Chapter 1

Introduction

One of the major achievements of human beings is the ability to record observational data in the form of photographs, a science which dates back to 1826. Humans have always tried to reach greater heights (treetops, mountains, platforms, and so on) to observe phenomenon of interest, to decide on habitable places, farming and such other activities. Curiosity motivates human beings to take photographs of the earth from elevated platforms. In the initial days of photography, balloons, pigeons, and kites were used to capture such photographs. With the invention of the aircraft in 1903, the first aerial photograph on a stable platform was made possible in 1909 [120]. In the 1960s and 1970s, the primary platform that was used to carry remote sensing instruments shifted from aircraft to satellites [120]. It was during this period that the word 'remote sensing' replaced the frequently used word 'aerial photograph'. Satellites can cover wider land space than planes and can monitor areas on a regular basis.

The new era in remote sensing began when the United States launched the first earth observation satellite called earth resources technology satellite (ERTS-1) dedicated primarily for land observation [120]. This was followed by many other satellites like Landsat 1-5, satellite pour l' observation de la terre (SPOT), Indian remote sensing (IRS), Quickbird, Ikonos, etc. Change in image format from analog to digital was another major step towards the processing and interpretation of remotely sensed data [120]. The digital format made it possible to display and analyze imagery using computers, a technology that was also undergoing rapid change during this period. Due to the advancement of technology and development of new sensors, the capture of the earth's surface through different portions of the electromagnetic spectrum is possible these days. One can now view the same area by acquiring the data as several images in different portions of the spectrum, beyond what the human eye can view. Remote sensing technology has made it possible to see things occurring on the earth's surface which may not be detected by the human eye.

The formal definition of *remote sensing* can be given as follows [120]: *it refers to the sensing of the earth's surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resource management, land use and the protection of the environment.* Remote sensing has enabled the mapping, studying, monitoring, and management of various activities and resources like agriculture, forestry, geology, water, oceans, etc. It has further enabled the monitoring of the environment, thereby helping in conservation. One of the major advantages of the satellite is its ability to provide repetitive observations of the same area, in intervals of a few minutes to few weeks depending on the sensor and orbit. This capability is very useful for monitoring dynamic phenomena such as cloud evolution, vegetation cover, snow cover, forest fires, etc.

In geology, for instance, remote sensing can be applied to study and analyze large geographical areas. Remote sensing interpretation makes it easy for geologists to identify the types of rocks and changes that occur in an area due to natural events such as floods or landslides. Remote sensing is also helpful in studying vegetation types. A farmer may use thematic maps to monitor the health of his crops without actually going out to the field. Interpretation of remote sensing images allows physical- and bio-geographers, ecologists, those studying agriculture, and foresters to easily detect which kind of vegetation is present in which areas and its growth potential. Those studying urban and other areas of land use also find remote sensing helpful because it allows them to easily pick out inhabited land in an area. This can then be used as data in city planning applications and in the study of species habitat. Because of its varied applications and ability to allow users to collect, interpret, and manipulate data over large, often not easily accessible, and sometimes dangerous areas, remote sensing has become a useful tool for all kinds of geographers. Similarly, a biologist can study the variety of plants in a certain location. In the last four decades, satellite imaging has evolved into a major tool for collecting information on almost every aspect related to the earth.

On-board imaging sensors can acquire information in different spectral bands, on the basis of exploited frequency, or at different resolutions. Therefore, a wide spectrum of data can be available for the same observed site. For many applications, the information provided by individual sensors is incomplete, inconsistent, or imprecise and additional processing may provide complementary data. Fusion of different pieces of information, results in a better understanding of the observed site, thus, decreasing the uncertainty related to information from single sources. In the interpretation of a scene, contextual information is important. For example, in an image labelling problem, a pixel considered in isolation may provide incomplete information about the desired characteristics. Context can be defined in the frequency, space and time domains. Images in different bands may be acquired by using either a single multi-spectral sensor or by using a number of sensors operating at different frequencies. The multi-spectral images improve the separation between various ground cover classes compared to a single-band image.

1.1 Characteristics of Remotely Sensed Imagery

Resolution is an important characteristic feature of aerial images. In a general sense, the term 'resolution' is defined as the smallest physical quantity that is discernable by an instrument. In other words, resolution is the power of the instrument to record fine details. High resolution of an instrument enables us to measure the quantity with more precision. In image processing, resolution refers to the ability of the imaging sensor to record the smallest measurable detail in a visual presentation. High resolution of an image is important in image processing as it helps us derive precise and accurate information for various applications.

Remote sensing images are characterized by four types of resolutions: spatial, spectral, radiometric, and temporal resolution.

- *Spatial resolution:* In digital imaging sensors, the analog images produced by the optical system are spatially sampled by the detector. Spatial resolution is a measure of the sensor's ability to record closely spaced objects such that they are distinguished as separate objects. If the imaging scenes are oversampled with a spatial frequency higher than the Nyquist frequency, it results in a high spatial resolution image. However, in practice, most digital image sensors undersample the analog scene. As a consequence, the resulting resolution is determined by the spatial sampling frequency. In remote sensing, this refers to the area of land space represented by one pixel in an image. It can be thought as the projection of the photo detecting element on to the ground. Thus, resolution is directly related to the area on the ground that represents a pixel in the detector. A sensor with a 1 m $\times$ 1 m spatial resolution can give finer details of the scene compared to a sensor with a 10 m $\times$ 10 m spatial resolution. Thus, high spatial resolution allows for sharp details and fine intensity transitions across all directions. For representing an object, a high spatial resolution image has more pixels compared to a low resolution (LR) image. In other words, as the spatial resolution increases, the associated file size increases. To capture a high spatial resolution, the camera needs a high density image sensor with closely spaced photo detectors.

  Different applications require varying spatial resolutions. For applications such as large area change detection, it is cost-effective to use medium-resolution imagery with large swath widths to observe areas where changes of interest have occurred. Similarly, for planimetric applications, it is recommended that imagery with the highest possible resolution be used to extract various features such as pavements, roads, etc. Different satellites capture images at different resolutions. For example, in Table 1.1, we list the spatial resolution of the various satellites for capturing multi-spectral (MS) and panchromatic (Pan) images.

- *Spectral resolution:* It refers to the frequency or spectral resolving power of a sensor and is defined as the smallest resolvable wavelength difference detected by the sensor. Spectral resolution represents the width of the band within the electromagnetic spectrum that can be sensed by a sensor. As the bandwidth becomes narrower, the spectral resolution becomes higher. Spectral resolution plays an important role in satellite imaging. High spectral resolution images captured by remote sensing cameras provide detailed information about mineral resources and geographical structures of the earth or any other planet under observation. They can be acquired by capturing images in a narrow spectral range. These images consists of pixels that represent the spectral response within the band. For example, in the case of vegetation, maximum reflectance occurs at the near-infrared (NIR) region. Hence, images captured in the band of NIR give more details of vegetation compared to images captured in red or green spectral bands. A set of images captured at different spectral bands can be used to monitor land and other natural resources, including vegetated areas, wetlands, and forests. In Table 1.2, we display the spectral resolutions of different MS bands and Pan images provided by two satellites namely, the Landsat enhanced thematic mapper plus (ETM+) and Quickbird.

Table 1.1 Spatial resolution of some satellites

Satellite	Multi-spectral image	Panchromatic image
Landsat	30 m × 30 m	15 m × 15 m
SPOT 2, 4	20 m × 20 m	10 m × 10 m
Ikonos	4 m × 4 m	1 m × 1 m
OrbView3	4 m × 4 m	1 m × 1 m
Quickbird	2.4 m × 2.4 m	0.6 m × 0.6 m

- *Radiometric resolution:* Pixels carry information of the image intensity in the form of binary digits called 'bits'. The intensity at any location in a real world scene may take a real value over a range. However, in a digital image, it is not possible to represent this entire range. In practice, this range is divided into finite levels and the real world intensity is quantized and assigned the nearest quantization level. Radiometric or brightness resolution refers to the smallest change in brightness that can be represented in an image. Each radiometric level is assigned a binary code and the increase in the brightness resolution requires more number

Table 1.2 Comparison of the spectral resolutions of Landsat ETM+ and Quickbird sensor's bandwidth (μm)

Spectral band	Landsat ETM+	Quickbird
Panchromatic	0.52–0.90	0.45–0.90
Blue (band-1)	0.45–0.51	0.45–0.52
Green (band-2)	0.52–0.60	0.52–0.60
Red (band-3)	0.63–0.69	0.63–0.69
Near-infrared (band–4)	0.75–0.90	0.76–0.90

of brightness levels and hence, more number of bits for each pixel. A binary image has two levels; black and white; hence, it requires only one bit for each pixel. A gray scale image is usually quantized using 256 gray levels with each level represented using 8 bits. Similarly, if each color plane of an RGB image requires 8 bits, then at least 24 bits are needed for representing each pixel. For illustration purpose, we display the radiometric resolution of different satellites in Table 1.3.

Table 1.3 Radiometric resolution of some satellites

Satellite	Radiometric resolution (bits)
Landsat	8
IRS	7
SPOT	8
Quickbird	11
Ikonos	11
OrbView3	11

- *Temporal resolution:* The term 'temporal resolution' is related to video signals. A video of an event is a sequence of images (frames) captured at regular and short time intervals between them. Temporal resolution, also known as frame rate, is the measure of the capability of the instrument to display the smallest movement/motion of the moving objects in the video. Thus, it refers to the number of frames captured per second. A video captured with low temporal resolution exhibits flicker or transitions of the moving objects in the scene/event. With high temporal resolution, the movement of the moving objects appears smooth and continuous. For a given duration of time, a high temporal resolution video requires more memory for storage and large bandwidth for transmission. In remote sensing, temporal resolution refers to the frequency at which a given geographical area is imaged. Higher temporal resolution enables monitoring the occurrence of rapid changes such as forests, floods, etc. This also improves the probability of obtaining cloud-free imagery over areas that experience frequent cloud cover. The revisit period of different satellites are listed in Table 1.4.

Table 1.4 Temporal resolution of various satellites

Satellite/Sensor	Revisit period (days)
Landsat	16
IRS	5
SPOT	5
Quickbird	3
Ikonos	3
OrbView3	<3

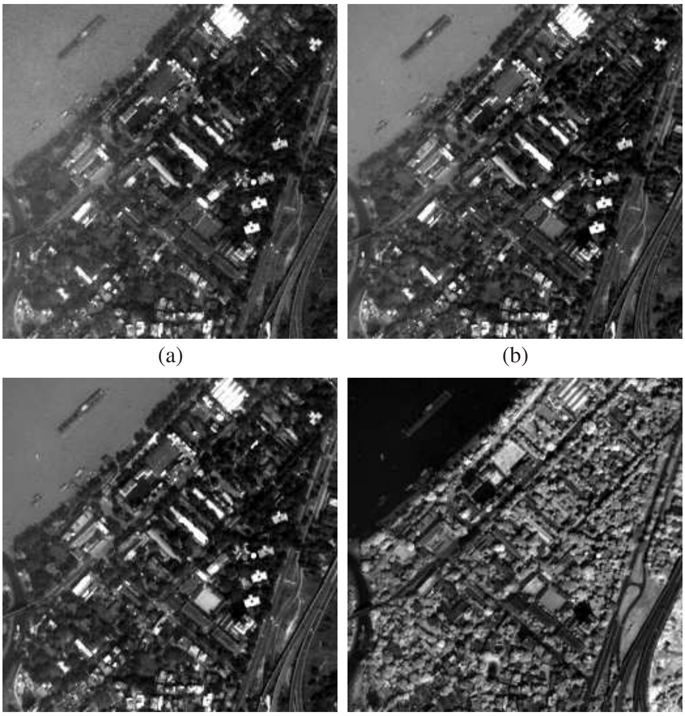
There exists a trade-off while selecting a sensor. For example, if we want a high spatial resolution, then the requirement is to keep low instantaneous field of view (IFOV) which reduces the energy of the reflected light acquired by the sensor causing reduction in signal-to-noise ratio. Thus, the captured image is degraded. One can improve the spatial resolution by capturing the image using higher spectral width for the sensor. However, this is possible only at the cost of poor spectral resolution since it requires higher bandwidth to get more energy. Thus, in order to have sensors with optimum performance, we are required to make the suitable choice as per the requirement. High spatial resolution images have better details which help in accurate measurement in the image. On the other hand, images with high spectral resolution give better classification of different regions which are benefitted by accurate identification of the object. In this work, we address the problem of reconstructing remotely sensed images that posses both high spatial and high spectral resolutions.

1.1.1 Multi-spectral images

Objects appear different through a red lens, or through blue or green lenses. Satellite sensors record reflected energy in the red, green, blue, or infrared bands of the spectrum for the purpose of better analysis of data. The process of acquiring images in different bands is called multi-spectral (MS) imaging. The improved ability of multi-spectral sensors provide a basic remote sensing data resource for quantitative thematic information, such as the type of land cover. Resource managers use this information from multi-spectral data to monitor fragile lands, vegetated areas, wetlands, forests, etc. Such data provides unique identification characteristics leading to a quantitative assessment of the earth's features.

In the area of remote sensing, we are interested in recognizing an object or a feature from the images that are captured using sensing devices. These features include vegetation, soil, rocks, minerals, water/ocean, snow, and artificial features. The recognition of such objects requires the sensor to have high spectral resolution. Remote sensing satellites are fitted with a camera that has a multi-channel detector with a few spectral bands. Each detector is sensitive to radiation within a narrow wavelength band. The resulting MS image contains both brightness and spectral (color) information of the targets being observed. Most MS sensors can record reflected energy in the red, green, blue or infrared bands of the spectrum. The improved ability of these sensors provides a basic remote sensing data resource for various kinds of applications. Examples of multi-spectral satellite systems include the following: Landsat TM, MS scanner (MSS), SPOT high resolution visible multi-spectral (HRV-XS), Ikonos MS, QuickBird MS.

In order to capture MS images, the light reflected from the scene is passed through filters with different spectral characteristics. These filters decompose the light into different spectral components which are then collected by multi-channel detectors and converted into a digital image. Since the optical power is divided into several components, the power available to each detector is reduced. This leads to poor signal-to-noise ratio making it necessary to acquire the MS images at low spatial resolution. Thus, multi-spectral images are characterized by high spectral resolution, that is, narrow bandwidth and low spatial resolution. As an example, in Fig. 1.1, we show images of MS bands captured by QuickBird. The spectral range of these bands are



(a) (b) (c) (d)

Figure 1.1 Multi-spectral (MS) images with spatial resolution of 2.4 m × 2.4 m corresponding to the Sundarbans, India, captured using Quickbird: (a) blue (band-1, 0.45–0.52 μm), (b) green (band-2, 0.52–0.60 μm), (c) red (band-3, 0.63–0.69 μm), and (d) near-IR (band-4, 0.76–0.90 μm). (Courtesy: www.glcf.umd.edu) as follows: blue (0.45−0.52 μm), green (0.52−0.60 μm), red (0.63−0.69 μm), near-infrared (0.76−0.90 μm). Each spectral band can be used in different kinds of analysis. Band-1 (blue) images are useful for representing water bodies, land, soil, vegetation, etc. Band-2 (green) images enable us to inspect the health of vegetation. Band-3 (red) images help in discrimination of vegetation, delineation of soil, and geologic boundaries. Band-4 (NIR) images identify crops, emphasize land–water contrasts, etc.

In order to visualize the image in RGB color format, it is necessary to combine the red, green, and blue bands. The resulting image is said to have natural color composition (NCC). However, in the case of vegetation where there is a maximum reflectance occurring at the NIR region, we need to observe those effects in color images. This can be accomplished by combining near-IR (NIR), red, and green bands in RGB color image format, which is referred to as false color composition (FCC) since the represented color is not the true color perceived by us. Examples of NCC and FCC images are displayed in Fig. 1.2.

(a) (b)

Figure 1.2 Color composition of MS image: (a) Natural color composition (NCC) and (b) false color composition (FCC). (Courtesy: www.glcf.umd.edu)

1.1.2 Panchromatic image

A panchromatic (Pan) sensor is a single channel detector sensitive to radiation within a broad wavelength range. Since the wavelength range coincides with