5 MULTISPECTRAL, THERMAL, AND HYPERSPECTRAL SENSING

5.1 INTRODUCTION

In Section 2.14 we described multiband imaging using film-based, digital, and video camera systems. With these camera types, generally only three or four relatively wide wavelength bands ranging from 0.3 to 0.9 μm were sensed. A *multispectral scanner* operates on the same principle of selective sensing in multiple spectral bands, but such instruments can sense in many more bands over a greater range of the electromagnetic spectrum. Utilizing electronic detectors, multispectral scanners can extend the range of sensing from 0.3 to approximately 14 μm. (This includes the UV, visible, near-IR, mid-IR, and thermal IR spectral regions.) Furthermore, multispectral scanner systems can sense in very narrow bands.

We begin our discussion in this chapter with a discussion of how multispectral scanner images are acquired physically. We treat the basic processes of across-track and along-track scanning, followed by a description of the basic operating principles of multispectral scanners. After our treatment of multispectral scanning, we discuss thermal scanning. A thermal scanner can be thought of as merely a particular kind of multispectral scanner—one that senses only in the thermal portion of the spectrum (in one or more bands). However, thermal images must be interpreted with due regard for the basic thermal radiation principles involved. We discuss these principles as we describe how thermal scanner images can be interpreted visually, calibrated radiometrically, and processed digitally. We conclude the chapter with an introduction to *hyperspectral sensing*, the acquisition of images in many (often hundreds) very narrow, contiguous spectral bands throughout the visible, near-IR, and mid-IR portions of the spectrum.

In this chapter we stress *airborne* scanning systems. However, as we see in Chapter 6, the operating principles of multispectral, thermal, and hyperspectral scanners operated from space platforms are essentially identical to the airborne systems described in this chapter.

5.2 ACROSS-TRACK SCANNING

Airborne multispectral scanner systems build up two-dimensional images of the terrain for a swath beneath the aircraft. There are two different ways in which this can be done—using *across-track* (*whiskbroom*) scanning or *along-track* (*pushbroom*) scanning.

Figure 5.1 illustrates the operation of an across-track, or whiskbroom, scanner. Using a rotating or oscillating mirror, such systems scan the terrain along *scan lines* that are at right angles to the flight line. This allows the scanner to repeatedly measure the energy from one side of the aircraft to the other. Data are collected within an arc below the aircraft typically of 90° to 120°. Successive scan lines are covered as the aircraft moves forward, yielding a series of contiguous, or just touching, narrow strips of observation comprising a two-dimensional image of rows (scan lines) and columns.

At any instant in time, the scanner "sees" the energy within the system's *instantaneous field of view (IFOV)*. The IFOV is normally expressed as the cone angle within which incident energy is focused on the detector. (See β in Figure 5.1.) The angle β is determined by the instrument's optical system and size of its detectors. All energy propagating toward the instrument within the IFOV contributes to the detector response at any instant. Hence, more than one land cover type or feature may be included in the IFOV at any given instant and the composite signal response will be recorded. Thus, an image typically contains a combination of "pure" and "mixed" pixels, depending upon the IFOV and the spatial complexity of the ground features.

Figure 5.2 illustrates the segment of the ground surface observed when the IFOV of a scanner is oriented directly beneath the aircraft. This area can be expressed as a circle of diameter D given by

$$D = H'\beta \tag{5.1}$$

where

D = diameter of circular ground area viewed
H' = flying height above terrain
β = IFOV of system (expressed in radians)

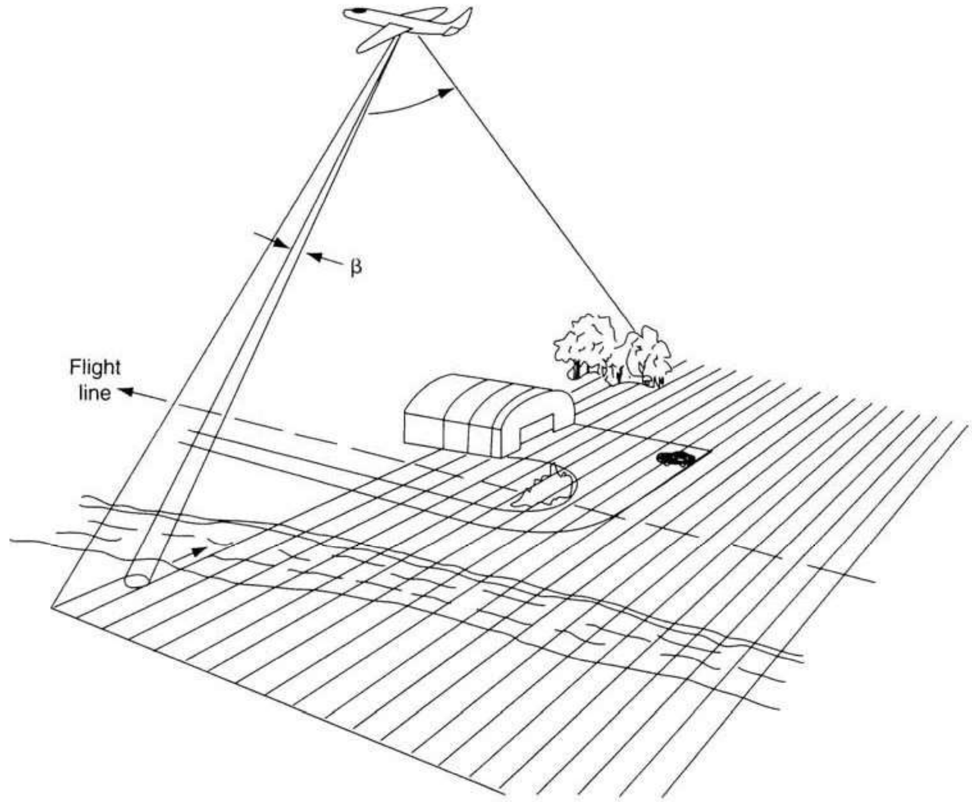

Figure 5.1 Across-track, or whiskbroom, scanner system operation.

The ground segment sensed at any instant is called the *ground resolution element* or *ground resolution cell*. The diameter D of the ground area sensed at any instant in time is loosely referred to as the system's *spatial resolution*. For example, the spatial resolution of a scanner having a 2.5-milliradian (mrad) IFOV and being operated from 1000 m above the terrain can be found from Eq. 5.1 as $D = 1000 \text{ m} \times (2.5 \times 10^{-3} \text{ rad}) = 2.5 \text{ m}$. That is, the ground resolution cell would be 2.5 m in diameter directly under the aircraft. (Depending on the optical properties of the system used, ground resolution cells directly beneath the aircraft can be either circular or square.) The size of the ground resolution cell increases symmetrically on each side of the nadir as the distance between the scanner and the ground resolution cell increases. Hence, the ground resolution cells are larger toward the edge of the image than near the middle. This causes a scale distortion that often must be accounted for in image interpretation or mathematically compensated for in image generation. (We discuss such distortions in Section 5.9.)

The IFOV for airborne multispectral scanner systems typically ranges from about 0.5 to 5 mrad. A small IFOV is desirable to record fine spatial de-

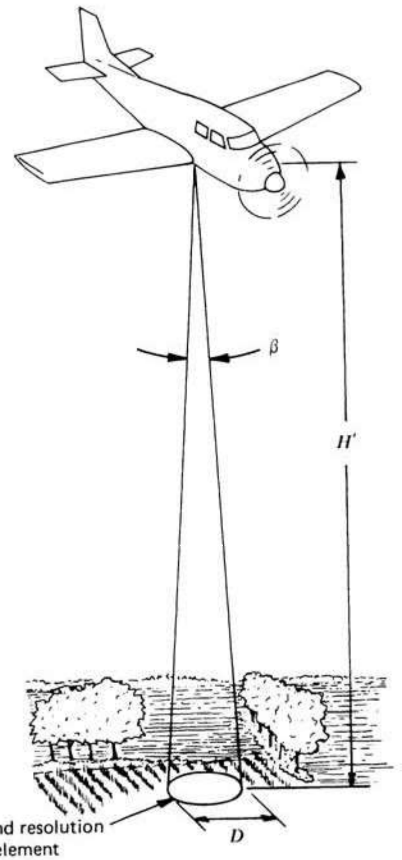

Figure 5.2 Instantaneous field of view and resulting ground area sensed directly beneath an aircraft by a multispectral scanner.

tail. On the other hand, a larger IFOV means a greater quantity of total energy is focused on a detector as the scanner's mirror sweeps across a ground resolution cell. This permits more sensitive scene radiance measurements due to higher signal levels. The result is an improvement in the *radiometric resolution*, or the ability to discriminate very slight energy differences. Thus, there is a trade-off between high spatial resolution and high radiometric resolution in the design of multispectral scanner systems. A large IFOV yields a signal that is much greater than the background electronic *noise* (extraneous, unwanted responses) associated with any given system. Thus, other things being equal, a system with a large IFOV will have a higher *signal-to-noise ratio* than will one with a small IFOV. Again, a large IFOV results in a longer *dwell time*, or residence time of measurement, over any given ground area. What is sacrificed for these higher signal levels is spatial resolution. In a similar vein, the signal-to-noise ratio can be increased by broadening the wavelength band over which a given detector operates. What is sacrificed in this case is *spectral resolution*, that is, the ability to discriminate fine spectral differences.

Again, what we have described above as a scanner's ground resolution cell (the scanner's IFOV projected onto the ground) is often simply called a system's "resolution" (we use this term often in Chapters 5 and 6, especially in tables describing system characteristics).

Most scanners use square detectors, and across-track scan lines are sampled such that they are represented by a series of just-touching pixels projected to ground level. The ground track of the aircraft ideally advances a distance just equal to the size of the resolution cell between rotations of the scanning mirror. This results in sampling the ground without gaps or overlaps.

The ground distance between adjacent sampling points in a digital scanner image need not necessarily exactly equal the dimensions of the IFOV projected onto the ground. As illustrated in Figure 5.3, the ground pixel size, or *ground sampled distance* (GSD), is determined by the sampling time interval (ΔT) used during the A-to-D signal conversion process (Section 1.5). In the case of Figure 5.3, the sampling time interval results in a ground pixel width that is smaller than the width of the scanner's IFOV projected onto the ground. The ground pixel height in the case shown in Figure 5.3 has been sampled to be equal to the scanner's IFOV. This illustrates that there can often be a difference between the projection of a scanner's IFOV onto the ground and the GSD. Often the term *resolution* is loosely used to refer to either of these dimensions.

While on the topic of resolution, we must also point out that the meaning of the term with respect to images acquired by film cameras is not the same as that with reference to electro-optical systems.

The concept of photographic film resolution (described in Section 2.11) is based on being able to distinguish two objects from each other. When lines and spaces of equal width are wide enough that they can just be distinguished on the film, the center-to-center line spacing is called the film resolution. When these lines are projected onto the ground, the resulting distance is called the ground resolution distance (GRD), as expressed by Eq. 2.13 and shown in Figure 5.4*a*. Applying this concept to a scanner's ground IFOV, we can see that it

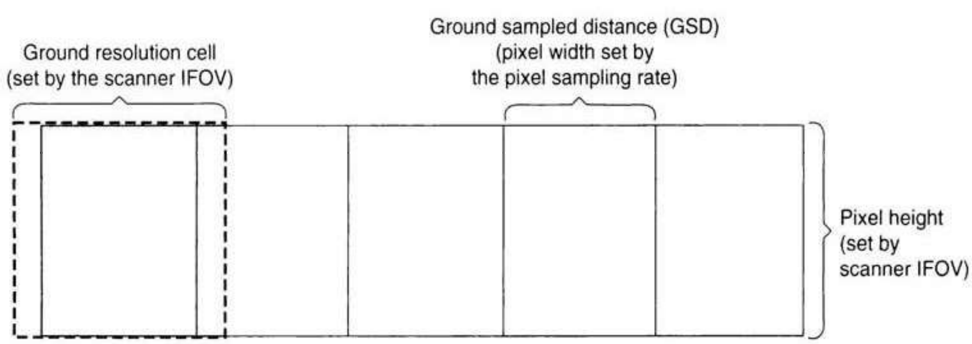

Figure 5.3 Ground sampled distance concept.

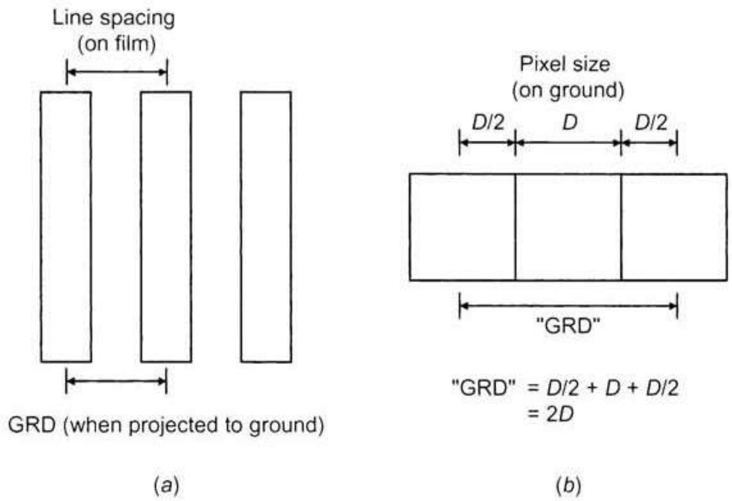

Figure 5.4 Resolution of film (*a*) and digital systems (*b*).

gives a misleading value of the ability of the scanner to resolve ground objects in that such objects must be separated from each other by at least the GSD to be distinguished individually (Figure 5.4*b*). Consequently, the nominal resolution of an electro-optical system must be approximately doubled to compare it with the GRD of a film-based camera system. For example, a 1-m-resolution scanner system would have the approximate detection capability of a 2-m-resolution film camera system. Looking at this concept another way, the optimal GRD that can be achieved with a digital imaging system is approximately twice its GSD.

As explained in Section 2.11, the image analyst is interested not only in object detection but also in object recognition and identification. In the case of scanner images, the larger the number of pixels that make up the image of an object on the ground, the more information that can be determined about that object. For example, one pixel on a vehicle might just be identified as an object on the ground (and this assumes adequate contrast between the vehicle and its background). Two pixels on the same object might be adequate to determine the object's orientation. Three pixels might permit identification of the object as a vehicle. And it might be possible to identify the type of vehicle when it includes five or more pixels. Thus, the effective spatial resolution of a digital imaging system depends on a number of factors in addition to its GSD (e.g., the nature of the ground scene, optical distortions, image motion, illumination and viewing geometry, and atmospheric effects).

5.3 ALONG-TRACK SCANNING

As with across-track systems, along-track, or pushbroom, scanners record multispectral image data along a swath beneath an aircraft. Also similar is the use of the forward motion of the aircraft to build up a two-dimensional image by recording successive scan lines that are oriented at right angles to the flight direction. However, there is a distinct difference between along-track and across-track systems in the manner in which each scan line is recorded. In an along-track system there is no scanning mirror. Instead, a *linear array* of detectors is used (Figure 5.5). Linear arrays typically consist of numerous *charge-coupled devices (CCDs)* positioned end to end. As illustrated in Figure 5.5, each detector element is dedicated to sensing the energy in a single column of data. The size of the ground resolution cell is determined by the IFOV of a single detector projected onto the ground. The GSD in the across-track direction is set by the detector IFOV. The GSD in the along-track direction is again set by the sampling interval (ΔT) used for the A-to-D signal conversion. Normally, the sampling results in just-touching square pixels comprising the image.

Linear array CCDs are designed to be very small, and a single array may contain over 10,000 individual detectors. Each spectral band of sensing requires its own linear array. Normally, the arrays are located in the focal plane of the scanner such that each scan line is viewed by all arrays simultaneously.

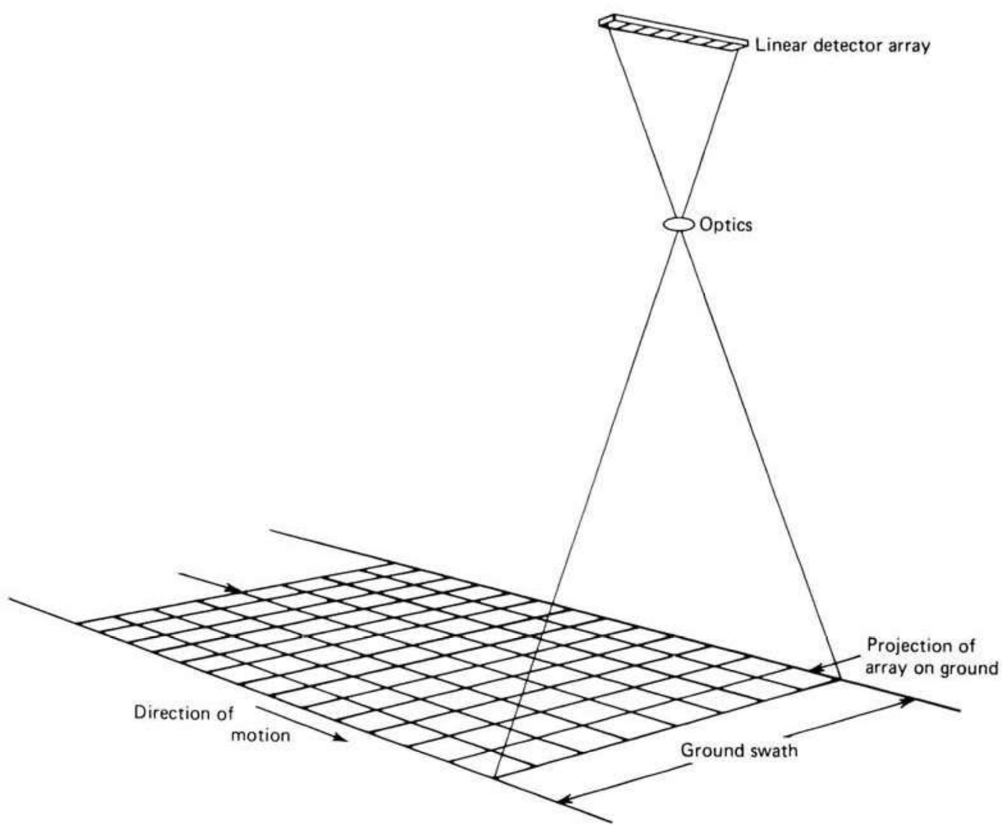

Figure 5.5 Along-track, or pushbroom, scanner system operation.

Linear array systems afford a number of advantages over across-track mirror scanning systems. First, linear arrays provide the opportunity for each detector to have a longer dwell time over which to measure the energy from each ground resolution cell. This enables a stronger signal to be recorded (and, thus, a higher signal-to-noise ratio) and a greater range in the signal levels that can be sensed, which leads to better radiometric resolution. In addition, the geometric integrity of linear array systems is greater because of the fixed relationship among detector elements recording each scan line. The geometry along each row of data (scan line) is similar to an individual photo taken by an aerial mapping camera. The geometric errors introduced into the sensing process by variations in the scan mirror velocity of across-track scanners are not present in along-track scanners. Because linear arrays are solid-state microelectronic devices, along-track scanners are generally smaller in size and weight and require less power for their operation than across-track scanners. Also, having no moving parts, a linear array system has higher reliability and longer life expectancy.

One disadvantage of linear array systems is the need to calibrate many more detectors. Another current limitation to commercially available solid-state arrays is their relatively limited range of spectral sensitivity. Linear array detectors that are sensitive to wavelengths longer than the mid-IR are not readily available.

5.4 OPERATING PRINCIPLES OF ACROSS-TRACK MULTISPECTRAL SCANNERS

Figure 5.6 illustrates the operation of a typical across-track, or whiskbroom, scanner. As previously mentioned, by using a rotating or oscillating mirror (Figure 5.6*b*), such systems scan the terrain along *scan lines* that are at right angles to the flight line. Successive scan lines are covered as the aircraft moves forward, yielding a series of contiguous, or just-touching, narrow strips of observation composing a two-dimensional image. The incoming energy is separated into several spectral components that are sensed independently. In Figure 5.6 we illustrate an example of a system that records both thermal and nonthermal wavelengths. A *dichroic grating* is used to separate these two forms of energy. The nonthermal wavelength component is directed from the grating through a prism (or diffraction grating) that splits the energy into a continuum of UV, visible, and near-IR wavelengths. At the same time, the dichroic grating disperses the thermal component of the incoming signal into its constituent wavelengths. By placing an array of electro-optical detectors at the proper geometric positions behind the grating and the prism, the incoming beam is essentially "pulled apart" into multiple narrow bands, each of which is measured independently. Each detector is designed to have its peak spectral sensitivity in a specific wavelength band. Figure 5.6 illustrates a five-band scanner. As we see later (Section 5.14), scanners with hundreds of bands are available.

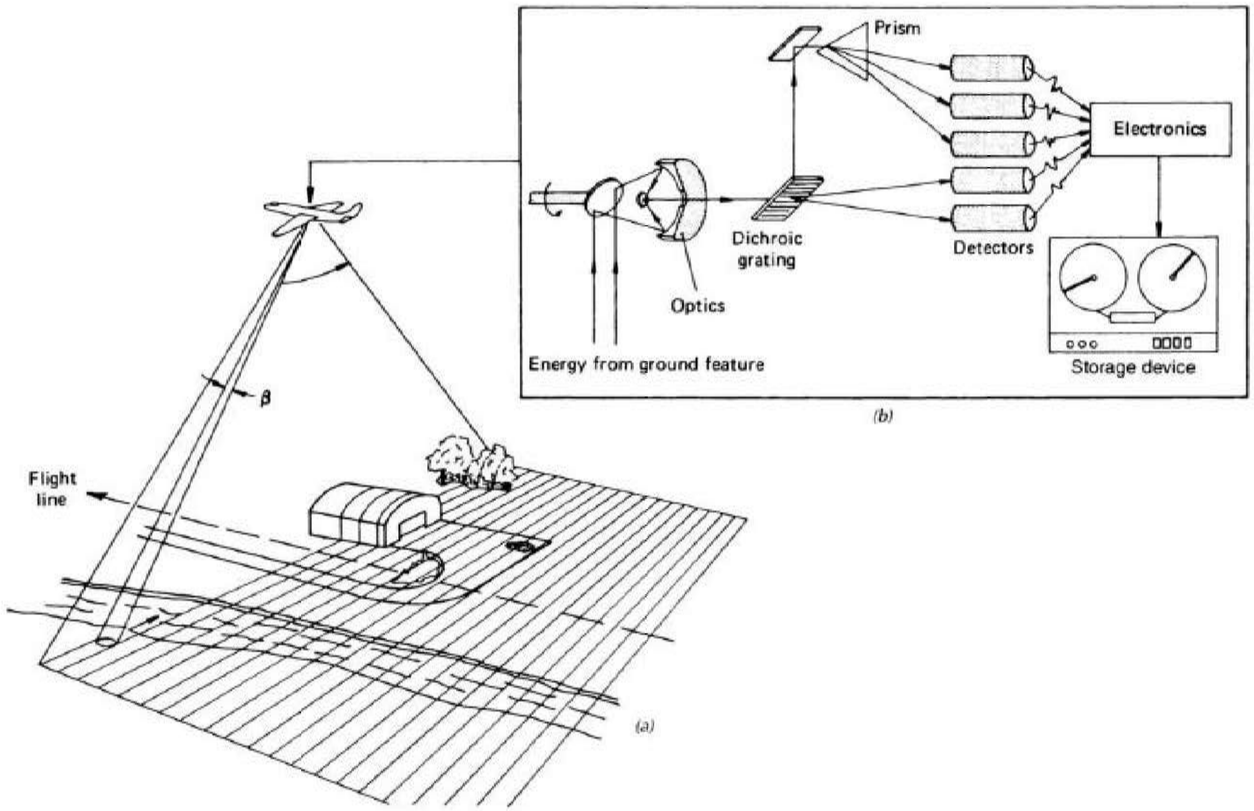

Figure 5.6 Across-track, or whiskbroom, multispectral scanner system operation: (*a*) scanning procedure during flight; (*b*) scanner schematic.

As shown in Figure 5.6, the electrical signals generated by each of the detectors of the multispectral scanner are amplified by the system electronics and recorded by a multichannel storage device. Usually, onboard A-to-D signal conversion (Section 1.5) is used to record the data digitally.

Figure 5.7 shows an across-track multispectral scanner system that has an IFOV of 2.5 mrad (1.25 mrad optional) and a total scan angle of 86°. The scanner acquires 8- or 12-bit (operator-selectable) digital data simultaneously in 6 bands (selected from a total of 10 available bands) within the wavelength range 0.32 to 12.5 μm and records these data on 8-mm digital tape. This system provides continuous video monitoring of the scene (see monitor at upper left in Figure 5.7*b*). An optional printer can provide continuous hardcopy images, and a VHS video recording can be made from the video monitor output.

Figure 5.8 shows six bands of multispectral scanner data acquired by the above scanner along a portion of the Yakima River in the state of Washington,

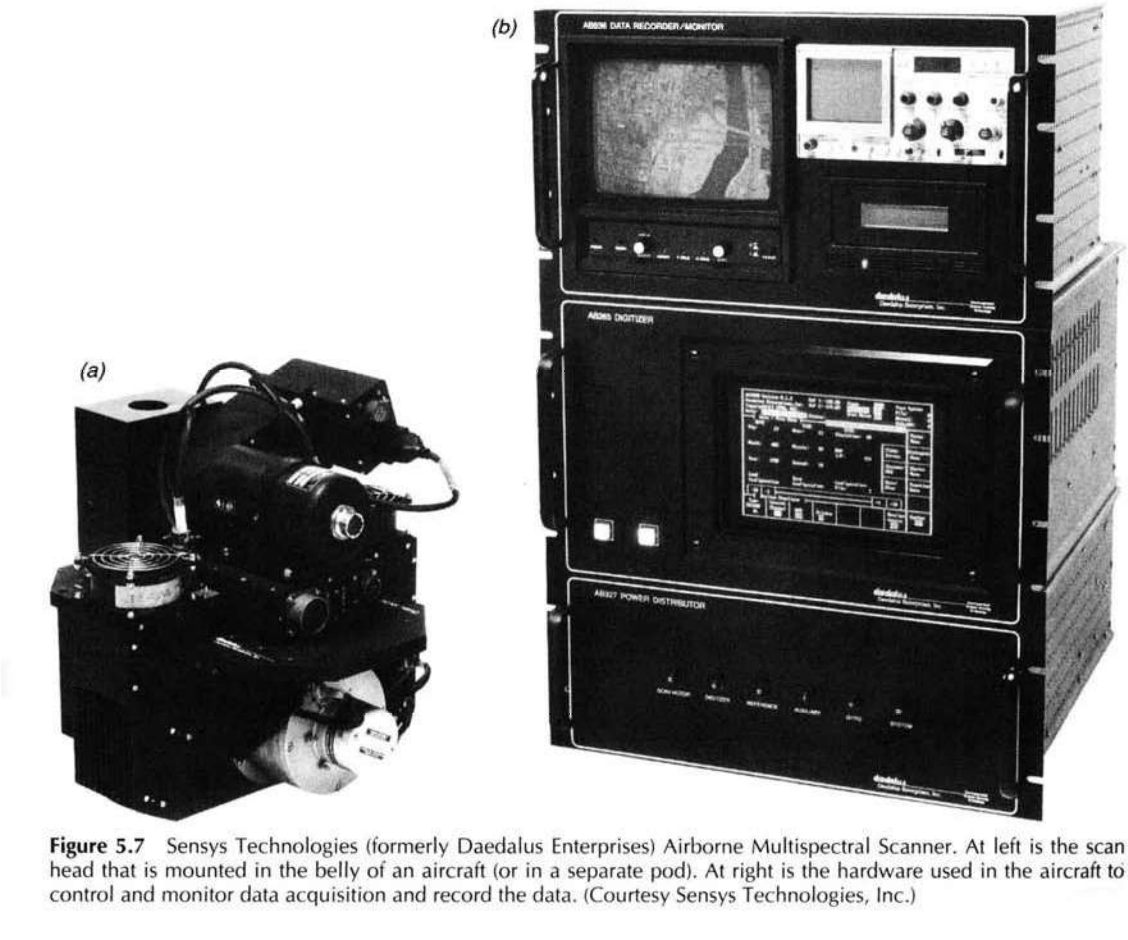

Figure 5.7 Sensys Technologies (formerly Daedalus Enterprises) Airborne Multispectral Scanner. At left is the scan head that is mounted in the belly of an aircraft (or in a separate pod). At right is the hardware used in the aircraft to control and monitor data acquisition and record the data. (Courtesy Sensys Technologies, Inc.)

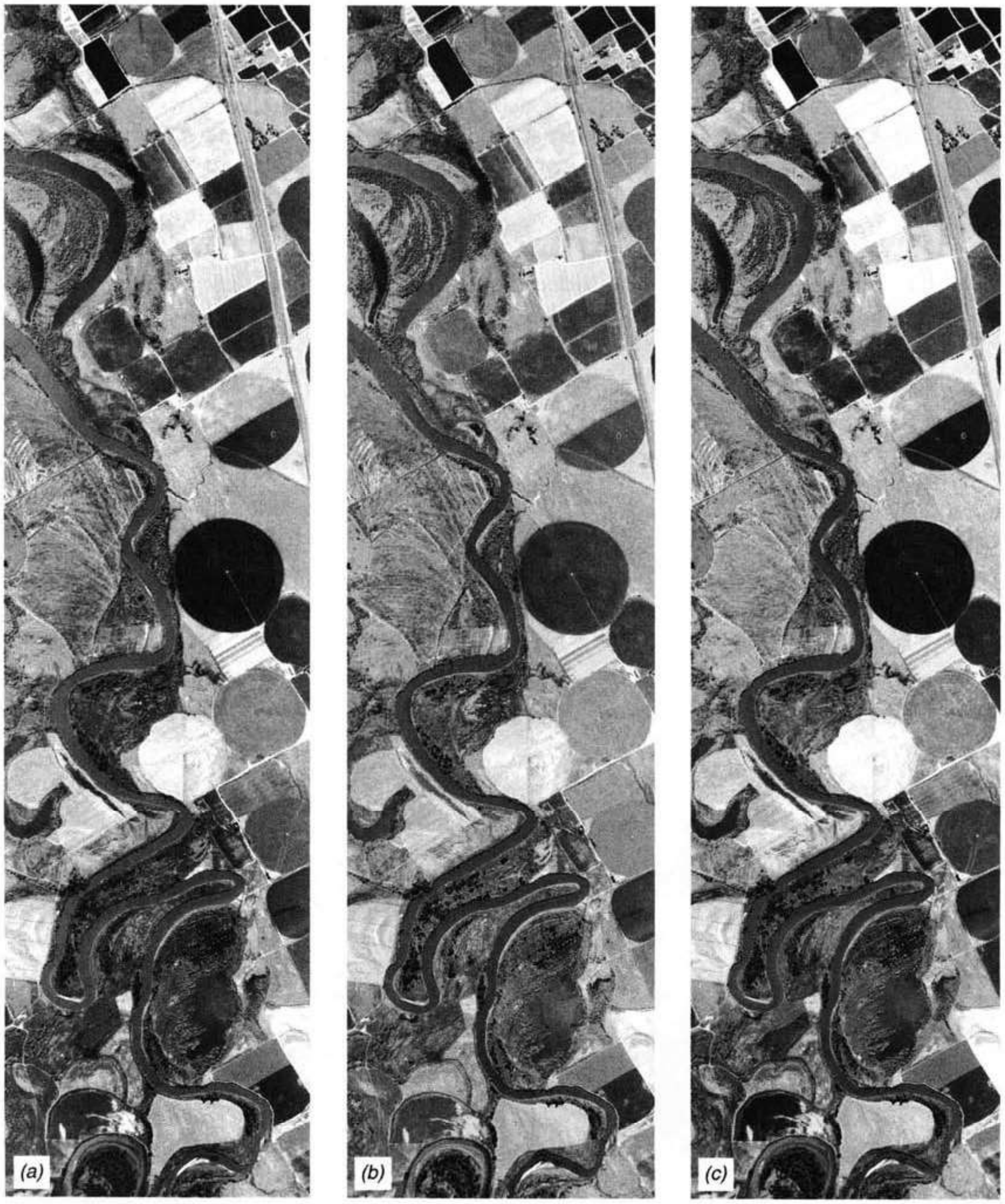

Figure 5.8 Six-band multispectral scanner data, Yakima River valley, Washington, mid-August 1997: (*a*) band 1, 0.42 to 0.52 μm (blue); (*b*) band 2, 0.52 to 0.60 μm (green); (c) band 3, 0.63 to 0.69 μm (red); (*d*) band 4, 0.76 to 0.90 μm (near IR); (*e*) band 5, 0.91 to 1.05 μm (near IR); (*f*) band 6, 8.0 to 12.5 μm (thermal IR). Scale 1: 50,000. (Courtesy Sensys Technologies, Inc.)

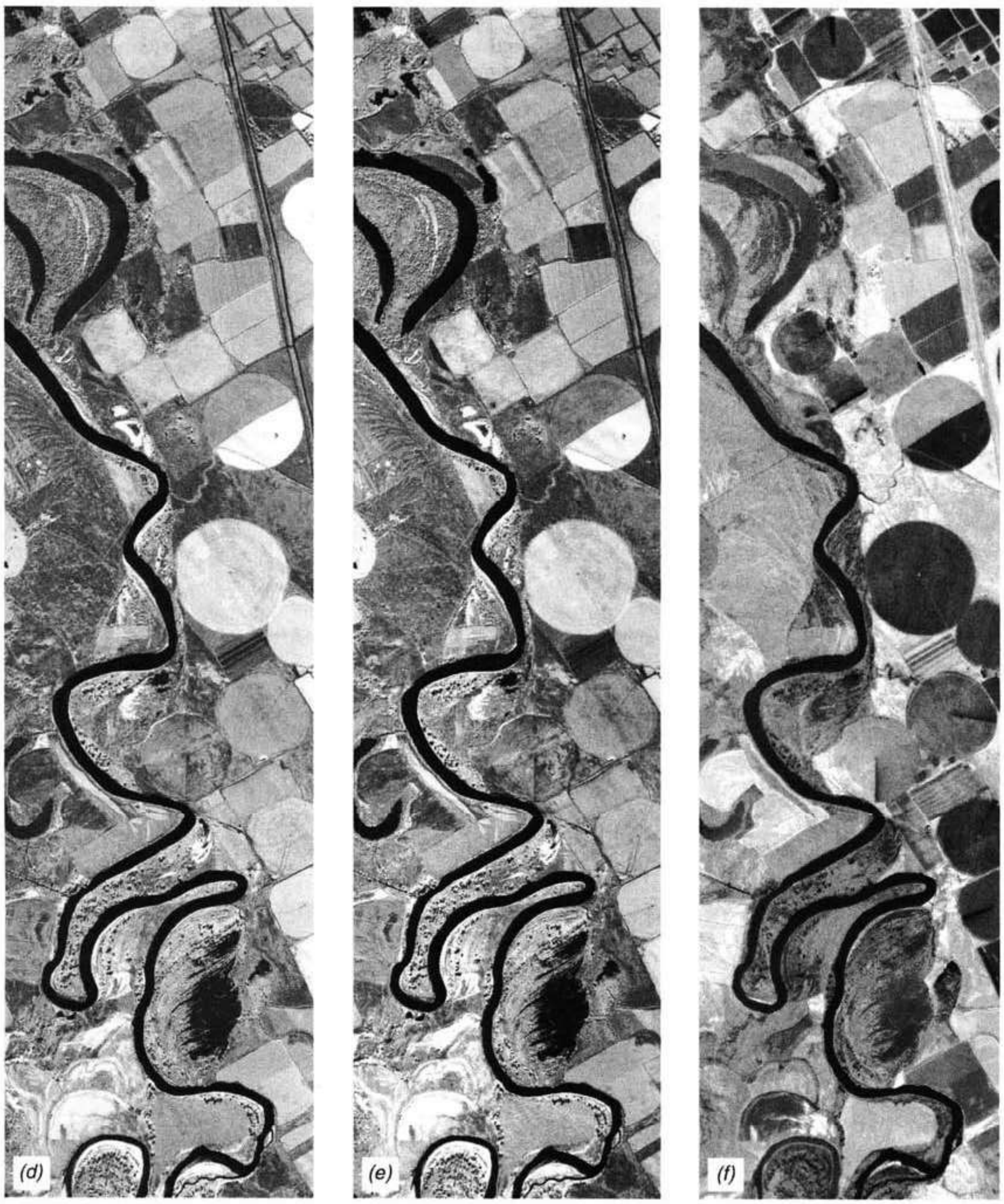

Figure 5.8 *(Continued)*

and Plate 14 shows normal color and color IR composites of three of these bands. (The circular areas appearing in these images result from the practice of center-pivot irrigation for agricultural production.) As is typical with multispectral data, the three bands in the visible part of the spectrum (bands 1, 2, and 3) show a great deal of correlation; that is, objects (fields) that are light toned in one visible band are light toned in the other two visible bands. There are, of course, some variations in reflectance, which is why different colors are seen (Plate 14*a*). In the near-IR bands, healthy vegetation is much lighter toned than in the visible bands, resulting in red tones where such vegetation is present (Plate 14*b*). As was seen in the photographs in Figure 2.17, water is extremely dark in the near-IR bands—compare the image tone of the Yakima River in (*a*) with its tone in (*d*) and (*e*). In the thermal band (*f*), healthy green vegetation (e.g., the darker toned large circular field near the middle of the images) is much cooler than less-vegetated areas in this daytime thermal image (additional thermal imagery is shown later in this chapter).

In the normal color and color IR combinations of multispectral scanner images shown in Plate 14, different crops are seen as different colors. In these mid-August images, the largest circular field (just above the center of the images) with the bright red color (in the color IR image) is seed grass. The bright red half-circle above the seed grass is alfalfa. The alfalfa and seed grass appear similar in color in the normal color and color IR images, but a close inspection of all bands shows that the alfalfa is brighter toned in the near-IR bands (bands 4 and 5), and thus the two crops can be distinguished from each other using these bands. The two circular fields below (and slightly to the right) of the seed grass field are also alfalfa, but at different growth stages. The upper half of the circular field near the top of the image that has alfalfa at the bottom contains asparagus in its upper half. In the normal color image, the tan field at the top of the image and the tan circular field just below the center of the image are winter wheat. Sweet corn is planted in the two nearly rectangular fields below the winter wheat at the top of the image. The bright pink color (in the color IR image) at the extreme left edge about a third of the way down from the top is an area of lily pads and algae in a lake. Note how the reflectance of this feature varies from that of the other cover types in the image among the various bands. Again, it is this difference in spectral reflectance that aids in the discrimination of cover types visually and in the process of automated image classification (discussed in Chapter 7).

5.5 EXAMPLE ALONG-TRACK MULTISPECTRAL SCANNER AND DATA

An example of an airborne along-track scanner is the *ADS40 Airborne Digital Sensor*, manufactured by LH Systems shown in Figure 5.9. It incorporates multiple linear arrays of CCDs for panchromatic and multispectral image ac-

Figure 5.9 The ADS40 along-track scanner system. (Courtesy Leica Geosystems.)

quisition, all sharing a single lens system, with a focal length of 62.77 mm. The ADS40 panchromatic arrays are sensitive over the range of wavelengths from 0.465 to 0.680 μm. Three visible-wavelength bands are present, with sensitivities of 0.430 to 0.490 μm, 0.535 to 0.585 μm, and 0.610 to 0.660 μm, as is one near-IR band (0.835 to 0.885 μm). The sensor has a wide dynamic range, and a total field of view of 64° across-track.

Three linear arrays can be used to collect panchromatic data, with one forward-viewing, one nadir-viewing, and one rear-viewing. Data from these arrays can be used for stereoscopic viewing and for photogrammetric analyses. The forward-viewing array is positioned at an angle of 28.4° off nadir, while the rear-viewing array is 14.2° off nadir. There are thus three possible stereoscopic configurations of the panchromatic images, with angles of 14.2° (using the nadir and rear-viewing arrays), 28.4° (using the nadir and forward-viewing arrays), and 42.6° (using the rear-viewing and forward-viewing arrays). These three configurations provide stereoscopic base-height ratios of 0.25, 0.54, and 0.79, respectively. The blue, green, and red multispectral arrays are inclined 14.2° off nadir in the forward direction, and the near-IR array is oriented 2° to the rear of nadir.

Each of the three panchromatic arrays consists of two lines of 12,000 CCDs, with the two lines offset by 0.325 μm, or half the width of a single CCD. In high resolution mode, both of the lines are used, yielding an effective IFOV of 0.05 mrad; if only one line is used, the IFOV is 0.1 mrad. At a typical flying height of 2880 m above ground level, this results in a ground sampling distance of 15 cm in high resolution mode or 30 cm otherwise.

Figure 5.10 shows an example of ADS40 panchromatic imagery acquired over the Texas state capitol in Austin. Data from the forward-viewing, nadir-

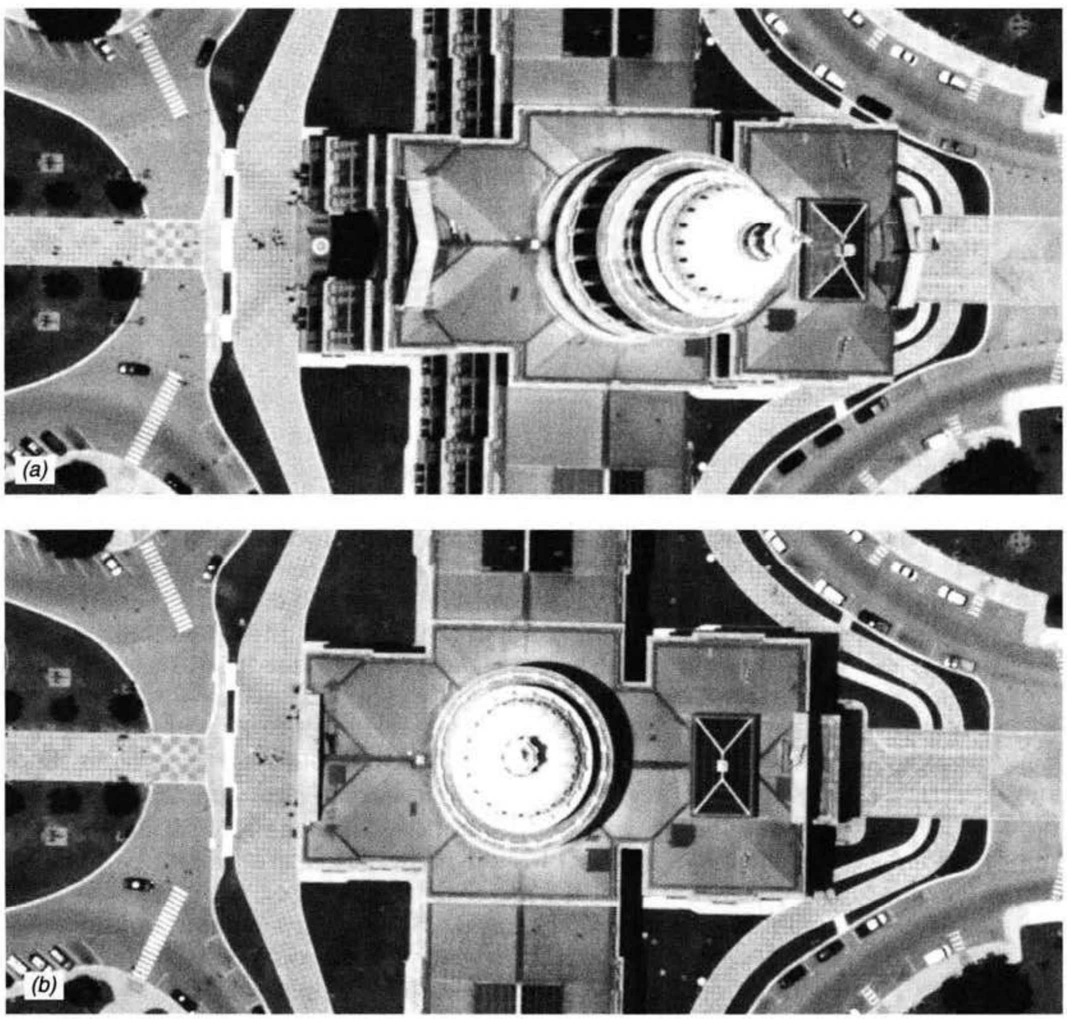

Figure 5.10 ADS40 panchromatic images of the Texas state capital, Austin, TX. Flight direction is left to right. (*a*) Forward-viewing array, 28.4° off nadir; (*b*) nadir-viewing array; (*c*) backward-viewing array, 14.2° off-nadir. (Courtesy Leica Geosystems.)

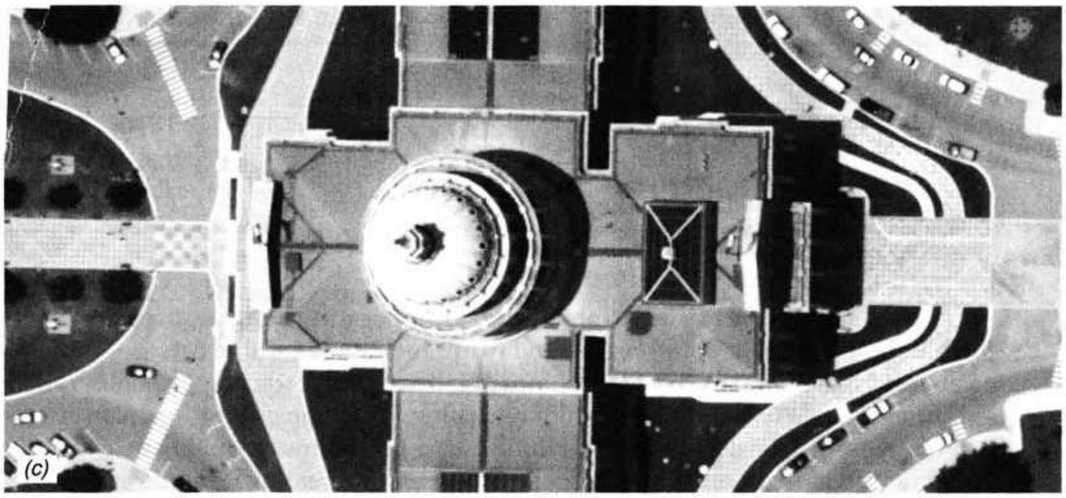

Figure 5.10 *(Continued)*

viewing, and backward-viewing linear arrays show the effects of relief displacement. The magnitude of displacement is greater in the forward-viewing image than in the backward-viewing image because the forward-viewing array is tilted further off-nadir. The data shown in Figure 5.10 represent only a small portion of the full image dimensions. For this data acquisition the sensor was operated from a flying height of 1920 m above ground level. The original ground sampling distance for this data set was 20 cm.

5.6 ACROSS-TRACK THERMAL SCANNING

As mentioned earlier, a *thermal scanner* is merely a particular kind of across-track multispectral scanner, namely, one whose detector(s) only senses in the thermal portion of the spectrum. Due to atmospheric effects, these systems are restricted to operating in either (or both) the 3- to 5-μm or 8- to 14-μm range of wavelengths (Section 1.3). *Quantum* or *photon* detectors are typically used for this purpose. These detectors are capable of very rapid (less than 1-μsec) response. They operate on the principle of direct interaction between photons of radiation incident on them and the energy levels of electrical charge carriers within the detector material. For maximum sensitivity, the detectors must be cooled to temperatures approaching absolute zero to minimize their own thermal emissions. Normally, the detector is surrounded by a *dewar* containing liquid nitrogen at 77 K. A dewar is a double-walled insulated vessel that acts like a thermos bottle to prevent the liquid coolant from boiling away at a rapid rate.

TABLE 5.1 Characteristics of Photon Detectors in Common Use

Type	Abbreviation	Useful Spectral Range (μm)
Mercury-doped germanium	Ge:Hg	3–14
Indium antimonide	InSb	3–5
Mercury cadmium telluride	HgCdTe (MCT), or "trimetal"	8–14

The spectral sensitivity range and the operating temperatures of three photon detectors in common use today are included in Table 5.1.

Thermal scanners became commercially available during the late 1960s. Earlier models used only direct film recording for image generation. Newer systems record data digitally. In addition, scan line output signals are generally monitored in flight on an oscilloscope or some other real-time monitor. Present-day systems are capable of temperature resolution on the order of 0.1°C.

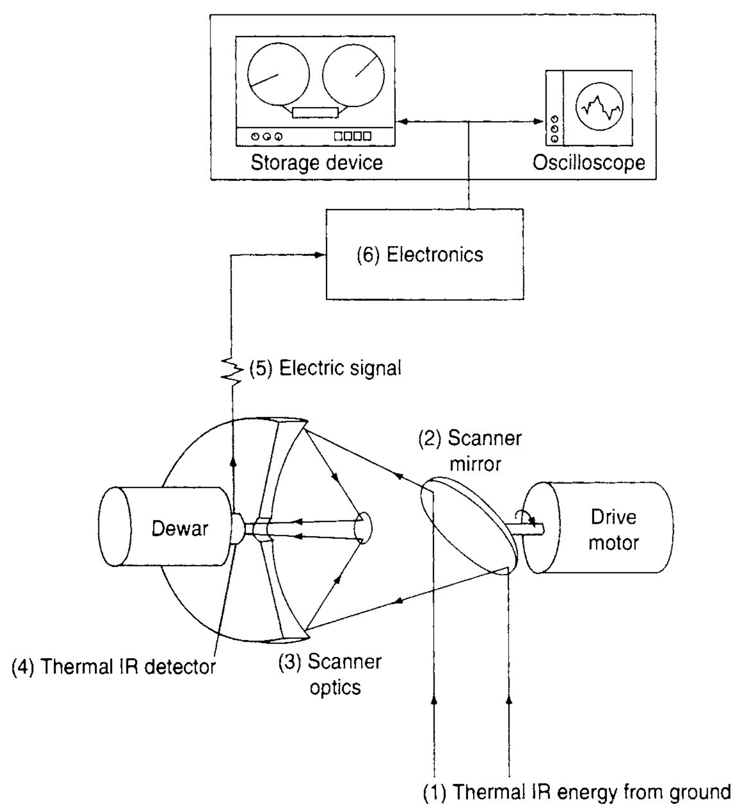

Figure 5.11 Across-track thermal scanner schematic.

Figure 5.11 illustrates schematically the basic operation of a thermal scanner system. The system works as follows. Thermal IR radiation from the ground (1) is received at the rotating scanner mirror (2). Additional optics (3) focus the incoming energy on the thermal IR radiation detector (4), which is encased by a dewar filled with a liquid nitrogen coolant. The detector converts the incoming radiation level to an electric signal (5) that is amplified by the system electronics (6). The signal (or an image) is displayed on the monitor and recorded digitally on a line-by-line basis after an A-to-D conversion.

A thermal scanner image is a pictorial representation of the detector response on a line-by-line basis. The usual convention when looking at the earth's surface is to have higher radiant temperature areas displayed as lighter toned image areas. For meteorological purposes, this convention is typically reversed so that clouds (cooler than the earth's surface) appear light toned.

5.7 THERMAL RADIATION PRINCIPLES

Implicit in the proper interpretation of a thermal scanner image, or *thermogram*, is at least a basic understanding of the nature of thermal radiation. In this section we review and extend some of the principles of blackbody radiation introduced in Section 1.2. We also treat how thermal radiation interacts with the atmosphere and various earth surface features.

Radiant Versus Kinetic Temperature

One normally thinks of temperature measurements as involving some measuring instrument being placed in contact with, or being immersed in, the body whose temperature is to be measured. When this is done, *kinetic temperature* is measured. Kinetic temperature is an "internal" manifestation of the average translational energy of the molecules constituting a body. In addition to this internal manifestation, objects radiate energy as a function of their temperature. This emitted energy is an "external" manifestation of an object's energy state. It is this external manifestation of an object's energy state that is remotely sensed using thermal scanning. The emitted energy is used to determine the *radiant temperature* of earth surface features. Later we describe how to relate kinetic and radiant temperature.

Blackbody Radiation

We have previously described the physics of electromagnetic radiation in accordance with the concepts of blackbody radiation (see Section 1.2). Recall