Imaging Spectrometry Using Linear and Area Arrays

- NASA Jet Propulsion Laboratory Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)
- Compact Airborne Spectrographic Imager 1500 (CASI 1500) and hyperspectral SWIR sensor (SASI 600)
- NASA Terra Moderate Resolution Imaging Spectrometer (MODIS)
- NASA Earth Observer (EO-1) Advanced Land Imager (ALI), Hyperion, and LEISA Atmospheric Corrector (LAC)

Digital Frame Cameras Based on Area Arrays

- Leica Geosystems Emerge Digital Sensor System
- Vexcel UltraCam Large Format Camera
- Z/1 Digital Modular Camera

Astronaut Photographic Systems

- NASA Space Shuttle and International Space Station Imagery

The following discussion identifies the spatial, spectral, temporal, and radiometric characteristics of the remote sensing systems.

Multispectral Imaging Using Discrete Detectors and Scanning Mirrors

The collection of multispectral remote sensor data using discrete detectors and scanning mirrors began in the mid-1960s. Despite the technology’s age, several new remote sensing systems still use it.

Earth Resource Technology Satellites and Landsat Sensor Systems

In 1967, the National Aeronautics & Space Administration (NASA), encouraged by the U.S. Department of the Interior, initiated the Earth Resource Technology Satellite (ERTS) program. This program resulted in the launch of seven satellites carrying a variety of remote sensing systems designed primarily to acquire Earth resource information. The most noteworthy sensors have been several Landsat Multispectral Scanners and Landsat Thematic Mappers (Figure 4; Tables 1 and 2). The Landsat program is the United States’ oldest land-surface observation satellite system, having obtained data since 1972. It has had a tumultuous history of management and funding sources.

The chronological launch and retirement history of the satellites is shown in Figure 4. The ERTS-1 satellite, launched on July 23, 1972, was an experimental system designed to test the feasibility of collecting Earth resource data by unmanned satellites. Prior to the launch of ERTS-B on January 22, 1975, NASA renamed the ERTS program Landsat, distinguishing it from the Seasat active-microwave satellite launched on June 26, 1978. At this time, ERTS-1 was retroactively named Landsat-1 and ERTS-B became Landsat-2 at launch. Landsat-3 was launched March 5, 1978; Landsat-4 on July 16, 1982; and Landsat-5 on March 1, 1984.

The Earth Observation Satellite Company (EOSAT) obtained control of the Landsat satellites in September, 1985. Unfortunately, Landsat 6, with its Enhanced Thematic Mapper (ETM) (a 15 × 15 m panchromatic band was added), failed to achieve orbit on October 5, 1993. Landsat 7, with its Enhanced Thematic Mapper Plus (ETM⁺) sensor system, was launched on April 15, 1999. Please refer to the NASA Landsat 7 home page for a detailed history of the Landsat program (NASA Landsat 7, 2006).

Landsats 1 through 3 were launched into Sun-synchronous polar orbits at a nominal altitude of 919 km (570 mi). The platform is shown in Figure 5a. The satellites had an orbital inclination of 99°, which made them nearly polar (Figure 5b) and caused them to cross the equator at an angle of approximately 9° from normal. The satellites orbited Earth once every 103 minutes, resulting in 14 orbits per day (Figure 5c). During each polar orbit, the satellites crossed the equator at approximately the same local time (9:30 to 10:00 a.m.) on the illuminated side of Earth.

Figures 5c and 6 illustrate how repeat coverage of a geographic area was obtained. From one orbit to the next, a position directly below the spacecraft moved 2,875 km (1,785 mi) at the Equator as the Earth rotated beneath it. The next day, 14 orbits later, it was back to its original location, with orbit 15 displaced westward from orbit 1 by 159 km (99 mi) at the equator. This continued for 18 days, after which orbit 252 fell directly over orbit 1 once again. Thus, the Landsat sensor systems had the capability of observing the entire globe (except poleward of 81°) once every 18 days, or about 20 times a year. There were approximately 26 km (16 mi) of sidelap between successive orbits. This sidelap was a...
maximum at 81° north and south latitudes (about 85%) and a minimum at the equator (about 14%). The sidelap has proven useful for stereoscopic analysis applications.

The nature of the orbiting Landsat system has given rise to a Path and Row Worldwide Reference System (WRS) for locating and obtaining Landsat imagery for any area on Earth. The WRS has catalogued the world’s landmass into 57,784 scenes. Each scene is approximately 185 km wide by 170 km long.

An elegant method of determining if remote sensor data (e.g., Landsat MSS, Thematic Mapper, Enhanced Thematic Mapper Plus) are available for a specific location is to use the U.S. Geological Survey’s Global Visualization Viewer (USGS GloVis, 2006). For example, suppose we are interested in locating a Landsat Thematic Mapper image of Charleston, SC. We can enter the Global Visualization Viewer and specify WRS Path 16 and Row 37 and search the database as shown in Figure 7. If we do not know the path and row designation, we could a) move the cursor on the regional map and place it on Charleston, SC, or b) input the latitude and longitude coordinates of Charleston, SC (33.2° N, -81° W). We can specify the month and year (e.g., May, 2005) and the amount of acceptable cloud cover. We can also specify whether the search should be conducted regionally as in Figure 7a (pixels resampled to 1000 m) or locally as in Figure 7b (pixels resampled to 240 m). A color version of the Global Visualization Viewer interface is shown in Color Plate 1.

In this section, we are interested in the type of sensors carried aloft by the Landsat satellites and the nature and quality of remote sensor data provided for Earth resource investigations. The most important sensors are the Multispectral Scanner and several Thematic Mappers.
The Landsat Multispectral Scanner (MSS) was placed on Landsat satellites 1 through 5. The MSS multiple-detector array and the scanning system are shown diagrammatically in Figure 8a. Sensors such as the Landsat MSS (and Thematic Mapper to be discussed) are optical-mechanical systems in which a mirror scans the terrain perpendicular to the flight direction. While it scans, it focuses energy reflected or emitted from the terrain onto discrete detector elements. The detectors convert the radiant flux measured within each instantaneous field of view (IFOV) in the scene into an electronic signal (Figures 3b and 8a). The detector elements are placed behind filters that pass broad portions of the spectrum. The MSS had four sets of filters and detectors, whereas the TM had seven. The primary limitation of this approach is the short viewing residence time of the detector in each IFOV. To achieve adequate signal-to-noise ratio without sacrificing spatial resolution, such a sensor must operate in broad spectral bands of $\geq 100$ nm or must use optics with unrealistically small ratios of focal length to aperture ($f/\text{stop}$).

The MSS scanning mirror oscillates through an angular displacement of $\pm 5.78^\circ$ off-nadir. This $11.56^\circ$ field-of-view

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**Table 1. Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) sensor system characteristics.**

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Resolution ($\mu$m)</th>
<th>Radiometric Sensitivity (NE$\Delta$P)$^a$</th>
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<th>Spectral Resolution ($\mu$m)</th>
<th>Radiometric Sensitivity (NE$\Delta$P)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4$^b$</td>
<td>0.5 – 0.6</td>
<td>0.57</td>
<td>1</td>
<td>0.45 – 0.52</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.6 – 0.7</td>
<td>0.57</td>
<td>2</td>
<td>0.52 – 0.60</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.7 – 0.8</td>
<td>0.65</td>
<td>3</td>
<td>0.63 – 0.69</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>0.8 – 1.1</td>
<td>0.70</td>
<td>4</td>
<td>0.76 – 0.90</td>
<td>0.5</td>
</tr>
<tr>
<td>8$^c$</td>
<td>10.4 – 12.6</td>
<td>1.4K (NE$\Delta$T)</td>
<td>5</td>
<td>1.55 – 1.75</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>10.40–12.5</td>
<td>0.5 (NE$\Delta$T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>2.08–2.35</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- **IFOV at nadir**: 79×79 m for bands 4 through 7, 240×240 m for band 8, 30×30 m for bands 1 through 5, 7, 120×120 m for band 6.
- **Data rate**: 15 Mb/s, 85 Mb/s.
- **Quantization levels**: 6 bit (values from 0 to 63), 8 bit (values from 0 to 255).
- **Earth coverage**: 18 days Landsat 1, 2, 3, 16 days Landsat 4, 5, 16 days Landsat 4, 5.
- **Altitude**: 919 km, 705 km.
- **Swath width**: 185 km, 185 km.
- **Inclination**: 99°, 98.2°.

$^a$ The radiometric sensitivities are the noise-equivalent reflectance differences for the reflective channels expressed as percentages (NE$\Delta$P) and temperature differences for the thermal infrared bands (NE$\Delta$T).

$^b$ MSS bands 4, 5, 6, and 7 were renumbered bands 1, 2, 3, and 4 on Landsats 4 and 5.

$^c$ MSS band 8 was present only on Landsat 3.
resulted in a swath width of 185 km (115 mi) for each orbit. Six parallel detectors sensitive to four spectral bands (channels) in the electromagnetic spectrum viewed the ground simultaneously: 0.5 to 0.6 μm (green), 0.6 to 0.7 μm (red), 0.7 to 0.8 μm (reflective near-infrared), and 0.8 to 1.1 μm (reflective near-infrared). These bands were originally numbered 4, 5, 6, and 7, respectively, because a Return-Beam-Vidicon (RBV) sensor system also onboard the satellite recorded energy in three bands labeled 1, 2, and 3.

When not viewing the Earth, the MSS detectors were exposed to internal light and Sun calibration sources. The

Figure 5  

a) Nimbus-style platform used for Landsats 1, 2, and 3 and associated sensor and telecommunication systems.  
b) Inclination of the Landsat orbit to maintain a Sun-synchronous orbit. c) From one orbit to the next, the position directly below the satellite moved 2,875 km (1,785 mi) at the equator as Earth rotated beneath it. The next day, 14 orbits later, it was approximately back to its original location, with orbit 15 displaced westward from orbit 1 by 159 km (99 mi). This is how repeat coverage of the same geographic area was obtained.
Table 1

<table>
<thead>
<tr>
<th>Band</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>Very High</td>
</tr>
</tbody>
</table>

Figure 8b shows the spectral sensitivity of the bands. Note that there is spectral overlap between the bands.

Prior to the launch of the satellite, the engineering model of the ERTS MSS was tested by viewing the scene behind the Santa Barbara Research Center in Goleta, CA. Bands 4 and 6 (green and near-infrared, respectively) of the area are shown in Figure 9. Note the spatial detail present when the sensor is located only 1 to 2 km from the mountains. The spatial resolution is much lower when the sensor is placed 919 km above Earth in orbit.

The IFOV of each detector was square and resulted in a ground resolution element of approximately 79 m × 79 m (67,143 ft²). The analog voltage signal from each detector was converted to a digital value using an onboard A-to-D converter. The data were quantized to 6-bits with a range of values from 0 to 63. These data were then rescaled to 7-bits (0 to 127) for three of the four bands in subsequent ground processing (i.e., bands 4, 5, and 6 were decompressed to a range of 0 to 127). It is important to remember that the early 1970s Landsat MSS data were quantized to 6-bits when comparing MSS data collected in the late 1970s and 1980s, which were collected at 8-bits.

During each scan, the voltage produced by each detector was sampled every 9.95 μs. For one detector, approximately 3300 samples were taken along a 185-km line. Thus, the IFOV of 79 m × 79 m became about 56 m on the ground between each sample (Figure 10). The 56 × 79 m area is called a Landsat MSS picture element. Thus, although the measurement of landscape brightness was made from a 6,241 m² area, each pixel was reformatted as if the measurement were made from a 4,424 m² area (Figure 10). Note the overlap of the areas from which brightness measurements were made for adjacent pixels.

The MSS scanned each line across-track from west to east as the southward orbit of the spacecraft provided the along-track progression. Each MSS scene represents a 185 m × 170 km parallelogram extracted from the continuous swath of an orbit and contains approximately 10 percent overlap. A typical scene contains approximately 2340 scan lines with about 3240 pixels per line, or about 7,581,600 pixels per channel. All four bands represent a data set of more than 30 million brightness values. Landsat MSS images provided an unprecedented ability to observe large geographic areas while viewing a single image. For example, approximately 5000 vertical aerial photographs obtained at a scale of 1:15,000 are required to equal the geographic coverage of a single Landsat MSS image. This allows regional terrain analysis to be performed using one data source rather than a multitude of aerial photographs.

Figure 6

Orbital tracks of Landsat 1, 2, or 3 during a single day of coverage. The satellite crossed the equator every 103 minutes, during which time the Earth rotated a distance of 2,875 km under the satellite at the equator. Every 14 orbits, 24 hours elapsed.