1 Introduction

This chapter provides an introduction to the basic principles of hyperspectral remote sensing. The main objective is to explain how information about the earth's surface is conveyed to a remote hyperspectral imaging sensor, which are the key factors determining the nature and quality of the acquired data, and how the data should be processed to extract meaningful information for practical applications. By definition, hyperspectral imaging systems collect co-aligned images in many relatively narrow bands throughout the ultraviolet, visible, and infrared regions of the electromagnetic spectrum.

1.1 Introduction

The term "remote sensing" has several valid definitions. In the broadest sense, according to Webster's dictionary, remote sensing is "the acquisition of information about a distant object without coming into physical contact with it." For our purposes, remote sensing deals with the acquisition, processing, and interpretation of images, and related data, obtained from aircraft and satellites that record the interaction between matter and electromagnetic radiation.

The detection of electromagnetic radiation via remote sensing has four broad components: a source of radiation, interaction with the atmosphere, interaction with the earth's surface, and a sensor (see Figure 1.1). The link between the components of the system is electromagnetic energy transferred by means of radiation.

Source The source of electromagnetic radiation may be natural, like the sun's reflected light or the earth's emitted heat, or man-made, like microwave radar. This leads to a classification of remote sensing systems into active and passive types. *Active systems* emit radiation and analyze the returned signal. *Passive systems* detect naturally occurring radiation either emitted by the sun or thermal radiation emitted by all objects with temperatures above absolute zero. With active systems, like microwave radar, it is possible to determine the distance of a target from the sensor (range); passive systems cannot provide range information.

Atmospheric interaction The characteristics of the electromagnetic radiation propagating through the atmosphere are modified by various processes, including absorption and scattering. This distortion is undesirable and requires correction if we wish to study the earth's surface, or desirable if we wish to study the atmosphere itself.

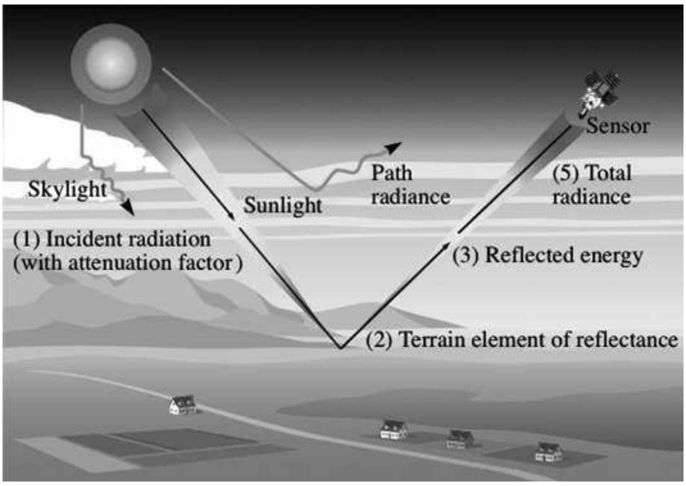

Figure 1.1 Pictorial illustration of how the atmosphere, the solar illumination, and the spectral response of the sensor affect the relationship between the observed radiance spectrum and the wanted reflectance spectrum of the ground resolution cell. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

Earth's surface interaction The amount and spectral distribution of radiation emitted or reflected by the earth's surface depend upon the characteristics of the involved "target" materials. The interaction between matter and electromagnetic energy is determined by (a) the physical properties of the matter, and (b) the wavelength of electromagnetic energy that is remotely sensed.

Sensor The electromagnetic radiation, which has interacted with the surface of the earth and the atmosphere and has undergone some form of spectral discrimination as it is transmitted through a spectral detector, is recorded by an electro-optical detector which converts electromagnetic radiation into an electrical signal directly related to the radiation in a particular spectral band from the scanned scene. The electrical signal is amplified, converted to digital data, and organized into a data structure for further processing.

Once the data have been collected by the sensor, they must be analyzed in real time or offline. However, before we start talking about analysis techniques, we should understand what information about the target material is conveyed by the reflected or emitted electromagnetic radiation and how this information has been modified by the sensor.

The radiation received by the sensor can be measured at different locations of a scene, over a range of wavelengths, and sometimes at different times (see Figure 1.2). This leads to rich data sets which can be organized and explored in many different ways. We consider electro-optical systems that include the visible, near infrared, and thermal infrared regions of the electromagnetic spectrum. We are interested in remote sensing imaging systems designed to form a two-dimensional representation of the two-dimensional distribution of radiant energy across the target at one or multiple spectral bands. Traditionally, data from a single wavelength band are used to form a digital image, where each pixel represents the radiant energy of a corresponding

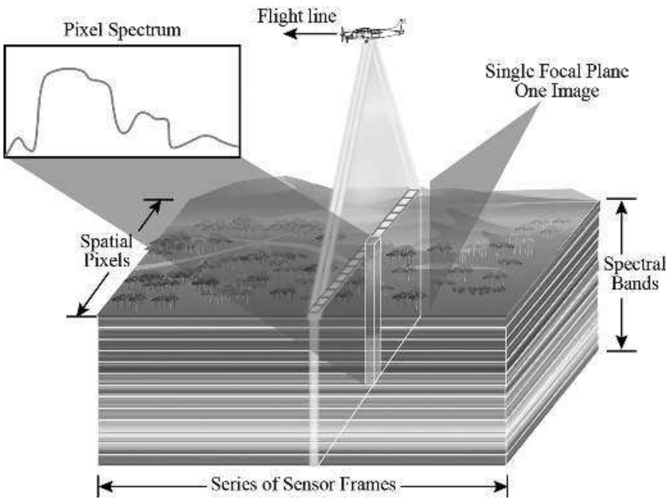

Figure 1.2 Principle of hyperspectral imaging sensing. The resulting “data cube” can be viewed as a set of co-registered images at multiple wavelength regions or as a set of spectra corresponding to each pixel of the image. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

ground element area. Each individual image can then be processed and analyzed using established image processing techniques that exploit geometrical or shape information. However, if we collect radiation measurements at different wavelength bands for the same spatial sample, and arrange them in a vector, we can analyze the resulting “spectral” data using multivariate statistical techniques.

In the remainder of this chapter, we discuss the basic principles underlying each part of the remote sensing system, we outline the key ideas of data preprocessing and exploitation techniques, and we summarize some common applications.

1.2 Infrared Sensing Phenomenology

The main sources of radiation in passive remote sensing is the electromagnetic radiation emitted by the sun and the self-emission of objects in the scene due to their temperature. Electromagnetic radiation is the means by which electromagnetic energy is propagated in the form of waves.

Electromagnetic waves are characterized by their location within the electromagnetic spectrum. The division of the electromagnetic spectrum into different regions, such as visible, infrared, or microwave, has more to do with the different methods used for sensing it rather than the nature of the radiation itself. Figure 1.3 shows the regions used in electro-optical remote sensing and the typical applications for each region.

1.2.1 Sources of Infrared Radiation

All objects with temperatures greater than absolute zero emit radiation whose amount changes as a function of wavelength. An object that absorbs all incident energy, converts

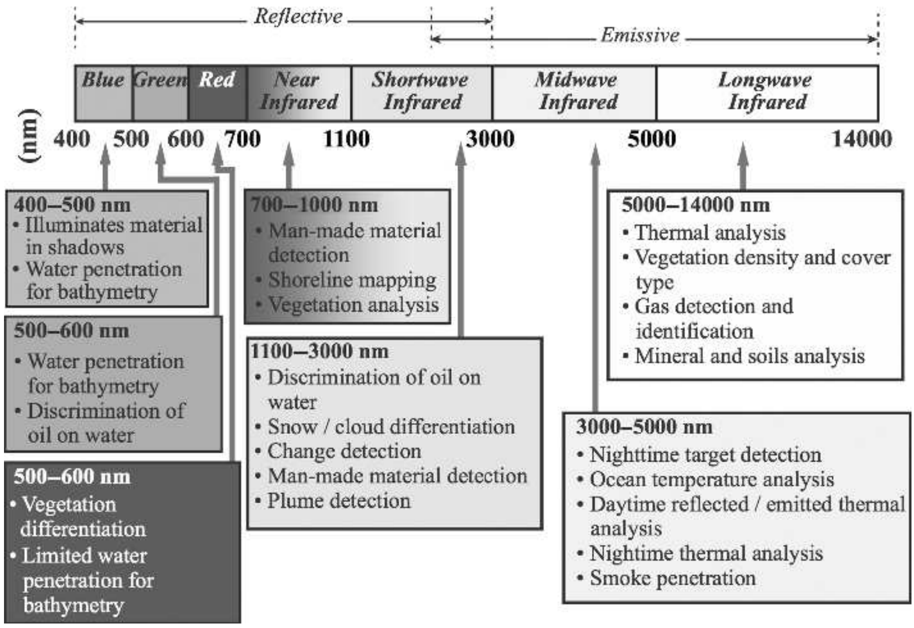

Figure 1.3 Typical examples of spectral information present at different spectral regions of the electromagnetic spectrum for different applications.

it to heat energy, and transforms the heat back into radiant energy at the maximum possible rate allowed by thermodynamic laws, is a perfect thermal emitter known as a *blackbody*. The spectral radiant emittance of a blackbody is given by Planck's law.

For our present purpose, the spectral radiant exitance, the power per unit area emitted by the sun, as seen from above the earth's atmosphere, can be approximated by a blackbody curve at a temperature of 5800 K. Thus the sun, with a temperature of 5800 K, will have a maximum emittance at a wavelength of 0.50 μm. In contrast, the earth's ambient temperature on a warm day, due largely to heating by the sun, is about 300 K or 27 °C and the maximum spectral radiant emittance from earth's features occurs at a wavelength of about 9.7 μm. This radiation is known as "thermal infrared" energy because it is related to terrestrial heat.

In the visible and near infrared regions of the electromagnetic spectrum we study the radiation from the sun as it is modified by the earth's atmosphere and surface. In the thermal infrared region we study the radiation emitted by the earth's atmosphere and surface. The dividing line between reflective and emissive wavelengths is approximately 4 μm. Reflective energy predominates below this wavelength and emissive energy predominates above it. This difference in the nature of radiation also has profound effects on the sensors used in the reflective and emissive regions of the electromagnetic spectrum.

Figure 1.4 shows the contrast between the solar spectral irradiance and the spectral irradiance from a blackbody at 300 K. Irradiance will be discussed in more detail in Chapter 2, but it describes the spectral energy per second that flows through a real or

Cambridge University Press
978-1-107-08366-0 — Hyperspectral Imaging Remote Sensing
Dimitris Manolakis , Ronald Lockwood , Thomas Cooley
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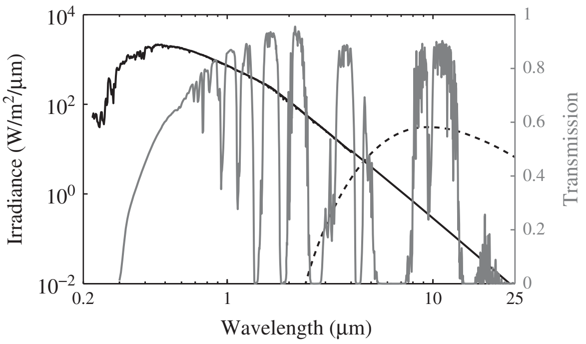

Figure 1.4 Irradiance and atmospheric absorption for the wavelength range 0 to 25 μm. The black curve is the exoatmospheric spectral irradiance and the dashed curve is the spectral irradiance from a blackbody at a temperature of 300 K with both referenced to the left vertical scale. The gray curve is the atmospheric transmission referenced to the right vertical scale. Note the presence of atmospheric windows in the thermal wavelength regions 3 to 5 μm and 8 to 14 μm.

imaginary aperture of unit area. The two curves cross at slightly longer than the 4 μm dividing line defined above.

1.2.2 Atmospheric Propagation

All radiation observed by remote sensing systems passes through some distance or path length of atmosphere, which has a profound effect on its radiant energy and spectral composition. The main mechanisms causing these effects are atmospheric scattering and absorption. Atmospheric *scattering* is the unpredictable diffusion of radiation by particles in the atmosphere. Unlike scattering, atmospheric absorption results in the effective loss of energy from the radiation field as it is converted to other forms.

The transmission curve, illustrated in Figure 1.4, also defines the spectral regions where remote sensing can occur. Aerosol scattering and molecular absorption limit the transmission range at the shortest wavelengths. The spectral region from about 0.35 to 2.5 μm defines the reflective range that is dominated by solar illumination and where the atmosphere is broadly transmissive. The large absorption features throughout the 0.2 to 25 μm range, where light transmission is severely attenuated or completely absorbed, are largely due to absorption by water although minor constituents such as carbon dioxide play an import role as well.

The regions of the electromagnetic spectrum in which atmospheric absorption is low are called *atmospheric windows* and it is through these “windows” that remote sensing of the earth’s surface takes place. We note that the peak of the solar spectrum coincides with the visible atmospheric window at 0.4–0.9 μm, whereas the peak of emitted “heat” from the earth extends through the atmospheric windows at 3–5 μm and 8–14 μm. The important point to note from Figure 1.4 is that *remote sensing of radiation is not possible if there is not sufficient energy from the radiation source within the atmospheric windows*.

1.2.3 Reflectance and Emissivity Spectra

When electromagnetic radiation interacts with earth's surface, various fractions of the energy are reflected, absorbed, and/or transmitted. In general, these fractions vary as a function of wavelength depending on the type and condition of the surface material. Therefore, it is important to describe those variations and investigate whether they can be used to characterize different materials.

In the reflective part of the spectrum, where solar illumination predominates, the reflectance properties of the earth's features are used to describe the surface characteristics. Depending on the surface roughness, there are two general classes of reflectors. *Specular* reflectors are flat surfaces that act like mirrors; that is, the angle of reflection equals the angle of incidence. In contrast, *diffuse* or *Lambertian* reflectors are rough surfaces that reflect uniformly in all directions. The behavior of real surfaces, which is between these two cases, is dictated by the surface's roughness in relation to the wavelength of the incident electromagnetic radiation.

In remote sensing, we are primarily interested in diffuse reflectance because this is the dominant type of reflectance for most materials, although there are exceptions such as water. The reflectance characteristics of an earth surface material may be quantified by its *reflectance spectrum*, which measures the percentage of incident radiation, typically sunlight, that is reflected by a material as a function of the wavelength of the radiation. Reflectance spectra are measured by special instruments called reflectometers in the laboratory or the field. Figure 1.5 shows typical reflectance spectra of green vegetation, dry vegetation, and soil. Dips of the spectral curve represent absorption of the incident radiation and are known as *absorption features*. In contrast, upward excursions

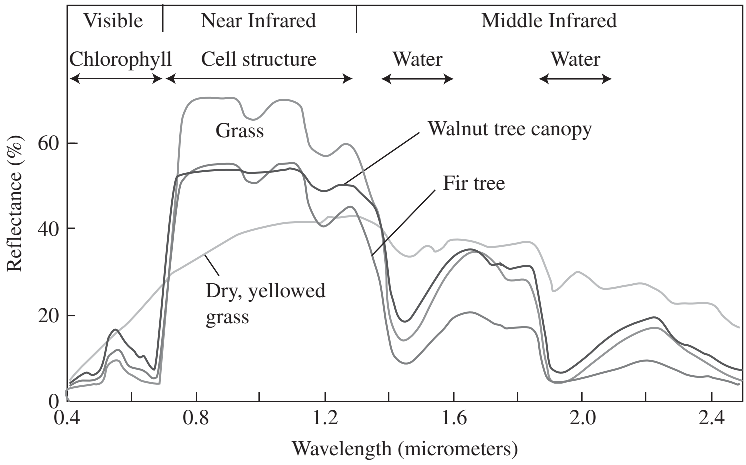

Figure 1.5 Typical spectral reflectance curves for different types of green and yellowed (dry) vegetation. The spectral curves for green vegetation at different regions are shaped by the components shown at the top.

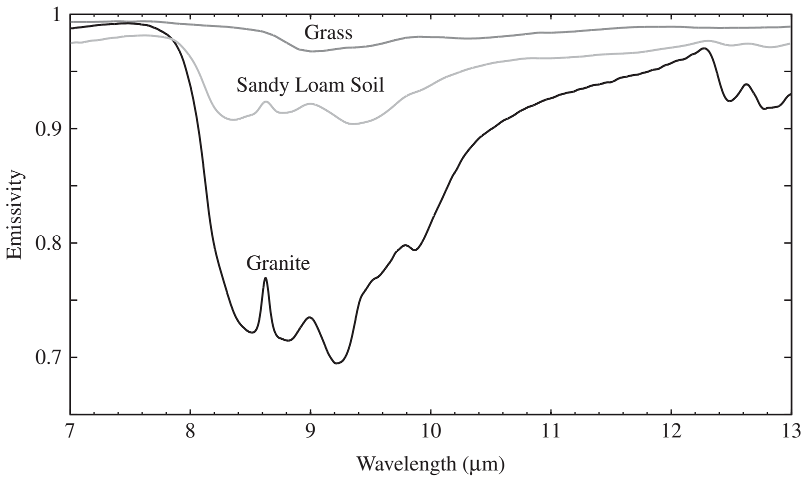

Figure 1.6 Typical emissivity spectra of grass, granite, and sandy loam soil materials in the thermal infrared window from 7 to 13 μm.

are called *reflectance peaks*. These spectral features provide valuable information for the identification of different materials.

Real materials are not perfect blackbodies, but instead emit radiation in accordance with their own characteristics. The ability of a material to emit radiation can be expressed as the ratio of its radiant emittance at a given temperature to the radiant emittance of a blackbody at the same temperature. This ratio is known as the *spectral emissivity* of the material. The plot of emissivity as a function of wavelength is called the *emissivity spectrum* of a material. Figure 1.6 shows examples of emissivity spectra with unique spectral features; the data were obtained from the ASTER spectral library described by Baldridge et al. (2009a).

Radiance in the thermal infrared, the mid-wave infrared and the long-wave infrared (MWIR and LWIR) is determined by both the emittance and temperature of the materials. Variations in temperature can cause both large radiance variations and large spectral variations at the input of a remote sensor. Furthermore, it is not possible to measure separately the spectral emissivity and temperature using hyperspectral sensing alone. Emissivities of most materials vary between 0.8 and 0.95 in the 8 to 14 μm thermal IR window. Thermal emission is generally the dominant term; the variations caused by variations in spectral emittance are small by comparison. This causes additional variability in the statistics of target and background clutter, which makes detection and discrimination in the thermal infrared more challenging.

In conclusion, the signal of interest in spectral remote sensing applications, that is, the information-bearing signal, is the reflectance or emissivity spectrum of the imaged material. The details and relationships between spectral reflectance, emittance, and temperature will be fully developed in subsequent chapters.

1.3 Hyperspectral Imaging Sensors

Hyperspectral sensors, more properly known as imaging spectrometers, collect simultaneously digital images in many relatively narrow, contiguous and/or noncontiguous spectral bands of the ultraviolet, visible, and infrared regions of the electromagnetic spectrum. The collection of spectral reflectance and emittance information in hundreds of spectral bands for each spatial location requires the design of special sensors. Hyperspectral imaging sensors consist of a scanning mechanism, an imaging system, and a spectrometer. Figure 1.7 illustrates the basic elements of a hyperspectral data collection sensor. All imaging spectrometers require some sort of scanning and pointing system in order to accumulate data and assign position coordinates. The imaging system, or fore optic, collects and images radiant energy from a location on the earth's surface (spatial sampling) with a certain spatial resolution. The image plane of the fore optic becomes the optical input, or the object, for the spectrometer. Finally, the spectrometer measures the radiant energy at a number of spectral bands (spectral resolution) for each spatial sample with a certain accuracy (radiometric resolution).

From a signal processing perspective, to acquire hyperspectral imaging data requires three sampling operations: spatial, spectral, and radiometric. Temporal sampling, which refers to how often data are obtained for the same area, is related to operational rather than signal processing considerations. Therefore, we concentrate on the physical implementation and the key parameters required for the characterization of spatial, spectral, and radiometric sampling operations.

1.3.1 Spectral–Spatial Data Collection and Organization

It is helpful at this point to discuss how the data from an imaging spectrometer are organized. Consider the data in the raw format of digital numbers as it is read from the

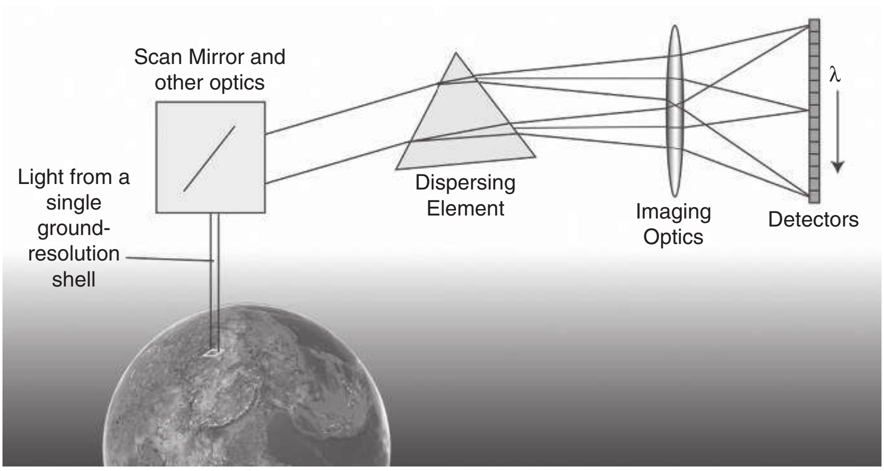

Figure 1.7 Basic principle of a hyperspectral remote sensor

individual detector elements. The data are stored in a data structure, known as a data cube, consisting of two spatial dimensions and one spectral dimension. Each datum in the cube is associated with a particular spatial location of a certain size and its value is proportional to the spectral radiant energy contained within that particular spectral sample and area.

The order and procedure by which each datum in the cube is populated are determined by the details of the imaging spectrometer. The challenge faced by the optical designer is to record a three-dimensional data set using the signal generated by either a two-dimensional array of detectors, a line array of detectors, or a single detector. Additionally, there is a limited number of ways that light can be separated into its spectral components.

As described above, the fore optic presents an image of a scene location at the input of a spectrometer. The spectrometer input is often a spatial mask of some sort. For example, a slit spectrometer employs a two-dimensional opening that is long and narrow. One can think of this imaging process in the reverse sense with the spectrometer input mask being imaged onto the scene. The spatial dimensions of the cube are then assembled as this projected mask is scanned across the scene of interest.

Figure 1.8 illustrates some of the different methods by which the data cube is populated depending upon the type of imaging spectrometer. The data subset marked with an "A" is from a slit spectrometer, which relies on a dispersing element to spatially separate the light into the different wavelength samples which are recorded by a two-dimensional detector array. A scanning mechanism is utilized to move the projected slit image across

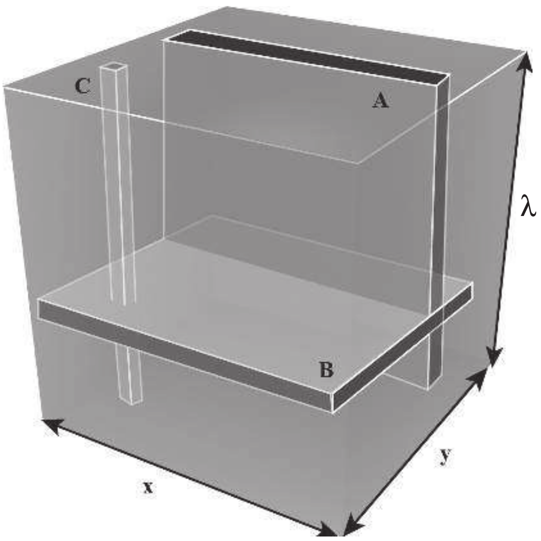

Figure 1.8 Three-dimensional illustration of a data cube showing the spatial dimension (x, y) and the spectral dimension λ. The numbers of spatial and spectral samples will depend upon the details of the sensor design. The regions, labeled A, B, and C, illustrate the portion of the data cube that is acquired during one acquisition cycle as described in the text.

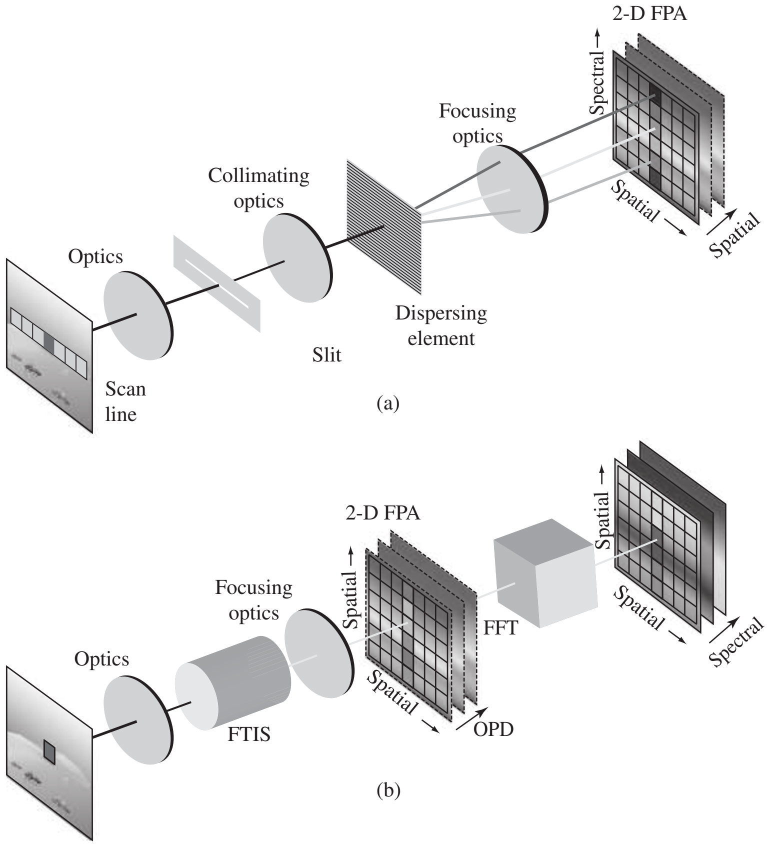

Figure 1.9 Illustration of two types of imaging spectrometers. Illustration (a) is a slit spectrometer with each data frame composed of spatial and spectral dimensions and the second spatial dimension generated through scanning the projection of the slit onto the scene. Illustration (b) is of a FTIS, with each data frame corresponding to both spatial dimensions at a particular OPD. The spectral information is recovered by taking the fast Fourier transform (FFT) of the interference data for each spatial location. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

the scene. The spatial image recorded by a single data frame has $m \times 1$ samples with m being the number of spatial samples along the long axis of the slit. The spectral information is recorded in the perpendicular direction by n detector elements. The entire data cube is assembled by scanning the slit along the scene and reading out the array of detector elements at an appropriate rate. This is often referred to as *pushbroom scanning*, with the forward motion of the airborne or space-based platform providing the slit scanning motion. The diagram in Figure 1.9(a) sketches this common and highly successful design.

A second example illustrated in Figure 1.8 and labeled as "B" is a *staring system* that utilizes a series of spectral filters mounted in a filter wheel. A system of this type "stares" at an area of the scene and cycles through a series of filters. A two-dimensional array records an area of the scene at the various filter wavelengths and the cube is populated