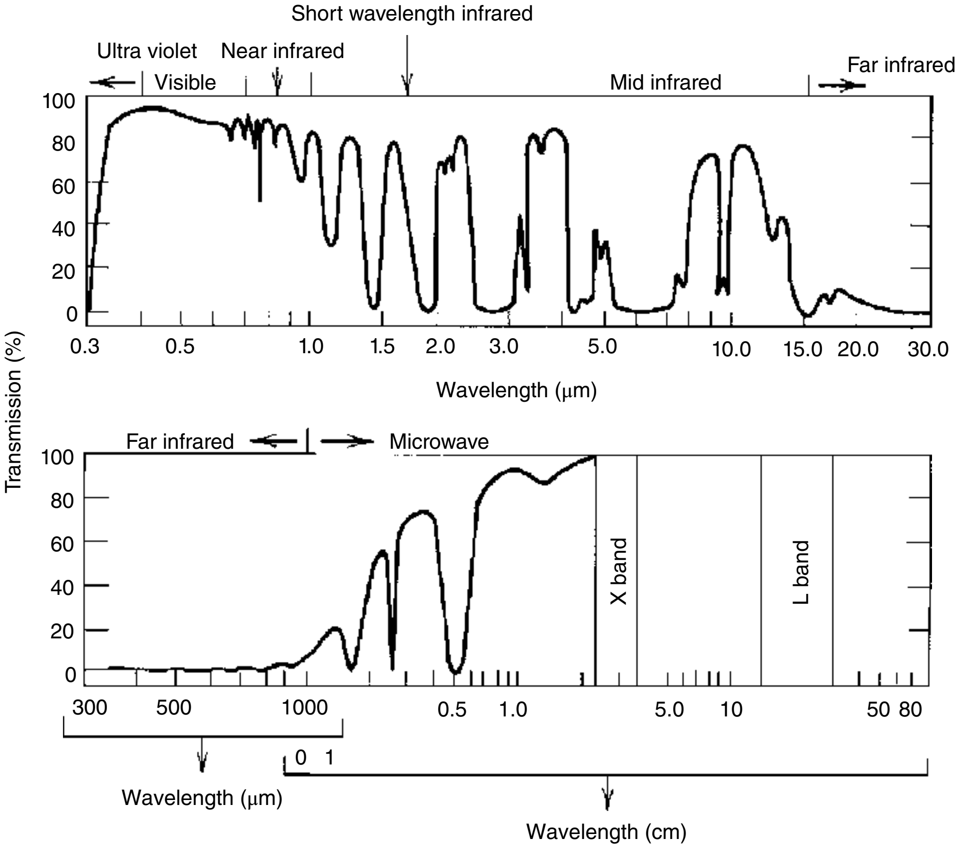


Figure 1.19 Generalized absorption spectrum of the Earth's atmosphere at zenith. The curve shows the total atmospheric transmission.

At radio frequencies below 10 MHz, the Earth's ionosphere blocks any transmission to or from the surface. In the rest of the radio frequency region, up to the low microwave (10 GHz), the atmosphere is effectively transparent. In the rest of the microwave region, there are a number of strong absorption bands, mainly associated with water vapor and oxygen.

In the submillimeter and far-infrared region, the atmosphere is almost completely opaque, and the surface is invisible. This opacity is due mainly to the presence of absorption spectral bands associated with the atmospheric constituents. This makes the spectral region most appropriate for atmospheric remote sensing.

The opacity of the atmosphere in the visible and near infrared is high in selected bands where the high absorption coefficients are due to a variety of electronic and vibrational processes mainly related to the water vapor and carbon dioxide molecules. In the ultraviolet, the opacity is mainly due to the ozone layer in the upper atmosphere.

The presence of clouds leads to additional opacity due to absorption and scattering by cloud drops. This limits the observation capabilities in the visible, infrared, and submillimeter regions. In the microwave and radio frequency regions, clouds are basically transparent.

In the case of the other planets, more extreme conditions are encountered. In the case of Mercury, the Moon, asteroids, comets, and Pluto, no significant atmosphere exists, and the whole electromagnetic spectrum can be used for surface observation. In the case of Venus and Titan, the continuous and complete cloud, or haze, coverage limits surface observation to the longer wavelength regions, particularly radio frequency and microwave bands. In the case of Mars, the tenuous atmosphere is essentially transparent across the spectrum even though a number of absorption bands are present. In the case of the giant planets, the upper atmosphere is essentially all that can be observed and studied remotely with some deeper access from emitted microwave radiation.

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