1a) Remote sensing may be more formally defined as the acquisition of information about the state and condition of an object through sensors that do not touch it.

1. An energy source, which produces the electromagnetic radiation that interacts between the sensor and the surface. The most important source of energy is the Sun, as it illuminates and heats the Earth.
2. Earth’s surface, consisting of vegetation, soils, water, rocks, snow, ice, and human structures. These surfaces receive the incident energy from the source (1) and, as a result of physical and chemical interaction with the incoming energy, reflect and emit a part of that energy back toward the satellite sensor. Part or the whole energy pulse may be filtered by the atmosphere, depending on its gas and particulate matter concentrations.
3. Sensor and platform. The sensor is the instrument measuring and recording the energy coming from the surface. The platform provides the major services for sensor operation, such as attitude and orbit control, power supply, and communications with the ground receiving system. Ordinarily an EO satellite includes different sensors, depending on its main mission. Meteorological satellites commonly include sensors to detect atmospheric humidity, temperature, albedo, ozone, or aerosol concentrations.
4. The ground receiving system collects the raw digital data measured by the sensor, stores the data, and formats them appropriately. Some basic preprocessing corrections are performed by the ground system, prior to the distribution of the imagery.
5. The analyst, who converts the processed image data into thematic information of interest, using visual and/or digital techniques.
6. The user community, which utilizes the information extracted from the original data for a wide variety of applications.

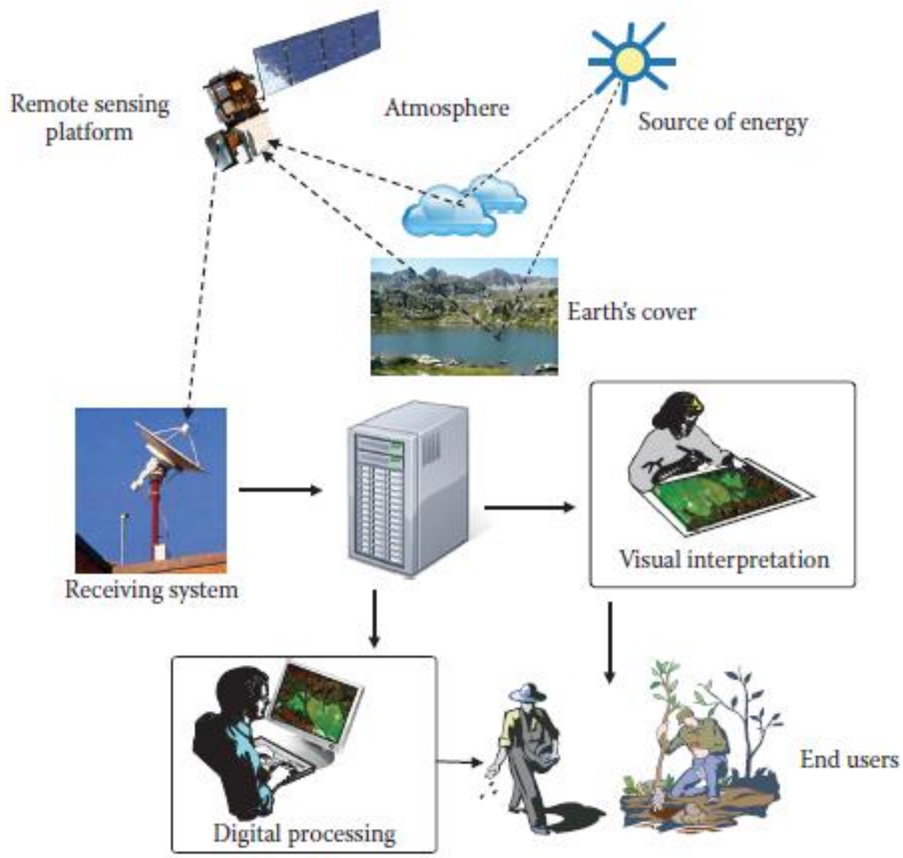

FIGURE 1.1 Illustration of the main components associated with remote sensing activities.

1 b)

The United Nations sponsored the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, also known as the Outer Space Treaty, which was adopted by the General Assembly and entered into force on October 10, 1967. Ninety-nine states have ratified, and an additional twenty-six have signed this treaty as of January 2008. The Outer Space Treaty provides the basic framework on international space law and guarantees that exploration and use of outer space shall be carried out for the benefit and in the interests of all countries. Additional principles governing the use of remote sensing included in this treaty are as follows:

- Remote sensing shall promote the protection of Earth's natural environment.
- Remote sensing shall promote the protection of humankind from natural disasters.

- The observed state shall have access to all primary and processed data acquired over its territory on a nondiscriminatory basis and on reasonable cost terms.
- The observed state shall also have access to the available analyzed information concerning the territory under its jurisdiction, taking particularly into account the needs and interests of the developing countries.
- States carrying out remote sensing activities shall promote international cooperation in these activities. To this end, they shall make available to other states opportunities for participation therein. Such participation shall be based in each case on equitable and mutually acceptable terms.
- Furthermore, a state must inform both the Secretary-General of the United Nations, as well as the interested nations that request it, of the remote sensing programs that will be developed.

2a)

1.4 BENEFITS OF ENVIRONMENTAL MONITORING FROM SATELLITE SENSORS

Satellite remote sensing has several advantages over other conventional methods of environmental sampling and monitoring, such as in situ field measurements or ground sensors. Spaceborne sensors provide a global view over the Earth's surface, at periodic times and including nonvisible regions of the electromagnetic spectrum. Data are accessible quickly and can be easily connected to other spatial databases, thus making a suitable information source for spatial data integration. More details on these characteristics follow.

1.4.1 Global Coverage

Satellite data are acquired by a platform that has a stable orbit around the Earth. Therefore, EO sensors make it possible to acquire consistent and repetitive imagery of the entire planet, including areas that are fairly remote and normally inaccessible, such as polar, mountain, desert, and forest areas. For example, remote sensing has been found to be highly useful in mapping and monitoring ice sheets, a particularly relevant topic for water mass studies in the context of Arctic warming (Figure 1.8). Other examples include the use of remote sensing in detecting remote forest fires, observing uncontrolled oil spills, and assessing damage from tsunamis or floods.

The global coverage provided by satellites is particularly useful in monitoring and understanding the dynamic processes affecting our environment. There is much concern over the many stresses placed on the environment, such as global warming, reduction in biologic diversity, depletion of freshwater, and land degradation and desertification. Tropical glaciers in the Peruvian Andes and the famous snows of Mount Kilimanjaro in East Africa are retreating rapidly and are predicted to disappear over the next two decades. By some estimates, as much as 40% of the Earth's land surface has been permanently transformed by human action, with significant consequences for biodiversity, nutrient cycling, soils, and climate.

1.4.3 Multiscale Observations

Satellite-based sensors, as will be discussed in more detail later, have a wide range of orbital altitudes, optics, and acquisition techniques. Consequently, the imagery acquired can be at very fine resolutions (fine level of detail) of 1 m or less with very narrow coverage swaths, or the images may have much larger swaths and cover entire continents at very coarse resolutions (>1 km) (Figure 1.10).

1.4.4 Observations over the Nonvisible Regions of the Spectrum

Satellite sensors are capable of acquiring data over various portions of the electromagnetic spectrum that cannot be sensed by the human eye or conventional photography. The ultraviolet, near-infrared, shortwave infrared, thermal infrared, and microwave portions of the spectrum provide valuable information over critical environmental variables. For example, the thermal infrared portion of the spectrum allows us to study the spatial distribution of sea surface temperatures and marine currents, as well as water stress in crops. The ultraviolet radiation is critical to monitor the ozone layer. The middle infrared region is ideal to sense CO_2 concentrations and the microwave radiation is more sensitive to estimate soil moisture and snow cover.

1.4.5 Repeat Observation

The orbital characteristics of most satellite sensors enable repetitive coverage of the same area of Earth's surface on a regular basis with a uniform method of observation. The repeat cycle of the various satellite sensor systems varies from 15 min to nearly a month. This characteristic makes remote sensing ideal for multitemporal studies, from seasonal observations over an annual growing season to interannual observations depicting land surface changes (see Section 7.3). Such periodic observations are vital given the highly dynamic nature of many environmental phenomena. There are many examples of multitemporal applications of remote sensing, including desertification studies (Figure 1.11), drought and flooding patterns, snow cover melting, deforestation assessments, and meteorological phenomena.

1.4.6 Immediate Transmission

Nowadays, all remote sensing systems record image data in digital format, facilitating a real-time transmission to the ground receiving station and eventually to the end user. This is particularly relevant when dealing with disasters and natural hazards that require quick access to imagery (as it is the case of the International Disaster Charter: https://www.disasterscharter.org/web/guest/home).

Traditionally, only meteorological sensors had direct transmission to the end user, as the signal was not codified and could be acquired by a relatively cheap receiving antenna. Currently, images from global sensors can still be acquired freely, in the case of MODIS, for instance, using a more sophisticated antenna. In addition, the Land Rapid Response system provides near-real-time data of some products, such as the active fire information that are received by email within hours of satellite acquisition. For most medium- and high-spatial-resolution sensors, images can be obtained fairly quickly using fast Internet connections, but ordinarily not yet in real time as the signal is usually coded. These sensor systems transmit images when they are within the coverage area of the antenna or otherwise record onboard for later transmission. The user obtains the image with a certain time delay, due to calibration and preprocessing of the data.

1.4.7 Digital Format

As most images are now in digital format, the integration of satellite-derived information with other sources of spatial data is relatively straightforward. Computer-assisted visualizations of image data are also possible, as in the generation of 3D views by combining satellite imagery with digital elevation models (Figure 1.12). These views can be created from different angles and under different simulated conditions.

2b)

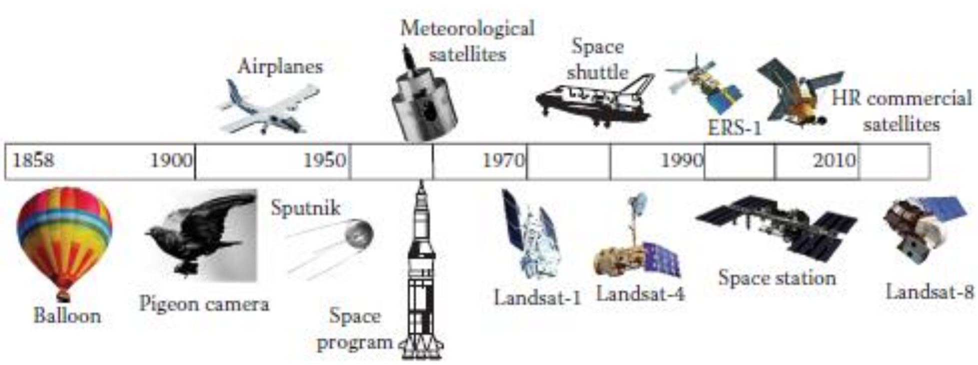

FIGURE 1.2 Historical development of remote sensing systems.

The first remote sensing acquisition can be traced back to the mid-1800s, along with the development of aerial photography. In 1839, the first ever photos were taken in France by Daguerre, Talbot, and Niepce, and by 1840 the French began using photos to produce topographic maps. In 1858, the first aerial photos were taken from a height of 80 m over Bievre, France, by Gaspard Félix Tournachon using cameras mounted on a hot air balloon. The first balloon photographies used for urban planning were acquired by James Wallace Black in 1860 over the city of Boston. The first attempts to use the new perspective provided by aerial platforms in military reconnaissance occurred in 1861, during the American Civil War, when Thaddeus Lowe

was appointed Chief of the Union Army Balloon Corps by President Abraham Lincoln. In the 1880s, the British used kites to obtain aerial photography, and in the early 1900s, carrier pigeons were able to fly as more advanced, smaller, and lighter cameras were developed. The great San Francisco earthquake of 1906 was captured on film using a panoramic camera mounted 600 m above San Francisco Bay and supported by a string of kites.

The next major milestone in remote sensing occurred in 1909, when Wilbur Wright shot the first photographs over Italy from an airplane, establishing a new era of observations from airborne platforms. By 1915 and during World War I, the British Royal Air Force was collecting aerial reconnaissance photos with cameras designed specifically for aircraft surveying (Brookes 1975). In 1930, the first aerial multispectral photographs were collected by Krinov and colleagues in Russia. The following year, the first near-infrared film was developed and tested by Kodak Research Laboratories.

In the 1940s, the military made significant advancements in the development and use of color infrared films, which were used to distinguish real vegetation from camouflaged targets that were painted green to look like vegetation. The greatest developments in aerial reconnaissance and photo interpretation were made during World War II. Other significant advancements were made with thermal scanners and imaging radar systems, which create images by focused radar beams that scan across an area.

In the late 1940s and early 1950s, improved navigation systems gave way to the first space-based sensor devices. Early experiments with the V-2, Aerobee, and Viking rockets recorded panoramic images of the Southwest United States from altitudes of 100–250 km. The first space-based photo was taken on March 7, 1947, at about 200 km above New Mexico while testing captured German V-2 rockets (Figure 1.3). In 1950, scientist Otto Berg pieced together several photos from one of these tests into a mosaic of a large tropical storm over Brownsville, Texas.

3a)

1. Radiant energy (Q), measured in joules (J), is the most basic energy unit and refers to the total energy radiated in all directions away or toward a surface.

Radiant irradiance (E) is the radiant flux density *incident upon* the surface per unit area and per unit time (W m^{-2}). It is the same concept as the radiant exitance, but in this case it refers to the energy arriving at the surface rather than leaving the surface.

Emissivity (ε): This is the relationship between the radiant exitance of a surface (M) relative to that of a perfect emitter at the same temperature (M_n). A perfect emitter is also known as a blackbody and has emissivity 1. Natural materials, on the other hand, are imperfect emitters with emissivity values ranging from 0 to <1. Emissivity values over different wavelengths are useful in characterizing materials.

Radiant exitance or emittance (M) is the radiant flux density *leaving the surface* in all directions per unit area and per unit time (W m^{-2}).

These unitless terms can also have *spectral* added to them, as in spectral reflectance. There are a few useful relationships that are derived from the aforementioned energy terms. The term *albedo* is the ratio of all outgoing energy to the incident energy for a given surface area. More specifically, albedo is the ratio of exitance (M) to irradiance (E) over all solar reflective, or shortwave, wavelengths and is the equivalent of hemispherical reflectance, that is, the reflectance integrated over all directions (Equation 2.4). Albedo is a fundamental variable in energy balance studies, climate modeling, and soil degradation studies. Spectral albedo refers to the exitance divided by the irradiance for a specific spectral band (Equation 2.5):

$$\text{Albedo} = \rho_{\text{hemispherical}} = \frac{M}{E} \quad (2.4)$$

3b)

Spectral signatures form the basis to discriminate objects from remote sensing measurements in the solar region of the EM spectrum. Unfortunately, these signatures are not constant for each cover, as the radiance flux detected by remote sensing depends not only on the intrinsic properties of the observed area but also on the external conditions of the measurement. The main factors affecting spectral signatures are the following (Figure 2.9):

(i) Atmospheric components, which affect both the absorption and the scattering of incoming and reflected radiation.
(ii) Land cover variations causing changes in chemical or physical composition, such as density, pigment contents, moisture, or roughness. They may be caused by vegetation or crop phenology, agricultural practices, grazing, etc.
(iii) Soil and geologic substrate, which are particularly important in open and sparse canopy covers, as the sensor will detect a stronger signal coming from the background.
(iv) Solar illumination conditions, which depend on the latitude, day of the year, and hour of the day.
(v) Terrain slope.
(vi) Aspect, both affecting the illumination conditions of a target cover.

4a)

2.4 ELECTROMAGNETIC RADIATION LAWS

There is a set of physical laws that govern the behavior and characteristics of EM radiation. We saw in Equation 2.3 that the energy content of EM radiation varies inversely with wavelength. The spectral distribution of EM radiation emitted by a blackbody (a perfect emitter) can be characterized by Planck's radiation law as follows:

$$M_{n,\lambda} = \frac{c_1}{\lambda^5 (e^{(c_2/\lambda T)} - 1)} \quad (2.8)$$

where

$M_{n,\lambda}$ (W m^{-2} μm^{-1}) indicates the radiant spectral exitance at a certain wavelength (λ in μm)
c_1 and c_2 are constants ($c_1 = 3.741 \times 10^8$ W m^{-2} μm^4 and $c_2 = 1.438 \times 10^4$ μm K)
T is the absolute temperature (K)

This equation describes the spectral exitance distribution of a blackbody at a certain temperature as a smooth curve with a single maximum (Figure 2.5). Planck's equation indicates that any object hotter than absolute zero (–273°C) emits radiant energy and that the energy increases in proportion to its temperature. As shown in

Figure 2.5, with increasing temperature, an object will radiate more energy and with higher exitance in shorter wavelengths.

The total radiant energy per unit surface area is a function of the object's temperature. The value can be obtained by integrating the spectral radiant exitance over all wavelengths. This is known as the Stefan–Boltzmann law:

$$M_n = \sigma T^4 \tag{2.9}$$

where

σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})

T is the temperature in Kelvin

As M_n is the fourth power of T, small changes in temperature result in large variations in radiant exitance.

Kirchoff's law enables us to extend the foregoing relationships describing blackbody emission behavior to naturally emitting surfaces through an emissivity (ε) correction:

$$M = \varepsilon \sigma T^4 \tag{2.10}$$

A blackbody is a perfect emitter in that it absorbs and emits all the energy it receives. When an object does not absorb any of the incident energy, it is called a white body,

4b)

2.8.2 Atmospheric Scattering

The scattering of EM radiation is caused by the reflection of incoming solar radiation by gases, aerosols, and water vapor present in the atmosphere. As a result, radiation detected by the sensor is a mixture of both surface and atmospheric reflected energy, and thus contains an undesirable noise that needs to be removed during the retrieval of the surface properties. At the surface, the direct irradiance is reduced, while diffuse radiance (coming from other objects) increases.

Aerosols originate from both natural and human causes. They can be oceanic, caused by the water movement, or continental, as in dust in suspension or particles emitted by combustion. Because these atmospheric particles are highly variable in time and space, correction of atmospheric scattering is rather problematic. However, this factor must be taken into account whenever a fine estimation of ground radiance is required: for instance, when satellite measures are compared with ground radiometric measurements, or when we try to detect changes between two images acquired several years apart. Normally, in situ atmospheric measurements are not available at satellite acquisition times, and therefore atmosphere correction often needs to rely on data extracted from the image itself. Some methods may involve changes in reflectance across several bands or from several observation angles (see Section 6.6).

Ideally, aerosol impacts need to be removed when the objective is the retrieval of ground properties. However, aerosols can also be the target of a remote sensing analysis, as they are very relevant for climate or human health, for instance. In this case, the retrieval of aerosol optical depth (AOD) is based on differential absorption (comparing reflectance measurements in wavelengths with high and low dispersion) or on differential observation angles (comparing reflectance measurements from nadir and off-nadir observations, analyzing different atmospheric thicknesses). Commonly, the satellite retrievals of AOD are compared with estimations from ground-based photometers, with very high correlations (de Leeuw et al. 2013).

Based on their origin and characteristics of aerosols, they vary widely in size, which causes different types of dispersion, since this process is highly dependent on the diameter of the scattering particles. The three main types of atmospheric dispersion are Rayleigh scattering, which is caused by particles smaller than the wavelength of the radiation; Mie scattering, when the particle is similar in size to the wavelength; and nonselective scattering, when the size of the particle is greater than the wavelength.

Rayleigh dispersion is highly dependent on the wavelength and mainly affects the shortest bands. It causes, for example, the blue color of the sky because blue is the lowest wavelength of the VIS spectrum. In aerial photography, the effect of Rayleigh scattering is very clear, as it leaves a bluish tone in photographs taken from high elevations.

Mie scattering is also dependent on the wavelength of incoming radiation, although to a smaller degree than Rayleigh scattering. Aerosols and atmospheric dust are the main causes of this type of dispersion, although it is also caused by forest fires or coastal mist.

Finally, the nonselective scattering affects various wavelengths equally. That is why clouds and fog tend to appear in gray tones, since they disperse the different bands of the VIS spectrum in a similar way.

5a)

3.1 RESOLUTION OF A SENSOR SYSTEM

In general terms, we can define the resolution of a sensor system as its ability to discriminate between information (Estes and Simonett 1975). This concept includes several aspects that deserve detailed discussion. First, the resolution of a sensor refers to the system as a whole instead of its individual components. For example, improvement of the lens does not imply acquisition of higher photographic resolution if a more sensitive film is not used or if exposure conditions are not modified.

3.1.1 Spatial Resolution

Spatial resolution identifies the smallest object that can be detected on an image. In a photographic system, spatial resolution identifies the minimum separation at which objects appear independent and isolated. It is measured in millimeters on the photograph or in meters on the ground, and it depends on the focal length of the camera and the height of the camera above the ground. In optical electronic sensors, the term "instantaneous field of view" (IFOV) is commonly used instead. The IFOV is defined as the angular section observed by the sensor, in radians, at a given moment in time. In practical terms, the most common definition of sensor spatial resolution is the size of the projected IFOV on the ground (*d*), computed as follows (Figure 3.1):

$$d = 2h \tan\left(\frac{\text{IFOV}}{2}\right) \qquad (3.1)$$

where

d is the distance on the ground per each information unit (pixel)
h is the height of the observation

3.1.4 Temporal Resolution

Temporal resolution refers to the observation frequency (revisiting period) provided by the sensor. This cycle is a function of the orbital characteristics of the satellite (height, speed, and declination), as well as the sensor FOV. Sensors with high temporal resolution have coarse spatial resolution as they will be able to observe a larger area in each image acquisition. Consequently, they also have wide FOV, which implies geometrical problems, as the same area may be observed from very different angles in a daily time series. We will later comment how this problem can be mitigated (see Section 6.7.3.4). If the sensor observes a smaller area (narrower FOV), it will need more orbits to repeat the same observed area; therefore, the acquisitions will have higher time gaps. To alleviate this problem, some sensors can make off-nadir observations, detecting adjacent areas to the orbit (pointing capacity typically goes from 0° to 20°). This is the case of cameras on board the SPOT or WorldView satellites. An alternative to nadir-looking sensors is to have several satellites with the same characteristics. This is the case of the RapidEye constellation (owned by a private company), which provides daily global acquisition frequency at 6.5 m resolution using five satellites.

5b)

3.2.3 Along-Track (Push-Broom) Scanners

In the early 1980s, a new scanning technology was tested by the German space agency on board a Space Shuttle mission, which became operational in 1986 with the launch of the French satellite SPOT. Along-track scanners avoid the use of an oscillating mirror by detecting the whole FOV of the sensor system at once, using a linear array of detectors. The sensor explores each line simultaneously and creates the image along with the satellite orbital track (Figure 3.11). For this reason, these sensors are named push-broom or along-track scanners. Similar to the across-track

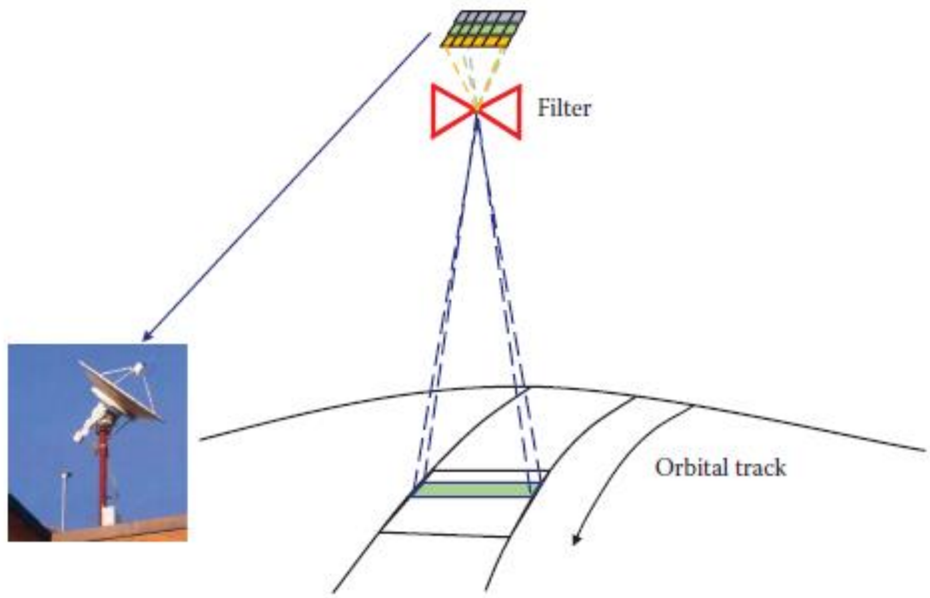

FIGURE 3.11 Scheme of the functioning of an along-track scanner.

The sensor samples the observed ground surface at systematic time intervals. Each of the instantaneous measurements becomes one digital value in the final image, which is the basis for the visual or digital interpretation of each pixel.

Multispectral scanner (MSS) systems were introduced in the early 1970s in EO satellite systems, such as the Landsat MSS, the Skylab S192, or the Nimbus Coastal Zone Color Scanner (CZCS). They presented several advantages over the then used analog cameras for EO satellites, as they were able to observe nonvisible bands

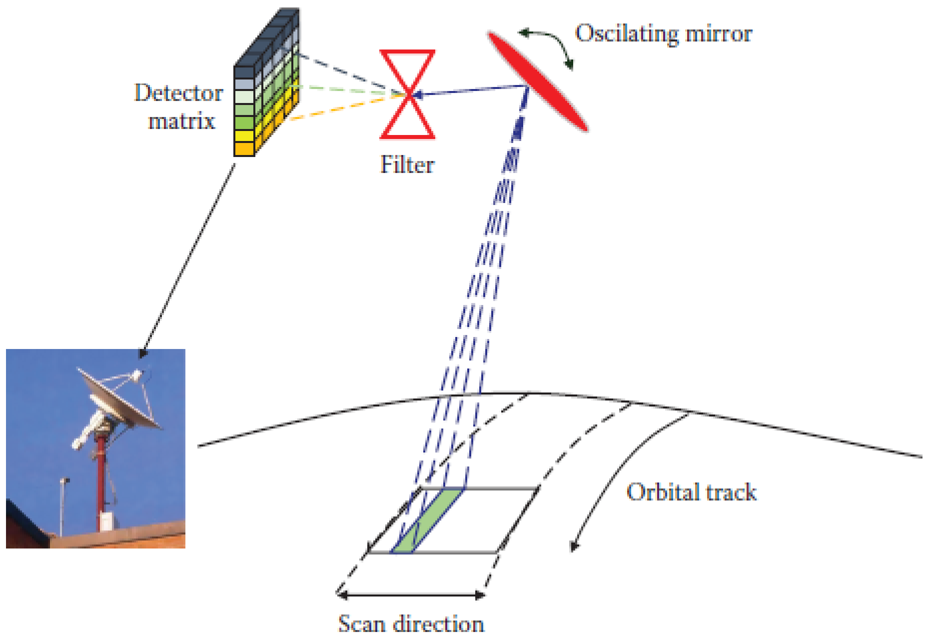

FIGURE 3.10 Scheme of the functioning of an across-track scanner.

6 a)

The range resolution depends on the length of the pulses emitted (Figure 3.14). Two objects can be discriminated when their ground distance is greater than half the pulse wavelength (half because the beam has to travel back and forth). Additionally, the discrimination depends on the incidence angle (θ). To increase the length of the pulse, it is necessary to decrease the frequency, but this will imply a higher noise. This paradox is solved by modulating the frequency of the emitted and received pulses. In summary, the range resolution is given by

$$r_{range} = \frac{c}{2B\sin\theta} \tag{3.3}$$

where

c is the speed of the electromagnetic energy

B is the spectral bandwidth

θ is the angle of incidence

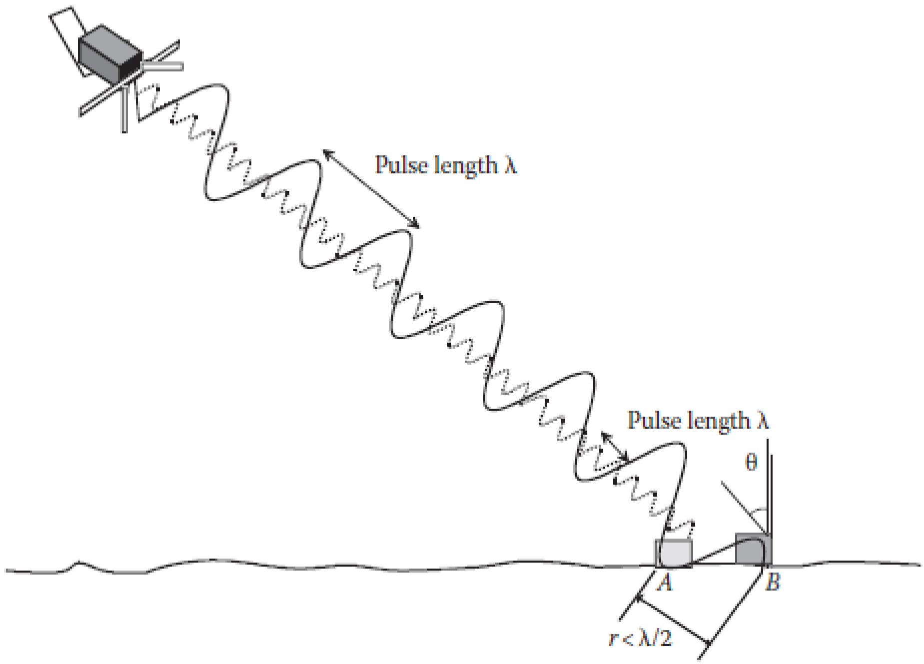

FIGURE 3.14 Range resolution of a radar system.

As for the azimuth resolution, the minimum distance on the ground between two discernible objects on the image depends on the wavelength (λ), the distance between the antenna and the surface (h), and the antenna's length (L_a) (Figure 3.15):

$$r_{az} = \frac{h\lambda}{L_a} \tag{3.4}$$

Although in a synthetic aperture system the length of the antenna is incremented artificially, since it is generated from the two different signals registered in two different moments along the trajectory, the azimuth resolution is still dependent on the distance of the observed object. In consequence, since the distance between the object and the antenna changes from the nearest end to the most distant column of the image, it changes the effective spatial resolution across the image. Homogenization of the pixel size, therefore, requires postprocessing. A common method is slant-range correction, which takes into account the change in pixel size across the satellite trajectory:

$$Pr = \frac{c\tau_p}{(2\sin\theta)} \tag{3.5}$$

where

τ_p is the pulse length
θ is the incidence angle

6b)

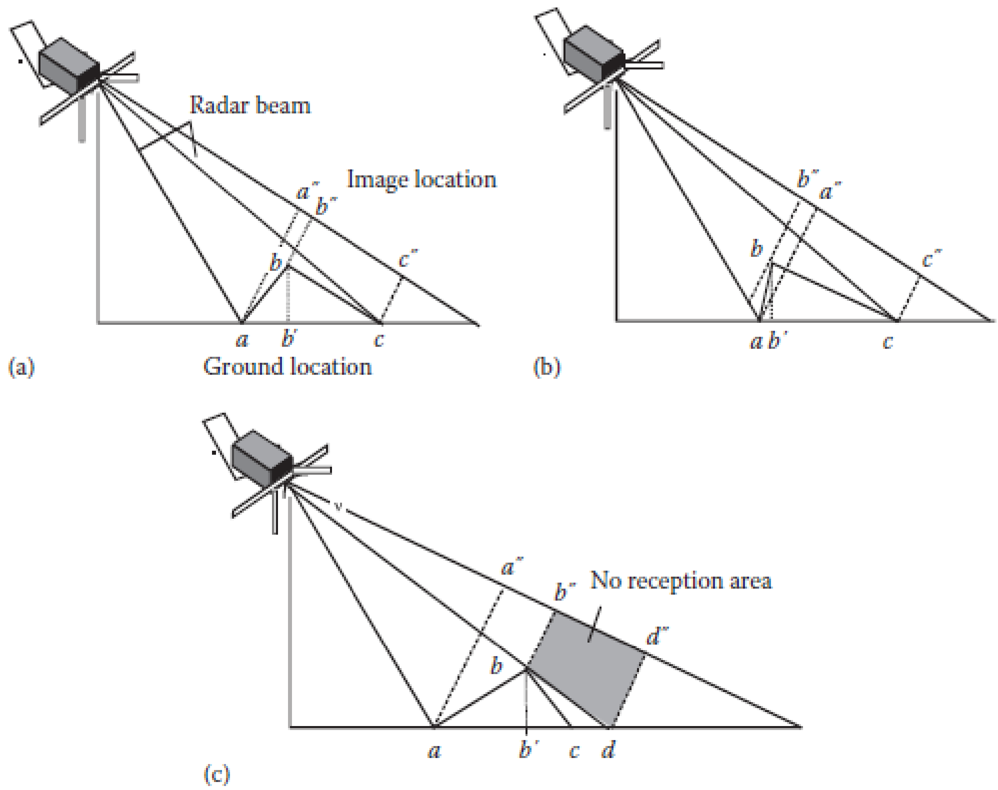

FIGURE 3.17 Terrain effects on a radar image: (a) shortening of radar-facing slopes, (b) layover, and (c) radar shadows.

effect may occur, that is, the inversion of the real position of objects throughout the slope, because the echoes reach the antenna in inverse order to their real location.

These factors can be corrected if detailed digital elevation models are available. Corrections are more complex when slopes facing away from the radar trajectory are not observed at all (radar shadows). That information may be retrieved if a satellite trajectory provides two or more observation angles, which frequently occurs with ascending and descending orbits of satellite radar missions. An example of two images acquired by the European satellite ERS-1 over a mountain area in Central Spain may help to understand better the impact of rough topography on radar images.

6c)

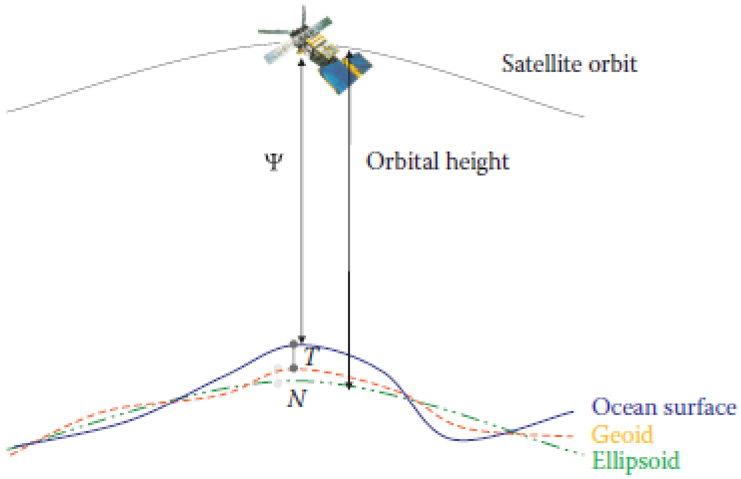

FIGURE 3.19 Principles of radar altimetry. (Adapted from Robin, M., La Télédétection, Nathan, Paris, France, 1998.)

$$r - Rs - \psi = N + T + Ar \tag{3.6}$$

where

- ψ is the radar altimeter measurement
- $r - Rs$ is the elevation with respect to the reference ellipsoid
- N is the height of the geoid–ellipsoid at the point
- T is the sea level ellipsoid
- Ar is the measurement error

Radar altimeter measurements have been very useful to monitor ocean currents associated with El Niño events or other climatic phenomena. They are also very useful for monitoring water reservoirs, both of dams and natural lakes (Birkett 1998) as well as sea level rise (Figure 3.20), which is one of the main negative impacts of global warming.

7a)

The interpretation of digital values acquired by the sensor can be approached in different ways, leading to several procedures to extract information from remote sensing data. Considering the final goal of the interpretation process and the target variables, four types of interpretation approaches can be distinguished (Figure 4.3): thematic classification, generation of biophysical variables, change detection, and spatial patterns.

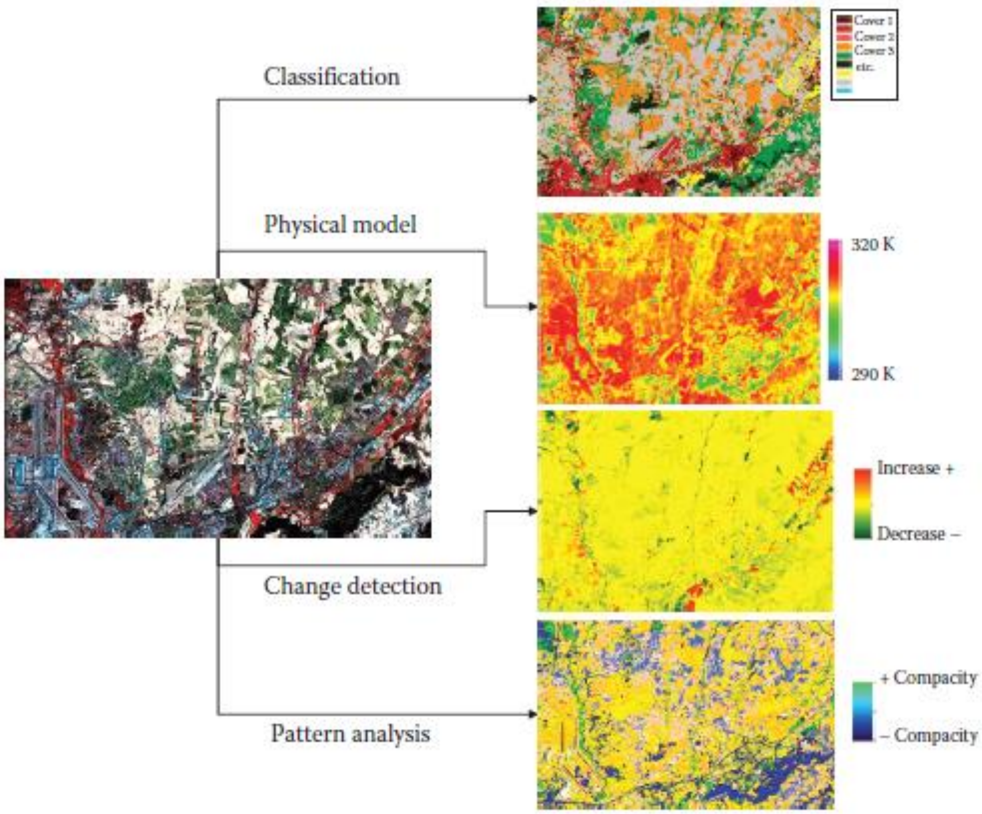

FIGURE 4.3 Different approaches to image interpretation.

8a)

4.4 INTERPRETATION PHASE

The applications of satellite remote sensing are numerous and diverse, making it difficult to establish a general framework applicable to all of them. However, we believe it is worth describing a general workflow that may help use remotely sensed imagery for a particular application with the necessary adaptations. We will review this process using as an example the case of a fishing company trying to locate a certain species breeding area, once it knows the ideal range of thermal and chlorophyll conditions.

The proposed scheme is included in Figure 4.6 and involves the following phases:

1. A clear and well-defined set of objectives is needed, indicating the limitations of the study area (heterogeneity), time, or scale required for the application (duration of project, maximum cost, thematic categories to be discriminated) and the resources available. In the case of the fishing industry, these requirements should be set by the company following its end needs.
2. Fieldwork is used in several stages of the interpretation phase. The first stage involves the general characterization of the study site, its environmental characteristics, and associated human activity, which may greatly help the selection of images (dates of the season, selecting the period when it is easier to discriminate the target phenomenon). During this phase, measurements with field radiometers can be taken (Figure 4.7) for a better spectral characterization of the area as well as to select the most adequate sensor and bands to discriminate the target variable. This work may also help identify ancillary data that may be needed for later interpretation and analysis of the image. Obviously for oceanographic applications, these analyses are

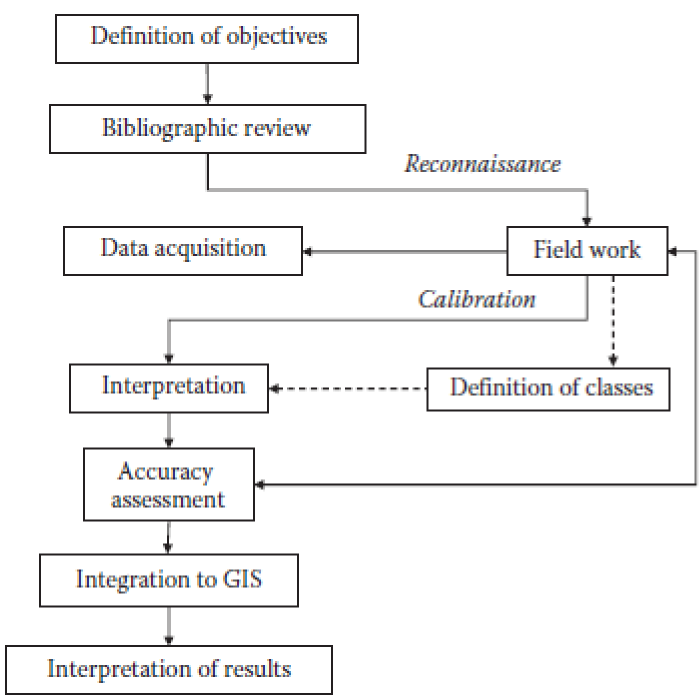

FIGURE 4.6 Generalized procedure for the interpretation of remote sensing imagery.

8b)

4.1.3 End-User Requirements

The use of remote sensing has been generalized in many applications, but for others it is still scarce or nonexistent. This may be either because the available data do not meet the real requirements of that user community or because the RS community has not properly understood user needs.

The beginning of EO satellite missions was characterized by few and general-purpose systems, which tried to maximize the benefits of the acquired information. This implied the selection of the spatial, spectral, and temporal resolutions that would serve a wide user community, as the investments to develop and launch satellite missions were very high.

Nowadays, the decrease in cost of technical components and weights makes an EO satellite mission affordable, even for medium-size countries and private corporations. This also implies that the needs of specific user communities can be met, optimizing the technical requirements. This has been the case of the atmospheric community, which has been able to develop specific missions for retrieving the concentration of certain gases, such as CO_2, CO, CH_4, ozone, water vapor and clouds, aerosols, etc. A similar conclusion can be drawn of oceanographic systems, but this is not yet the case of land applications community, which still lack specific missions that could serve the needs of a certain service. For instance, if satellite systems are intended to replace terrestrial observation networks for fire detection, they should provide very frequent observation ($\leq$30 min) of high-temperature sources for small areas (<50 m^2). There is not yet a single satellite mission that accomplishes all these requirements, and it is unlikely that a mission will be designed for this purpose in the near future. Consequently, satellite observation would not be an alternative for fire managers in those countries with good ground fire prevention infrastructures. However, it is very useful for countries that do not have field observations, since even one or two daily detections would significantly improve their current information. For those end users, current satellite missions may already be considered operational for detection of fires.

Something similar can be said about the estimation of vegetation biomass, which would need dedicated radar or lidar missions, which are still in the process of development.

9a)

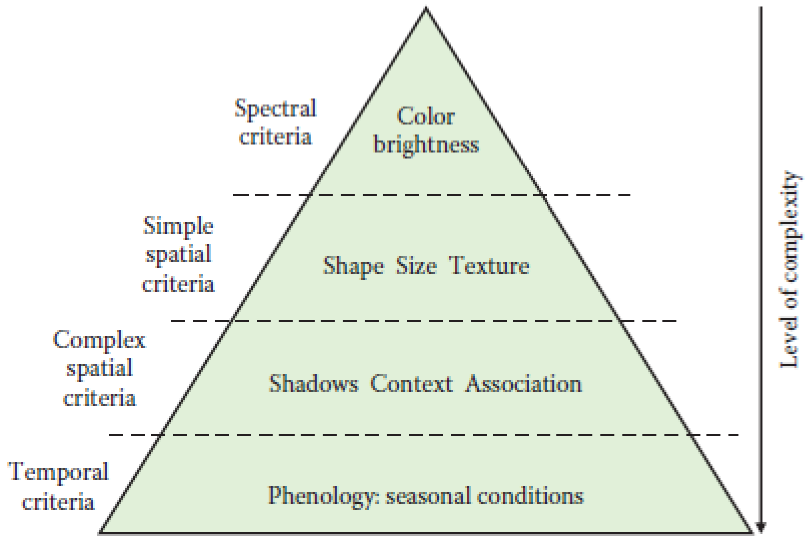

FIGURE 5.3 Hierarchical organization of visual interpretation criteria. (After European Commission, *Corine Land Cover: Guide Technique*, Office for Official Publications of the European Union, Luxembourg, Europe, 1993.)

5.4 ELEMENTS OF VISUAL ANALYSIS

Having reviewed the main criteria for visual interpretation, we will now review a series of elements that must be taken into account when working with satellite images.

5.4.1 Geometric Characteristics of a Satellite Image

Although satellite images have fewer geometric errors than aerial photographs, because of greater stability and higher flight altitude of the platform, they are not free from geometric errors, and therefore they cannot be directly overlaid on standard

5.4.2 Effect of Spatial Resolution in Visual Analysis

As previously mentioned, spatial resolution refers to the size of the minimum discernible unit on the image. This concept, in visual analysis, is related to the pixel size as well as the scale at which the image is represented. Therefore, spatial resolution has an important impact on the interpretation of the scene and its minimum discriminating unit. As we have seen, elements smaller than the pixel size will not be discriminated in the image; this is essential for selecting the most adequate sensor to meet the desired objectives. Higher resolution implies better definition of the

5.4.3 Effect of Spectral Resolution in Visual Analysis

As we have pointed out in several sections of this book, multispectral observations are the basis of identification and detection of surface features and covers in satellite images. The possibility of observing surface features in several bands of the spectrum extends remarkably our capacity to recognize them. The spectral signature

5.4.4 Color Composites

Once the brightness levels for the different land covers have been identified, it becomes simple to infer the color they will present in different color composites, keeping in mind what we previously learned regarding the additive process of color compositing. For instance, if using a false color composite (B2, B4, and B3 for MODIS applied to RGB, respectively, see Figure 5.8a), vegetation will be shown in red tones, since the brightness of vegetation in B2 is medium to high, while it is dark to very dark for B4 and B3. Similarly, snow will be white, since brightness levels are high in B2, B4, and B3, and water will be black for the opposite reason.

5.4.5 Multitemporal Approaches

The analysis of temporal change is very relevant for discriminating land covers, as well as for better understanding their seasonal trends. Figure 5.21 includes three MODIS images acquired at different times of the year: winter, spring, and the beginning of fall. This seasonal depiction enables us to discriminate the snow cover (winter image, white; spring and fall in dark), the permanence of irrigated crops (all dates dark), and the variations of turbidity in the Colorado River delta (note that in the May image, the sediments make the water appear very light in the red band). The bottom part of the figure shows the areas around Hoover Dam and part of the Grand Canyon. The variations of accumulated water (flooded areas) are notable, as well as the different shadowing effects caused by the variations in Sun's illumination on the canyon fringes.

10a)

A color composite can be obtained by combining three spectral bands using two different processes: *additive* and *subtractive*. In the additive process, a given color is obtained by adding light of different wavelengths. The more reflectance a pixel has, the more light (the brighter) that color will have in the composite. The three basic color guns are blue, green, and red. In the additive process, any other color is obtained by summing up light from two or more basic colors. For instance, cyan is the sum of blue and green, magenta is the sum of blue and red, and yellow is the sum of green and red. The three color guns together yield white color (Figure 5.5a). The additive process is the one used in electronic display systems (computer monitors, tablets, screen projectors), and it is the most commonly used for digital image processing systems.

The subtractive method is used in mechanical reproduction of color, typically in printed media (journals, books, etc.). The printed colors are obtained by mixing three basic inks: yellow, magenta, and cyan. In contrast to the additive process, the more reflectance a pixel has, the less ink it will have, since it needs to be brighter in the final composite. In other words, the more the ink, the darker the color, and the less reflectance in that particular band. As mentioned earlier, the subtractive process uses three elementary inks, and the other colors are obtained by mixing them (Figure 5.5b).

Among the multiple color combinations used in visual analysis, the most outstanding is known as "color infrared." This combination is obtained by shifting the visible bands toward longer wavelengths and applying RGB to the NIR, R, and G,

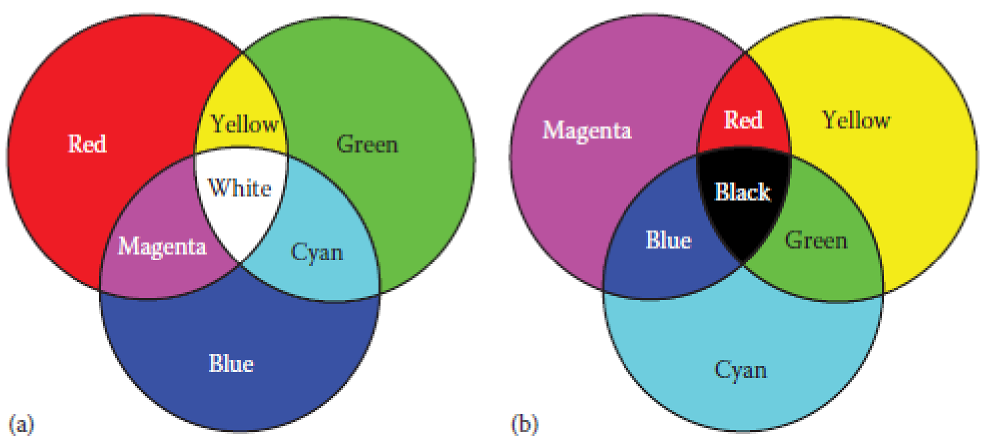

FIGURE 5.5 Processes in color formation: (a) additive and (b) subtractive.

10b)

5.3.6 Shadows

Variations of illumination conditions may create severe problems in discriminating particular surfaces, and therefore shadows are considered as added noise in image interpretation (see Chapter 6 for shadow removal techniques). However, they can be useful in object recognition, since shadows give an estimate of the height and depth of objects. In addition, shadows enhance the interpretation of geomorphologic features and texture of the image, especially in forested zones.

Object height can be precisely determined if the Sun's angle at the time of image acquisition is available. A simple trigonometric equation applies here (Figure 5.13):

$$h = \frac{l_s}{\tan\theta} \tag{5.1}$$

where
- h is the height of the building
- l_s is the length of its shadow
- θ is the solar zenith angle

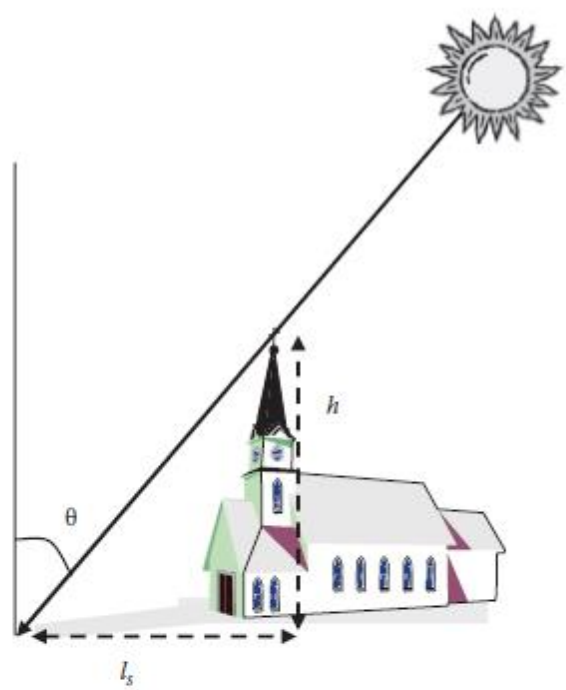

FIGURE 5.13 Estimation of a building height from its shadow length.