Satellite Imaging and Sensing

79.1 What Can Be Seen from Satellite Imagery?............................. 79-1
79.2 General Sensor Principles ................................................. 79-1
    Passive and Active Sensors • Polar Orbiting and Geostationary
    Earth Sensing Satellites • Sensor Characteristics • Direct Readout
    Data • Typical Attributes Measured from Space
79.3 Examples of Terrestrial Studies ........................................ 79-9
    Land-Cover Applications • Geologic Studies • Geophysics
    Studies • Ocean Studies • Space Science Applications
79.4 Management and Interpretation of Satellite Data....................... 79-15
    Fundamental Data Levels • Image Restoration • Data
    Compression • Image Registration • Dimension
    Reduction • Data Mining • Classification • Accuracy Assessment
79.5 Future in Satellite Imaging and Sensing .................................. 79-20
Acknowledgments ........................................................................ 79-21
References .................................................................................. 79-21

Robert F. Cromp
National Aeronautics and Space Administration

79.1 What Can Be Seen from Satellite Imagery?

Satellite imaging and sensing is the process by which the electromagnetic energy reflected or emitted from the Earth (or any other planetary) surface is captured by a sensor located on a spaceborne platform. The Sun as well as all terrestrial objects can be sources of energy. Visible light, radio waves, heat, ultraviolet, and x-rays are all examples of electromagnetic energy. Since electromagnetic energy travels in a sinusoidal fashion, it follows the principles of wave theory, and electromagnetic waves are categorized by their wavelength within the electromagnetic spectrum. Although it is continuous, different portions of the electromagnetic spectrum are usually identified and referred to as (from shorter to longer wavelengths) cosmic rays, γ rays, x-rays, ultraviolet, visible (0.4 μm, 0.7 μm), near-infrared (near-IR), mid-infrared (mid-IR), thermal infrared (thermal-IR, above 3 μm), microwave (1 mm, 1 m), and television/radio wavelengths (above 1 m). Figure 79.1 shows the electromagnetic spectrum and these subdivisions.

79.2 General Sensor Principles

Sensors are often categorized as “passive” or “active.” All energy observed by “passive” satellite sensors originates either from the Sun or from planetary surface features, while “active” sensors, such as radar systems, utilize their own source of energy to capture or image specific targets.
79.2.1 Passive and Active Sensors

All objects give off radiation at all wavelengths, but the emitted energy varies with the wavelength and with the temperature of the object. A “blackbody” is an ideal object that absorbs and reemits all incident energy, without reflecting any. If one assumes that the Sun and the Earth behave like blackbodies, then according to the Stefan–Boltzmann law, their total radiant exitance is proportional to the fourth power of their temperature. The maximum of this exitance, called dominant wavelength, can be computed by Wien’s displacement law (see Refs. [1–4] for more details on these two laws). These dominant wavelengths are 9.7 μm for the Earth (in the IR portion of the spectrum) and 0.5 μm for the Sun (in the green visible portion of the spectrum). It implies that the energy emitted by the Earth is best observed by sensors that operate in the thermal-IR and microwave portions of the electromagnetic spectrum, while Sun energy that has been reflected by the Earth predominates in the visible, near-IR, and mid-IR portions of the spectrum. Most passive satellite sensing systems operate in the visible, IR, or microwave portions of the spectrum. Since electromagnetic energy follows the rules of particle theory, it can be shown that the longer the wavelength, the lower the energy content of the radiation. Thus, if a given sensing system is trying to capture long wavelength energy (such as microwave), it must view large areas of the Earth to obtain detectable signals. It is obviously easier to achieve at very high altitudes, thus the utility of spaceborne remote sensing systems.

The most common active satellite sensor is radar (acronym for “radio detection and ranging”), which operates in the microwave portion of the electromagnetic spectrum. The radar system transmits pulses of microwave energy in given directions, and then records the reflected signal received by its antenna. Radar systems were initially employed by the military as a reconnaissance system because their main advantage was to operate day or night and in almost any weather condition. They are very important in satellite remote sensing because microwave radiations are hardly affected by atmospheric “screens” such as light rain, clouds, and smoke. The time it takes for the radar signal to return to the satellite is also measured by instruments such as altimeters which are very useful in determining surface height measurements.

79.2.2 Polar Orbiting and Geostationary Earth Sensing Satellites

Satellite remote sensing systems are also characterized by the different Earth orbiting trajectories of a given spacecraft. These two modes are usually referred to as “polar orbiting” and “geostationary” (or “geosynchronous”) satellites. A polar orbit passes near the Earth’s North and South poles. Landsat, SPOT, and NOAA are near-polar satellites; their orbits are almost polar, passing above the two poles and crossing the equator at a small angle from normal (e.g., 82° for Landsat-4 and -5). If the orbital period of a polar orbiting satellite keeps pace with the Sun’s westward progression compared to the Earth rotation, these satellites are also called “sun synchronous.” This implies that a sun-synchronous satellite always crosses the equator at the same local sun time. This time is usually very carefully chosen, depending on the application of the sensing system and the type of features that will be observed with such a system. It is often a trade-off between several Earth science disciplines such as atmospheric and land science. Atmospheric scientists prefer observations later in the morning to allow for cloud formation, whereas the researchers performing land studies prefer earlier morning observations to minimize cloud cover.
A geostationary satellite has the same angular velocity as the Earth so its relative position is fixed with respect to the Earth. Examples of geostationary satellites are the “Geostationary Operational Environmental Satellite” (GOES) series of satellites that orbit at a constant relative position above the equator.

79.2.3 Sensor Characteristics

79.2.3.1 Spectral Response Patterns

The design of new satellite instruments is based on the principle that targets of interest can be identified based on their spectral characteristics. For example, different Earth surface features, such as vegetation or water, present very distinctive reflectance or emittance curves that are a function of the energy wavelength. These curves are often called the “spectral signatures” of the objects being observed. Although these curves are very representative of each feature and can help identify them, they do not correspond to unique and absolute responses. Because of different reasons, such as atmospheric interactions, temporal or location variations, the response curves of a given object observed under different conditions might vary. For this reason, these curves are often called “spectral response patterns” instead of “spectral signatures.” Figure 79.2 shows an example of such reflectance patterns for several features: fir tree, clear lake water, barley, and granite.

79.2.3.2 Atmospheric Interactions

Earth satellite sensors are designed to take into consideration the fact that all observed radiation must pass at least once through the atmosphere; therefore, the energy interactions of the atmosphere must be considered during the design phase. The distance through which the radiation passes through the atmosphere is called “path length.” The effect of the atmosphere depends on the extent of the path length and on the magnitude of the energy signal. The two main atmospheric effects are known as “scattering” and “absorption.”

Scattering is the unpredictable redirection of radiation by particles suspended in the atmosphere. The type and the amount of scattering mainly depend on the size of the particles but also on the wavelength of the radiation and the atmospheric path length. If these particles are smaller than the radiation wavelength, this effect is known as “Rayleigh scatter.” It is scattering especially affects the shorter visible

![Figure 79.2](image-url)
wavelengths of the sunlight (i.e., blue visible wavelength) and it explains why the sky appears blue to the human eye. In the evening, when the path length is longer, the effect of the Rayleigh scatter is only visible on the longer red wavelengths of the sunlight and the sky appears red or orange. If the particles are about the size of the radiation wavelength, the scatter is known as “Mie scatter”; this scattering effect is often due to water vapor and dust. When the atmospheric particles are larger than the radiation wavelengths, a “nonselective scatter” occurs; all visible wavelengths radiations are scattered equally and this type of scattering explains why clouds appear white.

Atmospheric absorption occurs in specific wavelengths at which gases such as water vapor, carbon dioxide, and ozone absorb the energy of solar radiation instead of transmitting it. “Atmospheric windows” are defined as the intervals of the electromagnetic spectrum outside these wavelengths, and Earth remote sensors usually concentrate their observations within the atmospheric windows. An example, white areas of Figure 79.2 show the portions of the spectrum (i.e., the “channels” or “bands”) from visible to mid-IR used by the Landsat-Terra-matic M apper (TM).

### 79.2.3.3 Spectral, Radiometric, Spatial, and Temporal Resolutions

Although the spectral response patterns are not absolute, they play an important role in the design of new sensors. When a new sensor is being designed, the type of features to observe and the accuracy with which they will be mapped depends on which wavelengths are of interest, the widths of the wavelength intervals to be used, what is the accuracy to be achieved in these bandwidths, and what is the “smallest” or “faintest” feature that might be detected by the sensor. Following the examples of Figure 79.2, the best wavelength interval to distinguish between vegetation and granite will be the (1.55 μm, 1.75 μm) wavelength interval. The earlier sensor requirements correspond to the “resolutions” of the sensor by which it is usually identified—spectral, radiometric, spatial, and temporal resolutions. The term “resolution” is usually employed to denote the smallest unit of measurement or granularity that can be recorded in the observed data. The spectral resolution of a sensor is defined by the bandwidths utilized in the electromagnetic spectrum. The radiometric resolution defines the number of “bits” that are used to record a given energy corresponding to a given wavelength. The spatial resolution corresponds to the area covered on the Earth’s surface to compute one measurement (or one picture element, “pixel”) of the sensor. The temporal resolution (or frequency of observation), defined by the orbit of the satellite and the scanning of the sensor, describes how often a given Earth location is covered by the sensor.

### 79.2.3.4 Signal-to-Noise Ratio

Sensors are also characterized by their signal-to-noise ratio (SNR) (i.e., the noise level relative to the strength of the signal). In this case, the “noise” usually refers to variations of intensity that are detected by the sensor and that are not caused by actual variations in feature brightness. If the noise level is very high compared to the signal level, the data will not provide an accurate representation of the observed features. At a given wavelength λ, SNR is a function of the detector quality, the spatial resolution of the sensor, as well as its spectral resolution (see Ref. [1] for a detailed formula). To maintain or improve the SNR and therefore improve the radiometric resolution of the sensor, a trade-off must be made between spatial and spectral resolutions; in particular, improving spatial resolution will decrease the spectral resolution. Of course, other factors such as atmospheric interactions will also affect the SNR.

### 79.2.3.5 Multispectral and Hyperspectral Sensors

The remote sensing industry is experiencing a rapid increase in the number of spectral bands of each sensor. The first Landsat sensors (Landsat-1 and -2) were designed with four bands in the visible and near-IR portions of the spectrum. Landsat-4 and -5 were released with seven bands from visible to thermal-IR. Then, Landsat-6 and -7 were planned with an additional panchromatic band, which is highly sensitive over the visible part of the spectrum. In general, most Earth remote sensors are multispectral; that is, they utilize several bands to capture the energy emitted or reflected from Earth features. The addition of panchromatic imagery, which usually has a much better spatial resolution than multispectral
imagery in the visible part of the spectrum, provides higher quality detail information. Multispectral and panchromatic data, usually acquired simultaneously, are coregistered and can be easily merged to obtain high spatial and spectral resolution. Coregistered multispectral–panchromatic imagery is available from sensors such as the Indian satellite sensor, IRS-1, and the French sensor, SPOT.

Ideally, if a sensor had an infinite number of spectral channels (or bands), each observed area on the ground (or pixel) could be represented by a continuous spectrum and then identified from a database of known spectral response patterns. Adding more bands and making each of them narrower is the first step toward this ideal sensor. But, as previously explained in the previous section, due to technology limitations, it was very difficult until recently to increase the number of bands without decreasing the SNR. Due to recent advances in solid-state detector technology, it is now possible to increase significantly the number of bands without decreasing the SNR, thus seeing the rise of new types of sensors, called hyperspectral. Although the boundary between multispectral and hyperspectral sensors is sometimes defined as low as 10 bands, hyperspectral imaging usually refers to the simultaneous detection in hundreds to thousands of spectral channels. The aim of hyperspectral sensors is to provide unique identification (or “spectral fingerprints”) capabilities for resolvable spectral objects. Potential applications include agricultural yield monitoring, urban planning, land use mapping, mining and mineral deposits, disaster relief/assessment, tactical military operations, and forest fire protection management. The NASA Airborne Visible Infrared Imaging Spectrometer (AVIRIS) simultaneously collects spectral information from visible to IR ranges (from 0.4 to 2.5 μm) in 224 contiguous spectral bands. Each band has an approximate bandwidth of 10 nm (or 0.01 μm), with a spatial resolution of about 20 m. The instrument flies aboard a NASA ER-2 airplane at ~20 km above sea level. The science objectives of the AVIRIS project are mainly directed toward understanding processes related to the global environment and climate change.

79.2.3.6 Super Resolution

When data are collected from a satellite sensor, each sample of information represents an area on the ground that might correspond to several features with different spectral responses and the final information represents a “mixture” of several disparate information. When a sensor does periodic imaging over the same area, the direction of observation slightly changes, and even when successive data are correctly registered (i.e., in a perfect correspondence), two respective samples might represent two slightly different areas on the ground. Super resolution is an area of research that aims at combining such information from different directions but taken under similar lighting conditions in the goal of improving spatial and spectral resolutions. As an example, some recent work [5] utilizes a Bayesian method for generating subpixel resolution composites from multiple images with different alignments. Software products have also been proposed by some commercial systems, such as ERDAS-Imagine and ENVI, to help in the unmixing of spectral bands (see Ref. [6] for more detail).

79.2.4 Direct Readout Data

Examples of different spectral and spatial resolutions are given in Figure 79.3 with a summary of current Earth remote sensing systems that operate from visible to thermal-IR wavelengths. Figure 79.3 provides information about their bandwidths and their spatial resolutions. The table also indicates if the data from these sensors can be acquired by direct readout. Sensors can transmit data in two modes. The first mode, called “direct readout,” transmits data as soon as it “sees” them, and any receiving station within that satellite footprint can receive these data. In the second mode, the sensor records whatever it sees for playback at a later time, and specialized receiving stations (or “ground stations”) are required to receive these data since they are transmitted at higher rates than direct readout. The data received by these ground stations can cover a larger extent. Historically, the cost of acquiring and processing Earth remotely sensed data has limited satellite data collection to a small number of expensive ground stations around the world, operated by the owners of the satellites. Direct readout
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Number of Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVIRIR (D) (1.1 km)</td>
<td>5 Channels</td>
</tr>
<tr>
<td>TRMM/VIRS (2 km)</td>
<td>5 Channels</td>
</tr>
<tr>
<td>TOMS (50 km)</td>
<td>6 Channels</td>
</tr>
<tr>
<td>Landsat-TM (30 m)</td>
<td>7 Channels</td>
</tr>
<tr>
<td>Landsat-MSS (80 m)</td>
<td>4 Channels</td>
</tr>
<tr>
<td>IRS-1 (73m) LISS-2 (36.5m)</td>
<td>4 Channels</td>
</tr>
<tr>
<td>JERS-1</td>
<td>8 Channels</td>
</tr>
<tr>
<td>SPOT-HRV Panchromatic (10m)</td>
<td>1 Channel</td>
</tr>
<tr>
<td>SPOT-HRV Multispectral (20m)</td>
<td>3 Channels</td>
</tr>
<tr>
<td>CZCS (1 km)</td>
<td>6 Channels</td>
</tr>
<tr>
<td>SeaWIFS (D) (1.1 km)</td>
<td>8 Channels</td>
</tr>
<tr>
<td>TOYS-HIRS2 (D) (15 km)</td>
<td>20 Channels</td>
</tr>
<tr>
<td>GOES (15 km)</td>
<td>3 Channels</td>
</tr>
</tbody>
</table>

**TABLE:**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Number of Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVIRIR (D) (1.1 km)</td>
<td>5 Channels</td>
</tr>
<tr>
<td>TRMM/VIRS (2 km)</td>
<td>5 Channels</td>
</tr>
<tr>
<td>TOMS (50 km)</td>
<td>6 Channels</td>
</tr>
<tr>
<td>Landsat-TM (30 m)</td>
<td>7 Channels</td>
</tr>
<tr>
<td>Landsat-MSS (80 m)</td>
<td>4 Channels</td>
</tr>
<tr>
<td>IRS-1 (73m) LISS-2 (36.5m)</td>
<td>4 Channels</td>
</tr>
<tr>
<td>JERS-1</td>
<td>8 Channels</td>
</tr>
<tr>
<td>SPOT-HRV Panchromatic (10m)</td>
<td>1 Channel</td>
</tr>
<tr>
<td>SPOT-HRV Multispectral (20m)</td>
<td>3 Channels</td>
</tr>
<tr>
<td>CZCS (1 km)</td>
<td>6 Channels</td>
</tr>
<tr>
<td>SeaWIFS (D) (1.1 km)</td>
<td>8 Channels</td>
</tr>
<tr>
<td>TOYS-HIRS2 (D) (15 km)</td>
<td>20 Channels</td>
</tr>
<tr>
<td>GOES (15 km)</td>
<td>3 Channels</td>
</tr>
</tbody>
</table>

**FIGURE 79.3** Summary of the main current earth science satellite data operating from UV to thermal-IR. "D": Direct Broadcast.
sensors were mostly confined to meteorological applications that required timely data such as weather forecasting, severe weather identification and tracking, and disaster prediction and assessment. But this situation is changing; due to new technology, costs have been greatly reduced and direct readout data that were initially expensive and beyond the reach of the nontraditional user are now generating a growing interest. A small industry has evolved to design, install, and upgrade ground stations around the world that acquire direct readout data.

### 79.2.5 Typical Attributes Measured from Space

This section does not intend to be an exhaustive up-to-date description of all Earth and space applications of satellite imaging and sensing, but rather it presents a few representative applications and their associated satellite sensors. The References section as well as the World Wide Web (WWW) offers more extensive references to other applications and sensors.

#### 79.2.5.1 Earth Science Applications

Over the past few decades, a number of international global change research programs have been initiated whose goals are to understand the relation between human activities and the global Earth systems processes and trends. Mission To Planet Earth (MTPE [7]) is a multiagency program, whose goal is to achieve this kind of understanding, especially through improved satellite observations. As part of NASA’s Mission to Planet Earth program, the Earth Observing System (EOS [8]) will launch, over the next 2 decades, several platforms of sensors aimed at ecology, oceanography, geology, snow, ice, hydrology, cloud, and atmospheric studies. Each platform will carry one or several instruments, thus globally covering a wide range of spectral, spatial, and temporal resolutions. Europe and Japan have similar programs, such as the A D vanced Earth Observation Satellite (ADEOS [9]), developed by the Japanese space agency, NASA, in collaboration with France and the United States. ADEOS, launched in 1996, few for 9 months before it failed, and included remote sensing instruments for observing the Earth’s atmosphere, land surfaces, and oceans. Other examples of such programs are the ERS and ENVISAT satellites from European Space Agency (ESA) and the Indian satellites, IRS. ERS-1 and -2 were launched in 1991 and 1995, respectively, and ENVISAT was launched in 1999. All these satellites carry on the same platform with different instruments making simultaneous observations. The first satellite in the IRS series was launched in 1988, and in 9 years, India has designed and launched six remote sensing satellites. For more information on the IRS series, see Ref. [10].

In all the earlier programs, studies concentrate on global processes occurring in the atmosphere (especially lower parts of the atmosphere), on the Earth surface (terrestrial studies), and in the oceans (hydrospheric studies). Results of all these studies will contribute to international programs such as the World Climate Research Programme, the International Geosphere-Biosphere Programme, and the International Human Dimensions of Global Environmental Change Programme.

Several of these instruments show application promise for regional and local community interests, in helping farmers to monitor and control their agricultural productivity (weather, disease control), in early warning and in rescue efforts in case of severe storms (e.g., hurricanes), and in predicting the spread of diseases based on vegetation data combined with socioeconomic data.

#### 79.2.5.2 Examples of Atmospheric Studies

One of the key issues in climate research is to understand global atmospheric changes and how human activity affects the composition and chemistry of the Earth’s atmosphere. To create accurate models, a large number of multiyear global studies must be conducted.

The atmosphere is divided into several layers. From the Earth’s surface up to interplanetary space, which starts at about 1000 km, these layers are called troposphere, stratosphere, mesosphere, thermosphere, and exosphere. Figure 79.4 shows a simplified diagram of the different atmospheric layers. Each of these layers is characterized by differences in chemical composition that produce variations in temperature. The two
lower layers, troposphere (up to 10 km) and stratosphere (10–50 km above the Earth), are particularly important since 99% of the water vapor in the atmosphere is included in the troposphere, and 90% of the ozone of the atmosphere is included in the stratosphere. All weather phenomena occur within the troposphere, with some turbulence sometimes extending to the lower stratosphere. The concentration of ozone, which should stay mainly concentrated in the stratosphere, is being studied in both the troposphere and stratosphere.

Ozone is a relatively unstable molecule made up of three oxygen atoms. Depending on the altitude where it is found, ozone is referred to as “good” or “bad” ozone. The largest concentration of ozone is located in the stratosphere, at an altitude between 20 and 30 km, and plays a major role in the evolution and the protection of life on Earth. Since it absorbs most of the harmful ultraviolet radiation from the Sun, stratospheric ozone protects life on Earth. When found closer to the Earth’s surface, ozone may be harmful to lung tissue and plants. Recent studies have shown that the proportions of ozone in the air are increasing compared to decreasing amounts of protective ozone. However, studies still need to determine if these changes are due to human activity or if they are part of regular natural cycles.

The mission of the total ozone mapping spectrometer (TOMS) is to provide global measurements of total column ozone as well as of sulfur dioxide on a daily basis. The TOMS instrument measures the reflectivity of the atmosphere in six near-UV wavelengths (see Figure 79.3) and provides differential UV absorption and surface reflectivity data. From these measurements, total ozone is computed by searching precomputed albedo tables, which depend on solar zenith angle, view angle, latitude, surface reflectance, and surface pressure; a lower amount of radiation measured by TOMS corresponds to higher concentrations of ozone. Maps of volcanic eruptions are a by-product of TOMS sulfur dioxide measurements. The first TOMS instrument was flown on Nimbus 7 in 1978; successive ones were launched on a Russian Meteor spacecraft in 1991, on an Earth Probe satellite in 1994, and on the Japanese ADEOS satellite in 1996. See Refs. [11–16] for more information on TOMS and ozone measurements.

The TOMS measurements are also being compared to the ozone measurements provided by the National Oceanic and Atmospheric Administration (NOAA) series of the Television Infrared Observing Satellite (TIROS) Operational Vertical Sounder (TOVS) data. The TOVS sounding unit consists of three
instruments, including the High-Resolution Infrared Sounder-2 (HIRS-2) whose channels are shown in Figure 79.3. TOVS-type instruments have been flying since 1978. These instruments provide information about the structure of the atmosphere, vertical temperature and moisture profiles, as well as cloud amounts and heights. A rough analysis of this data, the TOVS Pathfinder data set is created and contains 74 layers of measurements on attributes such as temperature, water vapor, ozone level, precipitation, cloud coverage, etc. taken at various atmospheric pressure levels (e.g., 1000 mb, 850 mb). A full global coverage of TOVS data is produced twice daily, and a 16 year global data set for climate studies is being gathered [17].

Another satellite that obtains atmospheric data is the Upper Atmosphere Research Satellite (UARS). UARS was launched in 1991 and performs a comprehensive study of the stratosphere and furnishes important new data on the mesosphere and the thermosphere. UARS operates 585 km above the Earth in a near circular orbit inclined 57° to the equator. This orbit permits UARS sensors to provide global coverage of the stratosphere and mesosphere and measurements are made approximately every 36 days. The 10 UARS chemistry and dynamics sensors are making measurements of temperature, pressure, wind velocity, and gas species concentrations. All these simultaneous measurements will help define the role of the upper atmosphere in our climate and its variability.

The Tropical Rainfall Measuring Mission (TRMM [18]) is a joint project between the United States and Japan. The goal of this project is to measure precipitation at tropical latitudes and to provide accurate mapping of tropical rainfall. The mission consists of three instruments: precipitation radar, a multichannel microwave radiometer, and a visible-IR scanner. The data provided by TRMM will be very important to verify and develop climate models.

The French space agency, CNES, has also developed the POLDER (POLarization and Directionality of the Earth's Reflectances) instrument, which flew on ADEOS. This is the first French/Japanese cooperative project in the area of Earth observation. A second, identical instrument is to be flown on ADEOS-2, successor to ADEOS, in 1999. POLDER is a wide field-of-view imaging radiometer that will provide global, systematic measurements of spectral, directional, and polarized characteristics of the solar radiation reflected by the Earth/atmosphere system, as well as aerosols, land and sea surfaces, and water vapor measurements.

NOAA's Advanced Very High Resolution Radiometer (AVHRR [19]) is very useful to study biomass burning in the tropics, and the interactions of smoke particles with clouds. More generally, information from the AVHRR channels (see Figure 79.3) is integrated into clouds and climate models.

Weather images are an everyday occurrence televised all over the world. Several weather satellites are operated by several countries. In the United States, NASA and NOAA are operating the GOES series of geostationary satellites, which provide global weather data every 30 min since 1974, positioned at 36,000 km above the Earth. GOES image and sounder data are also used for climate studies. In Europe, the Meteosat weather satellites are developed and launched by ESA, and financed and owned by Eumetsat, an international organization of 17 European weather services. Meteosat-1 was launched in 1977, followed by five others in 1981, 1989, 1991, and 1993. Three of them are currently in service, each equipped with an imaging radiometer. Figure 79.3 shows the spectral ranges of operations of these two series of geostationary satellites. Several channels in the visible, water vapor, and thermal-IR spectral bands provide important information about cloud coverage, storm formation and evolution, as well as Earth radiation.

### 79.3 Examples of Terrestrial Studies

#### 79.3.1 Land-Cover Applications

There are two basic types of data considered most important for global change research [20]: the data for documenting and monitoring global change, and the data for discovering the dynamical interplay among the various elements that define our environment. Previous studies show that global studies of land transformations require extrapolation among several scales (spatial, radiometric, and temporal).
is extrapolation is especially important to control the minimum detectable change, whether spatial, spectral, or temporal. T is accuracy in change detection, which is based on the properties of the sensing systems [21], can be especially essential in distinguishing between nature- and human-induced changes.

Getting accurate quantitative information about the distribution and the areal extent of the Earth’s vegetation formations is a basic requirement in understanding the dynamics of the major ecosystems. Among all land transformations most critical to study for global change research, the assessment of tropical forests is one of the most important [22–25]. T he tropical forest biome forms 7% of the Earth land surface, and its extensive loss could have a major impact on the future of the Earth (habitat fragmentation, species extinction, soil degradation, global climatic modifications, etc.). Previous studies have shown that in the last 2 decades, 50% of the areal extent of tropical forests might have been lost to deforestation [23]. At present, there is a wide range of estimates of the areal extent of tropical forests and of their rates of deforestation. T herefore, there is a great need to produce accurate and up-to-date measurements concerning the Tropical Forest worldwide. A range of different sensors must be utilized for such applications.

Other examples of land-cover applications include agriculture and crop forecasting, water urban planning, rangeland monitoring, mineral and oil exploration, cartography, food monitoring, disease control, real estate tax monitoring, detection of illegal crops, etc. In many of these applications, the combination of remote sensing data and Geographic Information Systems (GISs; see Refs. [26,27]) shows great promise in helping the decision-making process.

Most instruments utilized to observe land features are on-board low Earth orbit satellites and are multispectral sensors with two or three bands in the visible part of the spectrum and at least one band in the IR [6].

T he Landsat series of satellites is the oldest land monitoring satellite system. Initiated in 1967, the Earth Resource Technology Satellites (ERTS) program was planning a series of six satellites to perform a broad-scale, repetitive survey of the Earth’s land areas. After the launch in 1972 of the first ERTS-1, the ERTS program was renamed “Landsat.” As of 1997, five Landsat satellites have been launched, each one carrying two instruments. T he payload of Landsat-1 and -2 included a Return Beam Vidicon (RBV) camera and a Multispectral Scanner (MSS), while Landsat-4 and -5 still use the MSS and the TM. T he first RBV system consisted of three television-like cameras with a ground resolution of 80 m, each looking respectively at the green, red, and near-IR portions of the spectrum. On Landsat-3, the RBV was 30 m panchromatic. MSS quickly became of primary interest due mainly to its capability of producing multispectral data in a digital format. T he four MSS spectral bands are shown in Figure 79.3, and the spatial resolution of MSS data is about 80 m. Very early on, the utility of MSS data was recognized for such applications as agriculture, mapping, forest monitoring, geology, as well as water resource analysis. T he same MSS system was kept on Landsat-4 and -5, but the RBV system was replaced by the TM system. Like MSS, TM is a MSS, but includes spatial, spectral, and radiometric improvements over MSS. With seven bands instead of four (see Figure 79.3), TM covers a larger portion of the visible wavelengths, and includes two mid-IR and one thermal-IR bands. Data are quantized over 256 levels (8 bits) instead of the 64 levels for MSS, and the spatial resolution of a TM pixel is about 30 m. TM data are usually chosen to perform classification of land-cover features, manmade or natural. In vegetation and change detection applications, leaf segmentation is studied with TM visible channel data, while cell structure can be seen in near-IR, and leaf water content is found in the mid-IR channel data. T he two mid-IR bands (5 and 7) are also useful for geologic applications. All the Landsat satellites are placed in low Earth orbit (at an altitude of about 900 km for Landsat-1 to -3 and 705 km for Landsat-4 and -5) and in a near-polar, sun-synchronous orbit. Landsat-4 and -5 cross the equator at 9:45 a.m. to hopefully take advantage of cloud-free imagery. Landsat-4 and -5 have a 16 day repeat cycle and their orbits are 8 days out of phase. Landsat-6 failed to achieve orbit in 1993; Landsat-7 is planned to be launched in 1998 and includes an improved TM instrument, the Enhanced T ematic M apper (ETM), which will also include a panchromatic band at a spatial resolution of 15 m. For a more in-depth description of Landsat systems, see Refs. [1,29,30]; for more applications and analysis of Landsat data, see Ref. [30].
As previously mentioned, NOAA's AVHRR is primarily used for atmospheric applications but is also utilized for land surface applications. Having a near-polar, sun-synchronous orbit (at 833 km above the Earth's surface), the AVHRR instrument provides global data with a 1.1 km spatial resolution at nadir, and includes five bands, with daily or twice-daily (for thermal-IR) coverage. Since 1978, AVHRR data are available at full resolution (called Local Area Coverage [LAC]) or subsampled to 4 km (known as Global Area Coverage [GAC]). Because of its high temporal resolution, the AVHRR instrument is very useful in applications such as food, storm, or fire monitoring, as well as volcanic eruption. Because of its GAC, AVHRR is also of en utilized for studying geologic or physiographic features, vegetation conditions, and trends at a global, continental, or regional level, snow cover mapping, soil moisture analysis, and sand storms and volcanic eruptions worldwide. A popular parameter extracted from AVHRR data is the Normalized Difference Vegetation Index (NDVI), computed from GAC data as $\text{NDVI} = (\text{Channel 2} - \text{Channel 1})/(\text{Channel 1} + \text{Channel 2})$. GAC data are processed daily and composited on a weekly basis to produce a global map showing vegetation vigor. An example of NDVI applications is the monitoring of the Sahara desert extent. AVHRR data are also used for sea surface temperature.

The first Système Pour I’Observation de la Terre (SPOT), designed by CNES, was launched in 1986. SPOT-2 and SPOT-3 were launched, respectively, in 1990 and 1993. The SPOT satellites fly in a near-polar, sun-synchronous low Earth orbit at an altitude of 832 km and cross the equator at 10:30 a.m. SPOT’s repeat cycle is 26 days, but due to its of-nadir viewing capability (viewing angle up to 27°), SPOT has a “revisiting” capability with which the same area can be seen up to every 26 days. This capability also enables some stereo imaging possibilities. The SPOT payload includes two identical high-resolution visible (HRV) imaging instruments that can be employed in panchromatic or multispectral mode, with pointing capabilities. Spectral coverage of these two modes is given in Figure 79.3. The panchromatic mode is 10 m spatial resolution, while multispectral data have a 20 m spatial resolution. Whereas Landsat is a scanning mirror-type instrument, SPOT employs a push-broom system with a linear array of detectors simultaneously acquiring all data pixels in one image line, which minimizes geometric errors. SPOT data are very useful for applications involving small features. Due to its increased spatial resolution, revisit and pointing capabilities, simultaneous panchromatic and multispectral data, and stereo data capabilities, SPOT opens a new range of applications, such as topographic mapping, studies of earthfolds (e.g., land, rock, and mudslides), urban management, and military applications. SPOT-4 is planned for launch in 1998, and SPOT-5 in 2002. Among the planned improvements, a mid-IR channel will be added to SPOT-4, which will also carry a new AVHRR-type instrument, the European Vegetation instrument.

Since 1988, India has launched a series of five satellites, the IRS series. These satellites were designed in support of India's agriculture and exploration businesses, and they seem to be successful in this challenge of bringing remote sensing to the users (see Ref. [10]). For land applications, IRS-1A, -1B, and -1C all carry the LISS instrument, which is a MSS very similar to Landsat-TM. LISS-2 acquires imagery in four bands similar to bands 1-4 of Landsat-TM (from visible to near-IR) at the spatial resolution of 36.5 m (see Figure 79.3 for wavelengths description). LISS-3, carried on IRS-1C, also acquires imagery in four bands, but the visible blue band has been suppressed and replaced by a mid-IR band similar to TM/band 5. Due to their similarity to Landsat data, IRS/LISS-2 data could be used as complements or replacements to Landsat data if needed until Landsat-7 is launched. IRS-1C also carries a 5 m panchromatic instrument whose data are coregistered with LISS-2 data. For more details on IRS data, see Refs. [10,27].

Other instruments are also available. JERS-1, designed by Japan, was launched in 1992, and its payload includes both an SAR instrument and an optical imaging system; see Figure 79.3 for its spectral channels from visible to mid-IR wavelengths, with spatial resolutions of 18 and 24 m. MODIS, the German Modular Optoelectronic Multispectral Scanner, has been flying as a research instrument on U.S. Space Shuttle missions, and has a spatial resolution ranging from 4.5 to 13.5 m; see Ref. [27] for more details on these different instruments.

Among the first EOS instruments to be launched is the Moderate Resolution Imaging Spectrometer (MODIS). MODIS is being developed to provide global monitoring of the atmosphere, terrestrial
ecosystem, and oceans, and to detect climate change. MODIS will cover the visible to IR portions of the spectrum with 36 channels at spatial resolutions of 250 m to 1 km. Many interesting land studies will be performed by fusing together AVHRR, Landsat, and MODIS data.

The fusion of several of these types of data is becoming a very important issue [26]. Already, sensors such as SPOT or LISS-3 present the advantage of acquiring coregistered panchromatic and multispectral data. It would be of great interest to combine data from sensors with different spectral and spatial resolutions, as well as different viewpoints. The combination of coarse resolution viewing satellites for large-area surveys and finer resolution sensors for more detailed studies would offer the multilevel information necessary to assess accurately the areal extent of features of interest (e.g., tropical forests). The fusion of multispectral data with SAR data would provide information on ground cover reflectance with the shape, roughness, and moisture content information from SAR. Of course, multidata fusion requires very accurate registration of the data, as will be described in the next section.

### 79.3.2 Geologic Studies

Other examples of terrestrial studies are the mapping of geologic features, such as geologic faults and earthquake sites, or volcanic eruptions. Although many geologic features lie beneath the surface of the Earth, remote sensing (aerial or satellite) provides a valuable tool to perform geologic mapping, landforms and structures analysis, as well as mineral exploration. This is due to the fact that topography and soil properties provide clues to underlying rocks and structural deformations. Landsat and SPOT gather data about the effects of subsurface geologic phenomena on the surface. These data are especially useful to recognize some specific landforms (such as volcanoes), to depict topographic features, to discriminate some geologic facies and rock unit distribution patterns, and more generally to provide regional overviews of surface geology. In mineral exploration, rock or soil alteration can be detected by spaceborne sensors and may indicate the presence of mineral deposits or oil reservoirs. Other types of sensors that are very useful for geologic applications are radar sensors, such as the two radar systems, SIR-C and X-SAR, carried on the Space Shuttle Endeavour in 1994. These sensors captured in real time the eruption of a volcano in Russia and an earthquake in Japan [31]. For more information on geologic applications, see Refs. [2,32].

### 79.3.3 Geophysics Studies

Other satellites, such as the LAGEOS-1 and -2, have proved very useful in geophysics for the study of the Earth’s gravity field, tectonic plate motion, polar motion, and tides. LAGEOS sensors are reflector orbs covered with laser beams. For more information on these studies, see Refs. [33,34].

### 79.3.4 Ocean Studies

Oceans cover 75% of the Earth’s surface and contain most of the energy of the planet. Although their role in climate evolution is very important, it is still poorly understood. By understanding chemical, physical, and biological processes in oceans, scientists will be able to model the interactions between oceans and the atmosphere and determine how these interactions affect Earth temperature, weather, and climate.

An example of interaction between oceans and the atmosphere is illustrated by the phenomenon known as El Niño/Southern Oscillation, which occurs in the tropical Pacific Ocean, usually around Christmas time. El Niño is due to a mass of warm water, usually located off Australia which moves eastward toward equatorial South America. El Niño develops every few years (observed on average every 4 years to a maximum of 7 years), and alters the weather in Australia, Africa, South Asia, and the tropical parts of the Americas. By understanding how winds and waves move in the tropical Pacific Ocean, scientists have been able to predict the El Niño phenomenon up to 1 year in advance. Similar phenomena are being studied in the Atlantic Ocean, where patterns seem to move much more slowly.
Satellite Imaging and Sensing

Besides being used to create global models, and in storm and weather forecasting, ocean data
are also very important for day-to-day applications such as ship routing, oil production, and ocean
fishing.

79.3.4.1 Ocean Colors

Ocean color data are critical for the study of global biogeochemistry and to determine the ocean’s role
in the global carbon cycle and the exchange of other critical elements and gases between the atmo-
sphere and the ocean [35, 36]. It is thought that marine plants remove carbon from the atmosphere at
a rate equivalent to terrestrial plants, but knowledge of interannual variability is very poor. For most
oceans, the color observed by satellite in the visible part of the spectrum varies with the concentration
of chlorophyll and other plant pigments present in the water. Subtle changes in ocean color usually
indicate various types and quantities of microscopic marine plants (i.e., phytoplankton are present in
the water); the more phytoplankton present, the greater the concentration of plant pigments and the
greener the water.

The launched (October 1997) Sea-viewing Wide Field-of-view Sensor (SeaWiFS), which is a part of
MTPE, provides quantitative data on global ocean biooptical properties to the earth science commu-
nity. SeaWiFS is a follow-on sensor to the Coastal Zone Color Scanner (CZCS), which ceased operations
in 1986. See Figure 79.3 for a channel description of these two sensors; notice that all channels are con-
centrated in the (0.4, 0.7 μm) interval of the electromagnetic spectrum.

Other sensors for ocean color are the imaging spectrometer for ocean color applications MOS-IRS,
lunched on the Indian Remote Sensing Satellite IRS-P3 in March 1996, and the imaging spectrom-
eter MOS-PRIRODA, launched aboard the Russian multisensor remote sensing module PRIRODA
docked to space station MIR in April 1996.

79.3.4.2 Ocean Dynamics

By studying ocean circulation and sea-level trends, scientists will be able to create global maps of ocean
currents and of sea surface topography. Since sea surface height and sea-level variations are related to
sea surface temperatures, the monitoring of mean sea levels enables the gathering of evidence that can
measure global warming or El Niño-type events. For example, conditions related to El Niño may result
in a change in sea surface height of 18 cm or greater [37].

TOPEX/Poseidon (T/P) is an important collaboration between USA/NASA and France/CNES. T/P
uses radar altimetry to provide 10 day maps of the height of most of the ice-free oceans’ surface.
Circling the world every 112 min, the satellite gathers data for 3–5 years, and could be operational for
10 years. The T/P satellite was launched in August 1992 on an Ariane rocket. TOPEX measures the
height of the ocean surface, as well as changes in global mean sea level. From these altimetry data,
global maps of ocean topography are created, from which speed and direction of ocean currents are
computed worldwide. Changes in mean sea level are monitored and currently are viewed mostly as
related to natural ocean variability and not climate change. Climate change must be studied over a
much longer time series of altimeter data. T/P also enables study of tides, wave geophysics, and ocean
surface winds.

Sea winds are also being studied with scatterometers such as the NASA Scatterometer (NASCAT)
and the soon to be launched EOS Scatterometer, SearWinds. These high-frequency radar instruments
measure the reflected signals from the ocean surface to detect wind speed and direction.

ERS-1 is another satellite utilized to measure ocean dynamics. ERS-1 was launched in 1991 on a sun-
synchronous, near-polar low-Earth orbit at an altitude of 780 km. ERS-1 orbits the Earth in 100 min
and covers the entire planet in 3 days. Its payload consists of two specialized radars and one IR sensor.
The Active Microwave instrument, consisting of a synthetic aperture radar and wind scatterometer,
produces extremely detailed images of 100 km swath of the Earth’s surface, with a spatial resolution of
20 m. The radar altimeter provides accurate range to sea surface and wave heights, and the along-track
scanning radiometer constructs detailed pictures of the thermal structure of the seas and oceans from
surface temperature measurements at accuracy of <0.5 °C. ERS-1 images are also utilized for land applications where the instruments need to “look through” the cloud cover.

The study of sea ice with passive and active microwave sensors is also very important and additional reading in this topic can be found in Refs. [14,38].

### 79.3.5 Space Science Applications

Astronomical satellites have been developed to observe far distant objects that are usually beyond the range of ground-based instruments. They explore phenomena in the solar system, and beyond. Satellite observation of astronomical objects is also less sensitive to atmospheric interactions and can achieve higher accuracy than ground-based measurements. This section will give a brief description of the most important space science satellites.

The first astronomical satellite to be put into synchronous orbit was the International Ultraviolet Explorer (IUE) laboratory. IUE was launched in 1978 under a joint program involving NASA, ESA, and the United Kingdom. In more than 15 years of service, IUE gathered observations on >10,000 celestial objects. A program for coordinating its observations with those of the ROSAT satellite has been carried out under the title RASS (Rosat-IUE All-Sky Survey). ROSAT, the Roentgen Satellite, is a joint collaboration between Germany, the United States, and the United Kingdom, and was launched in 1990. It is an x-ray observatory that carries two instruments, the x-ray telescope and the wide field camera.

The Infrared Astronomical Satellite (IRAS) is a joint project of the United States, the United Kingdom, and the Netherlands. The IRAS mission was intended to provide a survey of IR point sources (from 12 to 100 μm), but has also produced very high-quality image data. The Mid-Course Space Experiment (MOS), the Infrared Space Observatory (ISO), and the Space InfraRed Telescope Facility (SIRTF) are other examples of recently or soon-to-be launched sensors that provide an even finer resolution.

Hipparcos (High Precision Parallax Collecting Satellite) is an astronomy satellite launched in August 1989, with the purpose of determining the astrometric parameters of stars with unprecedented precision. After a life of 4 years, Hipparcos has produced two catalogs. The Hipparcos Catalogue provides position, parallax, and proper motion measurements with accuracy of 2 milliarcsec at 9 mag for over 120,000 stars. The Tycho Catalogue is the result of somewhat less precise astrometric measurements for some 1 million stars.

COBE, the Cosmic Origin Background Explorer developed by NASA, was launched in 1989. Designed to measure the diffuse IR and microwave radiation from the early universe, it carried three instruments: a Far Infrared Absolute Spectrophotometer (FIRAS), a Differential Microwave Radiometer (DMR), and a Differential Infrared Background Experiment (DIRBE). The first full-sky coverage was completed in 1990.

The Hubble Space Telescope (HST) is one of the most well-known astronomical satellites. It was built as a joint NASA/ESA project, and was launched in 1990 as a long-term space-based observatory. The heart of the system is a large reflector telescope 2.4 m in diameter. All the instruments on-board the HST use the light gathered by the reflector telescope. Current HST instruments are the Wide/Field Planetary Camera 2 (WFPC2), the Space Telescope Imaging Spectrograph (STIS), the Near-Infrared and Imaging Spectrograph (NICMOS), and the Faint Object Camera, FOC, provided by ESA. These differential instruments can observe astronomical objects from UV to IR wavelengths. In 1993, the HST was serviced to correct a preliminary fault afecting the mirror with a corrective optical apparatus named COSTAR. Despite the preliminary mirror fault, and even more after correction, the HST has achieved much better results than those from observatories on Earth. Since it is located above the Earth’s atmosphere (at 600 km), the HST produces highly detailed images of the stars and can detect objects beyond the range of ground-based instruments. Observations with the HST are scheduled as a space-based observatory according to worldwide astronomers’ proposals.

The Advanced Satellite for Cosmology and Astrophysics (ASCA) is the product of a Japan/U.S. collaboration. Launched in 1993, this x-ray astronomy mission was still operational in 1997, and carries four large-area x-ray telescopes with arc minute resolution. ASCA data are being archived and can
be searched and retrieved online at the High Energy Astrophysics Science Archive Research Center, HEASARC. Gamma Ray Observatory (GRO) and the Advanced X-ray Astrophysics Facility (AXAF) are other examples of space sensors which operate in this spectrum range.

### 79.4 Management and Interpretation of Satellite Data

Satellite sensors gather the electromagnetic energy reflected or emitted from Earth (or any other planetary) surface features. The energy is then converted into a digital representation that is visualized by a user and interpreted either visually or with a computer. This section summarizes some preliminary ideas on how the digital representation is formed and the basic types of data processing necessary before any further interpretation of the data. For more details on the processing of remote sensing data, see Refs. [39–42].

#### 79.4.1 Fundamental Data Levels

After transmission from the satellites, raw data are usually processed, calibrated, archived, and distributed by a ground-based data system. Most of NASA satellite data products are classified in the following data levels [7]:

- **Level 0 data** are the reconstructed raw instrument data at full resolution.
- **Level 1A data** are reconstructed, time-reference raw data, with ancillary information including radiometric and geometric coefficients.
- **Level 1B data** are corrected Level 1A data (in sensor units).
- **Level 2 data** are derived geophysical products from Level 1 data, at the same resolution and location, for example, atmospheric temperature profiles, gas concentrations, or winds variables.
- **Level 3 data** correspond to the same geophysical information as Level 2, but mapped onto a uniform space-time grid.
- **Level 4 data** are model output or results from analysis of lower-level data.

#### 79.4.2 Image Restoration

Ideally, the scene as viewed and recorded by a sensor would be an exact rendering of the features within the sensor’s viewing extent, represented as a spectral curve indicating the amount of energy reflecting/radiating for each point in a scene for a range of given wavelengths. From an engineering standpoint, this is impossible, however, because each image is discretized into a finite number of pixels. Variability defines nature, so each pixel will map into a region of the scene that contains a number of features, each producing its own unique spectral curve. The spectral signature recorded for a pixel is a function of these features and their relative sizes within the region covered by the pixel. The spectral response itself is also discretized into a finite number of bandwidths, where each bandwidth covers a small continuous band of the spectrum. The sensor records for each pixel the amount of energy observed for each band. The number itself, referred to as a Digital Number (DN), must be represented in a finite amount of computer memory, such as 8 bits, meaning that each band records activity as a whole number ranging from 0 to 255.

In practice, a number of events outside human control affect the quality of the observation, such as atmospheric scattering, variations in sun angle, high albedo, and instrument errors. Depending on the application, it may be desirable to correct for the presence of thin clouds within an image. The process of image restoration attempts to control and correct for these conditions [42].

Electromechanical effects due to the instrument itself can be discovered due to their periodic nature (such as caused by the repeated motion of a push broom, or the revolving of a mirror, or the physical process of gathering calibration points). A Fourier transform applied to an image from a sensor undergoing periodic interference exhibits strong noise spikes. A filter can then be used to remove the ending data.
Unfortunately, this also removes any good data that happens to fall at the same frequency, although normally this is but a small portion of the data. Data outages and instrument recorder failures appear as streaks in the image parallel with the scanline, and can be discovered by comparing the respective readings of the pixels in the surrounding scanlines of the image.

To account for the atmospheric effects of Rayleigh and aerosol scattering, an estimate of the portion of the signal that is due to the atmosphere is computed and subtracted from the recorded value. The reflectance of water in the near-IR region of the spectrum should be effectively zero, so the value to subtract for the near-IR band corresponds to the reading of the sensor observed over clear open water. To compute values to be subtracted for each of the other spectral components, a histogram should be formed for each band of a number of sample readings over clear open water. The lowest reading in each band is then used as an estimate of the value to subtract from each pixel to account for the atmospheric effect. In addition, information derived from TOVS, balloon readings, or the atmospheric correction software 55 can be useful in dealing with atmospheric effects.

### 79.4.3 Data Compression

Data compression is one of the most important tools to overcome the problems of data transmission, storage, and dissemination [43]. Data compression methods are usually classified as either lossless or lossy. With a lossless data compression scheme, the original data can be reconstructed exactly without any loss; in a lossy compression scheme, original data are reconstructed with a degree of error. For transmission from the satellite to the ground station, a lossless data compression must be utilized. For browsing purposes, lossy compression enables quick searches through large amounts of data. A compression scheme is also characterized by its compression ratio, that is, the factor by which the amount of information which represents the data is reduced through compression. For earth science data, lossless compression schemes provide compression ratios up to 2 or 3, while lossy techniques can reduce the amount of information by a factor of 20 or more without degrading the visual quality of the data.

Among the lossless compression methods, the Joint Photographic Experts Group (JPEG) developed a lossless compression method that is based on a predictor, an entropy encoder for prediction error, and an entropy code specification. Another lossless compression scheme is the Rice algorithm, which can adapt to data of any entropy range. It is based on a preprocessor that spatially decorrelates the data, followed by a variable-length encoder. This algorithm gives some of the best compression ratios among all lossless methods, and has been implemented on VLSI chips at NASA.

JPEG also developed a lossy method based on the Discrete Cosine Transform (DCT). Other methods like vector quantization or wavelet compression provide either lossless or lossy compressions. In a vector quantization technique, a dictionary of representative vectors is also called a codebook, and all data are encoded relative to the codebook. In this method, the one-time encoding step is computationally expensive but the decoding step at the user end is fast and efficient. Vector quantization is also utilized in a progressive scheme for "quick look" browsing purposes. In a subband/wavelet compression method, signals are decomposed using quadrature mirror or wavelet filters [44]. Most energy is contained in the low-frequency subbands and high compression ratios can be obtained by compressing the high-frequency information.

For more information or references on data compression techniques, see Ref. [43].

### 79.4.4 Image Registration

In studying how the global environment is changing, programs such as Mission to Planet Earth [7] or the New Millennium program [45] involve the comparison, fusion, and integration of multiple types of remotely sensed data at various temporal, radiometric, and spatial resolutions. Results of this integration can be utilized for global change analysis, as well as for the validation of new instruments or of new data analysis. The first step in this integration of multiple data is registration, either relative image-to-image registration or absolute georegistration, to a map or a fixed coordinate system. Another case of
image registration is coregistration of multiple bands of one sensor. When the detectors of each spectral band have different spatial locations on the satellite’s focal plane, there could be misregistration between each band’s raw image [46,47].

Currently, the most common approach to image registration is to extract a few outstanding characteristics of the data, which are called control points (CPs), tie points, or reference points. The CPs in both images (or image and map) are matched by pair and used to compute the parameters of a geometric transformation. Most available systems follow this registration approach; and because automated procedures do not always offer the needed reliability and accuracy, current systems assume some interactive choice of the CPs. But such a point selection represents a repetitive, labor-, and time-intensive task that becomes prohibitive for large amounts of data. Also, since the interactive choice of control points in satellite images is sometimes difficult, too few points, inaccurate points, or ill-distributed points might be chosen, thus leading to large registration errors. A previous study [48] showed that even a small error in registration can have a large impact on the accuracy of global change measurements. For example, when looking at simulated 250 m spatial resolution MODIS data, a 1 pixel misregistration can produce 50% error in the computation of the NDVI. So, for reasons of speed and accuracy, automatic registration is an important requirement to ease the workload, speed up the processing, and improve the accuracy in locating a sufficient number of well-distributed accurate tie points.

Automatic image registration methods can be classified into two types: those that follow a human approach, by first extracting control points, and those that take a more global approach. Among the first methods, the most common features utilized as control points are the centers of gravity of regions—with or without region attributes such as areas, perimeters, ellipticity criteria, affine-invariant moments, and interregions distances. More recently, features extracted from wavelet decomposition have also been utilized, such as maxima and minima of wavelet coefficients, high-interest points, or local curvature discontinuities. A few methods utilize Delaunay triangulation methods to progressively increase the number of accurate control points. For the methods that do not match individual pairs of control points, the transformation is either found by correlation or by optimization, in the spatial or in the frequency domain. When in the spatial domain, correlation or optimization is performed either in the original data or on edge gradient data. Other methods propose a global image matching of edge segments or vectors linking feature points. Some recent research has also focused on the use of wavelets for global image registration. More complete surveys of image registration methods can be found in Refs. [47,49,50].

79.4.5 Dimension Reduction

The first step in analyzing multichannel data is to reduce the dimension of the data space. It is particularly important when the analysis method requires a training step, for example, supervised classification (see next section). The main issue in this case has often been referred as “the Curse of Dimensionality” [51]. If the original data have a large number of bands (e.g., for hyperspectral data), theoretical studies have shown that a very large training set should be utilized; but using a large training set deteriorates the estimation of the kernel density. To solve this problem, various dimension reduction schemes enable to perform classification in a smaller-dimensional subspace. Since the information contained in multiple channels is often redundant, it is possible to decorrelate spectrally the channels and reduce the number of channels to be analyzed without losing any information. Principal Component Analysis (PCA) and Projection Pursuit are the most common techniques for dimensionality reduction. For more information on these methods, refer to Refs. [39–42].

79.4.6 Data Mining

One objective of the NASA-initiated Mission to Planet Earth is to gather sufficient data to enable scientists to study the Earth as a dynamic system, resulting in a better understanding of the interactions between humans, the atmosphere, and the biosphere [8]. The episodic nature of most interesting events
would cause them to be missed if the data were not being gathered continuously. Comprehensive data sets allow scientists to construct and evaluate complex models of many Earth-related processes. But currently, due to computation and time constraints, only a small percentage of the data gathered by remote sensing are actually viewed by an individual user. Data-gathering missions tend to be multidisciplinary, so different aspects of the data sets are pertinent to different researchers.

Data mining can be defined as the process by which data content is automatically extracted from satellite data, enabling a scientist to query the data holdings based on high-level features present within an image [52]. Given the projected large volumes of data, it is not feasible to rely solely on conventional data management paradigms. Standard methods of segmenting images are inadequate as standalone techniques for image recognition, regardless of the speeds of processing, because there are no general methods for automatically assigning meaningful semantics to any homogeneous regions that are isolated. Metadata derived directly from the image header are not rich enough to enable robust querying of a database in most instances, but limit a user to retrieving all images at a given latitude/longitude during some time period, for example, regardless of the image quality or the unique features existing due to some unexpected set of circumstances. New approaches based on techniques such as image classification (described in the next section) are now feasible, due to the phenomenal increases in computing speed, the availability of massively parallel architectures, and the breakthroughs in signal processing.

An example of data mining is the browsing of 15 years of TOVS data with two complete coverages per day, which would require looking through 10,958 scenes per attribute. Of the several products generated, the scientists are primarily interested in browsing those with some given resolution. After locating a browse product that seems to indicate an interesting structure or phenomenon, a scientist might then retrieve this data temporally, or any supporting data set for further analysis. Scientists using the TOVS data sets desire a more intelligent form of querying so they can quickly and easily find relevant data sets that are pertinent to their research. Certain TOVS observations are more “interesting” than others, and the definition of “interesting” is a combination of objective fact and subjective opinion. Data mining is applicable here to aid in evolving a retrieval heuristic based on an individual scientist’s definition of “interestingness.” In one approach, the scientist could prepare a representative set of images that are labeled as positive or negative instances of “interesting,” and a machine learning system (e.g., neural network, genetic algorithm) could perhaps be trained to classify the remaining images in the TOVS data set according to this definition. In a second approach, the scientists could be asked to identify explicitly structural features within the images that make them interesting, and image processing routines could then be applied to detect images with these features. Over time, a scientist could provide feedback to the heuristic classifier to improve its performance. Both approaches require that the underlying representation language (structures, bin size, spatial and temporal relationships) be robust and flexible enough to permit an appropriate level of expression.

### 79.4.7 Classification

Image classification is the task of developing a statistical model that labels every potential point in some multidimensional space. A parametric classifier assumes that data are described by some underlying parameterized probability density function (PDF). A training set of representative data from the domain is then used to supply appropriate values. For example, if a Gaussian or normal distribution is assumed, then the means, standard deviations, and joint-covariance matrix can be computed from the training data. A nonparametric or unsupervised classifier is typically used when there is insufficient knowledge about the type of underlying PDF for the domain. Self-organizing classifier models, such as certain kinds of neural networks, are also considered nonparametric classifiers when they make no a priori assumptions about any PDF.

In a statistical or supervised classifier, knowledge about the distribution of the data is utilized to assign a label to an unclassified pixel. Using “ground-reference data,” a training set of known points is created. A prototype vector can then be calculated as the mean of all samples for each of the classes.
Assuming a Gaussian distribution in each of the channel readings for a given class, the standard deviation for each class is computed based on the sample. Even, the lowest distance from the given feature prototypes to an unclassified point determines the class of this incoming point. As simple and elegant as this approach might appear, in reality its utility is limited. Features are not so discernable from a random labeling of an image. Thus, although this algorithm is inaccurate, it is consistent in its mislabelings. The algorithm’s deterministic nature and underlying use of a continuous function combine to produce predictable behavior. In general, this algorithm labels all points similarly if they fall within the same neighborhood in the feature space.

Other parametric classifiers follow the Maximum Likelihood Decision Rule, which allows the construction of discriminant functions for the purposes of pattern classification. For more details on this technique, refer to Ref. [53].

The classifiers discussed earlier are, by definition, required to assign an unclassified pixel to the one nearest class. No measurement of the distance to that class or proximity to other classes is recorded, and no information on the confidence of the labeling is provided. Fuzzy classifiers, on the other hand, are not obligated to pigeonhole a pixel into a single class. Instead, the pixel is assigned a degree of membership for each possible class. Intuitively, and indeed for mathematical tractability, the pixel’s memberships must sum to one, and the degree of membership for a given class must be between 0 and 1, inclusively. Two examples of fuzzy classifiers are given as follows. The Fuzzy Nearest Neighbor nonparametric classifier places an unclassified vector in the dominant class of its k-closest training vectors. If no class has an outright majority, then distances to the nearby vectors for each class which tied are summed and the unclassified vector is placed in the class with the minimum sum. The Fuzzy Decision Tree Classifier utilizes a decision tree as the data structure that encapsulates knowledge of what to do given a set of conditions. See Ref. [52] for more information on this method. Although this algorithm is conceptually simple, it is only recently that it has become computationally feasible due to the need to search the tree for each unclassified pixel to locate the nearest path. The search algorithm can also be sped up by running the algorithm on a parallel architecture such as a Single Instruction Multiple Data (SIMD) machine.

Many researchers have investigated the use of neural networks for automatically extracting metadata from images [54]. Many different neural network models have been considered, but with respect to performance accuracy, the backpropagation training technique has shown to be the best classifier [55]. The backpropagation algorithm is the most common method for training a neural network, and is the backbone of much of the current resurgence of research into neural nets [56]. With respect to pattern recognition, backpropagation can be considered to be a nonparametric technique for estimation of a posteriori probabilities.

### 79.4.8 Accuracy Assessment

A measurement derived solely from satellite imagery is of questionable use unless the technique employed for computing that measurement on those data has been validated. A technique that appears to work accurately on satellite imagery over some given location at some given time may perform abysmally on data from the same sensor at another location, or for the same location at another time. The reasons for this are many: through the course of a year, the sun angle changes causing different lighting conditions; from pass to pass, the viewing angle of the instrument can be different; with seasonal changes, surface reflectance varies due to weather conditions and the alteration of land cover as crops appear in different stages; atmospheric conditions fluctuate; and the sensor and spacecraft themselves age and possibly perform differently.

The key factor in any accuracy assessment of remote sensing data is the method and source used for determining what the satellite sensor is actually viewing. This ground reference data is gathered independently of the remote sensing data itself. There are several sources that can be construed as ground reference data, and each source has its own degree of accuracy. The most obvious is an actual site visit to the
area of interest. What is observed, also known as “ground truth,” is recorded and compared to the digital rendition of the same spatial extent. This approach usually has a high degree of accuracy, but it is often prohibitively expensive. Depending on the time between the on-site ground reference gathering and the imaging of the area, the validity of the ground reference data may be lessened due to anthropomorphic or natural influences. The shorter the life of the feature being measured, the more difficult it is to find or gather meaningful time-critical ground reference data. If ground reference data are not available, it may be possible to perform photointerpretation with some degree of success. This itself depends on the knowledge of the photointerpreter, and the availability and suitability of a display device for viewing the image data and recording the photointerpreter’s assessment. A newer approach is to compare the digital image with other sources of ground reference data such as air photos or appropriate reference maps, provided the feature of interest is detectable using those sources. The degree of correspondence between the ground reference data and the measurements derived from the sensor data can then be compared for accuracy. In the worst case, the lack of adequate/accurate ground reference data requires using an unsupervised clustering approach that is usually less accurate but much cheaper to produce.

### 79.5 Future in Satellite Imaging and Sensing

Success of future earth and space science missions depends on increasing the availability of data to the scientific community who will be interpreting space-based observations, and on favoring interdisciplinary research for the analysis and use of this data. One of the main challenges in the future of satellite imaging and sensing will be to handle, archive, and store all of these data in a way that can be easily accessible and retrieved by anyone who needs to use them. Systems such as the EOS Data and Information System (EOSDIS) [57, 58] will require that over 1 terabyte per day be collected and processed into several levels of science data products within several hours after observation. After 15 years, the estimated amount of collected, processed, analyzed, and stored data will equal about 11,000 terabytes. Also at NASA, efforts are underway to design an advanced information system, based on an object-oriented database, with the express purpose of developing, incorporating, and evaluating state-of-the-art techniques for handling EOS-era scientific data challenges [59].

Another challenge will be to analyze this tremendous amount of data, and to find out new ways to fuse, integrate, and visualize this data. In particular, research in fast computational capabilities, such as field programmable gate arrays (FPGAs), will be of great importance.

On the other hand, the wide distribution of satellite data to the general public will be facilitated by regional distribution systems such as the Regional Application Centers (RACs) [60, 61], whose goal is to provide local users, such as industry, agriculturalists, urban planners, regional communities, with local and “on-time” information about regional applications.

Satellite imaging and sensing is a field with a history of more than two decades, but is still in full expansion. The future in satellite imaging and sensing will see developments in several areas. The next millennium will see an explosion of commercial satellite systems and the profusion of satellite data, which will have economic and sociopolitical implications. As of this writing, over 30 commercial Earth sensing satellites are either being planned or being built. MTEP and EOS will generate unprecedented amounts of diverse resolution data. The future will also see the development of locally directed satellite systems, in answer to specific applications for specific areas of the planet. Telecommunications will also be a large part of the space market. In space, after the large success of the Mars Pathfinder mission, exploration of distant planets will see a flourishing of distant satellite systems providing unprecedented amounts of data to analyze regarding other planets’ surface features, atmospheric, and magnetic properties. The understanding of other planets will also enable scientists to learn more about the Earth comparatively to other planets such as Mars, and to build a comprehensive data set to aid in planning future missions. The Mars Global Surveyor is an example of such as a mission; it will map the entire planet Mars by taking high-resolution pictures of the surface. The future might see a 10 year NASA program that will send pairs of Surveyor-like orbiters and Pathfinder-like landers to Mars every 26 months.
In order to gather novel and interesting data, this type of mission will need an increasing amount of on-board processing that will perform mission planning, image processing and understanding, as well as data compression and fusion. The design of systems including on-board processing will require new computational capabilities, such as reconfigurable hardware and parallel processors, as well as new developments in intelligent systems. In the near future, satellite imaging and sensing is a field that will produce unprecedented information about the Earth, its environment, and our solar system.

Acknowledgments

The authors would like to thank William J. Campbell for his support and for his useful comments upon reviewing our paper, Bob Mahoney for providing the spectral libraries used to generate Figure 79.2, and all the anonymous or nonanonymous authors of Web pages that we consulted during the research part of this endeavor. In particular, the online remote sensing tutorial by N. M. Short, edited by J. Robinson at the URL http://code935.gsfc.nasa.gov/Tutorial/TofC/Coverpage.html, and the list of selected links on remote sensing compiled by U. Malmberg and found at the URL http://www.ssc.se/rst/rss/index.html were very useful.

References

37. TOPEX/Poseidon: Decoding the Ocean, French Space Agency/CNES Report, December 1993, available from Centre National d’Etudes Spatiales, 2 Place Maurice Quentin, 75039 Paris Cedex 01, France.