Orbital Linear or Area-Array Remote-Sensing and Information-Extraction Methods

In 1994, the U.S. government made a decision to allow civil commercial companies to market high-spatial-resolution remote-sensor data (approximately 1×1 m to 4×4 m). This resulted in the creation of a number of commercial consortia that have the capital necessary to engineer, launch, and market high-spatial-resolution digital remote-sensor data. The most notable companies include Space Imaging, Inc., and ORBIMAGE, Inc. These companies have targeted the GIS and cartographic mapping markets traditionally serviced by the aerial photogrammetric industries. These commercial remote-sensing firms hope to have a crucial impact in markets as diverse as agriculture, natural resource management, local and regional government, transportation, emergency response, mapping, and eventually a suite of layperson consumer products (Space Imaging, 1999a; 4).

Most noteworthy is Space Imaging, Inc., which launched IKONOS-2 in 1999. The IKONOS-2 sensor system obtains panchromatic imagery at 1×1 m and four bands of multispectral data at 4×4 m. There are several innovative characteristics of this type of remote-sensing data collection, including the following:

- The data are obtained using linear arrays of stable detectors that achieve a higher degree of geometric stability in the imagery (Figure 4c).
- The orbital (as opposed to suborbital) platform is not buffeted by atmospheric turbulence, thus significantly decreasing roll, pitch, and yaw error.
- The digital remote-sensor data are collected as a continuous swath (in this case, 11-km wide), thus significantly reducing the amount of data that must be mosaicked for a given project.
- The data are collected in 11 bits of radiometric resolution (brightness values ranging from 0 to 2,047), which is far superior to previous 8-bit (0 to 255) remote-sensing systems or photographic film silver halide sensitivity.
- The system can obtain overlapping stereoscopic views of the terrain.
- The sensor is always in orbit and pointable, meaning that weather permitting, there is a high probability of obtaining imagery of interest.

An IKONOS-2 panchromatic image of the capitol building in Columbia, S.C., is shown in Figure 9a. The aforementioned soft-copy photogrammetric techniques can be applied to the IKONOS-2 stereoscopic 1×1-m panchromatic data to extract many of the types of information listed in Table 1. A pan-sharpened image of Columbia is shown in Figure 9b. It contains the high-spatial information from the 1×1-m panchromatic band, merged with the spectral information from the 4×4-m multispectral bands.

ORBIMAGE, Inc., is scheduled to launch OrbView 3 in 2001, with a sensor-system payload very similar to IKONOS-2. A constellation of high-spatial resolution orbital remote-sensing systems would (a) provide a greater opportunity for data collection and (b) produce competition that would hopefully reduce the cost of the data to the community of users. EarthWatch, Inc., failed to launch its Earlybird and Quickbird high-resolution satellite remote-sensing systems in 1996 and 2000, respectively.
LIDAR and Information-Extraction Methods

Many transportation-related solutions require very accurate x-, y-, and z-elevation data as well as slope and aspect information. The elevation data are typically summarized as (a) isolines of equal elevation on topographic maps, (b) a raster (matrix) of equally spaced elevation values referred to as a DEM, or (c) a triangular irregular network of elevations derived from individual spot elevations. Although it is possible to obtain very accurate x, y, z information using GPS-surveying techniques, it is also possible to obtain accurate elevation information using remote sensing based on

- Metric stereoscopic aerial photography and soft-copy photogrammetric techniques,
- LIDAR-sensor systems with accurate canopy removal algorithms in place, and
- Interferometric synthetic aperture radar (IFSAR) imagery.

Photogrammetric methods of deriving DEMs have been around since the 1930s. Therefore, this paper focuses only on new developments associated with LIDAR and IFSAR remote sensing.

Many cities, counties, and even entire states are having private commercial firms (many of them photogrammetric engineering firms) collect LIDAR data to obtain accurate DEMs. LIDAR sensors measure active laser pulse travel time from the transmitter onboard the aircraft to the target and back to the receiver (9). As the aircraft moves forward, a scanning mirror directs the laser pulses back and forth across the track (Figure 10). This results in a series of data points

FIGURE 9 IKONOS-2 imagery of Columbia, S.C., obtained on October 28, 2000: (a) panchromatic 1×1 m and (b) pan-sharpened color-infrared composite resampled to 1×1 m.
FIGURE 10 LIDAR data-collection characteristics.

FIGURE 11 Examples of elevation information for portion of Princeville, N.C., obtained using photogrammetric, LIDAR, and IFSAR data: (a) rectified color-infrared air photo; (b) individual LIDAR postings overlaid on rectified aerial photography; (continued)
arranged across the flightline. For example, Figure 11a is a vertical aerial photograph of an area near Princeville, N.C. LIDAR elevation postings obtained in a portion of the region are shown in Figure 11b. Multiple flightlines can be combined to cover the desired area. Data-point density is dependent on the number of pulses transmitted per unit time, the scan angle of the instrument, the elevation of the aircraft above ground level, and the forward speed of the aircraft. The greater the scan angle off nadir, the more vegetation must be penetrated to receive a pulse from the ground, assuming there is a uniform canopy (4).

LIDAR data avoids the problems of aerial triangulation and orthorectification because each LIDAR measurement is individually georeferenced (Flood and Gutelius, 1997). Information about the scanning mirror and aircraft attitude allow precise determination of where the LIDAR instrument was pointed at the time of an individual laser pulse. Exact aircraft position is determined from onboard GPS and inertial navigation equipment. The combination of all these factors allows 3-D georeferenced coordinates to be determined for each laser pulse.

To a certain degree, LIDAR can penetrate vegetation canopy and map the surface below. Penetrating through the canopy is more difficult using aerial photography and IFSAR. Although some of the LIDAR laser energy will be backscattered by vegetation above the ground surface, only a portion of the laser needs to reach the ground to produce a surface measurement. Both of these partial returns (vegetation and ground) can be recorded by the LIDAR instrument, allowing measurements of both vegetation canopy height and ground-surface elevation. When LIDAR imagery is obtained during leaf-off periods in the early winter, the effects of the tree canopy on
the extraction of accurate elevation values is minimal. However, when LIDAR imagery is obtained during leaf-on periods, the LIDAR-derived DEM may be useable but less accurate.

DEMs for an area in North Carolina derived using LIDAR, IFSAR, and photogrammetry data are shown in Figure 11c, d, and e, respectively. The statistical relationship between elevation measurements obtained using the LIDAR instrument versus those obtained at 450 locations that were surveyed in the field by the geodesists is displayed in Figure 12. Although very accurate in many respects, the LIDAR elevation data were not as accurate as the in situ surveyed data in areas with increased canopy height and density. This suggests that (a) LIDAR is best acquired during leaf-off conditions and (b) the algorithm used to reduce the effects of canopy penetration should be as accurate as possible.

The logic and results of using LIDAR derived-elevation data to identify the least-cost location for a new lead-track railroad line from the Bridgestone–Firestone Tire plant near Aiken, S.C., to the main railroad line are summarized in Figures 13 and 14 (9). There are no operational satellite LIDAR systems. NASA’s vegetation canopy LIDAR is scheduled to be launched into orbit in 2001. Data obtained from it will most likely also have value for urban applications.

**Multispectral Remote-Sensing and Information-Extraction Methods**

“Multispectral remote sensing” is the collection of reflected, emitted, or backscattered energy from an object or area of interest in a few selected bands (regions) of the electromagnetic spectrum (usually ≤20). “Hyperspectral remote sensing” involves data collection in more than 20 bands, usually a few hundred bands. “Ultraspectral remote sensing” involves data collection in many hundreds of bands.

Scientists have been able to obtain remote measurements in multiple regions of the electromagnetic spectrum (e.g., blue, green, red, near infrared, middle infrared, thermal infrared)
for more than 50 years (10, 11). The first multispectral remote sensing was performed by exposing normal color and color-infrared film through special filters. The result was multiband aerial photography. Eventually, electro-optical remote-sensing instruments were placed on aircraft and then in satellites to measure the amount of radiant flux reflected or emitted from the Earth’s surface. Multispectral measurements obtained by the Landsat Multispectral Scanner (first launched in 1972), Landsat Thematic Mapper (first launched in 1982), and the SPOT High-Resolution Visible Sensor System (first launched in 1986) have provided for decades a valuable historical record of the reflectance and emittance characteristics of the Earth’s surface. The land cover and land use information derived from such imagery continues to have significant value in many transportation-related studies.
FIGURE 14  (a) Planimetric view of DEM derived using LIDAR data and comparison of modeled and surveyed routes and (b) modeled cumulative cost surface. When cost of laying track is low, cumulative cost surface is relatively flat. When cost of track across road or stream is high, modeled cost surface appears as bright peaks. (c) 3-D view of terrain comparing traditional proposed surveyed route and remote-sensing and GIS-assisted model route (9).
There are three primary methods by which multispectral remote-sensing data are collected: (a) multispectral scanning systems, (b) linear-array detectors, and (c) area-array detectors. The characteristics of a typical multispectral scanning system are shown in Figure 4c. A mirror scans the terrain perpendicular to the flight direction. While it scans, it focuses radiant flux from the terrain onto discrete detector elements. The detectors convert the reflected solar radiant flux measured within each instantaneous field of view (IFOV) in the scene into an electronic signal. Airborne multispectral scanners are routinely used to collect high-spatial and spectral-resolution remote-sensor data. For example, NASA’s Calibrated Airborne Multispectral Scanner (CAMS) imagery is compared with digitized National Aerial Photography Program (NAPP) color infrared aerial photography for an area centered on Sun City–Hilton Head Island, S.C., to quantitatively measure change from 1994–1996 (Figure 15).

**Landsat 7 ETM^+**

Scanning (often called “wiskbroom”) technology continues to mature, despite the fact that the technology introduces geometric error in the data-collection process and does not allow the detectors to remain on any spot on the Earth for very long. A case in point is the NASA Landsat 7 ETM^+ scanner, which was launched on April 15, 1999. It is the United States’ primary multispectral Earth resource-oriented remote-sensing system. It has particular relevance to transportation-related problems that would benefit from the collection of regional, rural land use or land cover information. It is generally not that useful for obtaining detailed urban infrastructure information.

The ETM^+ sensor carries one nadir-pointing instrument that cannot be pointed off axis to view important events taking place in a nearby geographic area that are not directly beneath the spacecraft. It revisits the same point on the Earth every 16 days. It collects data in a swath 185-km wide in 8 bands. ETM^+ Bands 1–5 and 7 have 30×30-m spatial resolution, and the thermal infrared Band 6 has 60×60-m spatial resolution. The ETM^+ also has a new 15×15-m panchromatic Band 8 (0.52–0.90 μm). The Landsat 7 ETM^+ has excellent radiometric calibration. This improves our ability to monitor water quality, leaf-area index, biomass, productivity, and land use and cover. An example of Landsat 7 imagery obtained over Palm Springs, Calif., is shown in Figure 16.

It is significant for transportation-related research that Landsat 7 has already acquired complete cloud-free coverage of the United States. Landsat 7 is being tasked to archive additional nationwide coverages. The imagery is available for the cost of reproduction from the EROS Data Center in Sioux Falls, South Dakota.

**High-Spatial-Resolution Linear Array Multispectral Remote-Sensing Systems**

Linear array remote-sensor systems use CCDs to record the reflected or emitted radiance from the terrain. Linear array sensors are often referred to as pushbroom sensors because, like a single line of bristles in a broom, the linear array stares constantly at the ground while the spacecraft moves forward (Figure 4d). This results in a more accurate measurement of the reflected radiant flux because there is no moving (scanning) mirror and the linear array detectors are able to dwell longer on a specific portion of the terrain. The successful French SPOT image and the Indian remote-sensing systems are based on linear array, pushbroom-detector technology. These moderate resolution multispectral sensors have spatial resolutions ranging from 10 to 20 m in a few multispectral bands.
FIGURE 15 Digitized aerial photography and CAMS data used to assess change at Sun City, S.C.: (a) NAPP imagery (0.7–0.9 μm), obtained January 22, 1994, digitized to 2.5×2.5 m; (b) CAMS Band 6 data (0.7–0.9 μm) of Sun City, acquired September 23, 1996, at 2.5×2.5 m; and (c) change between dates highlighted using write-function-memory insertion change detection technique [red green blue (RGB) = CAMS, NAPP, none].

The commercial sector has now placed in orbit very-high-spatial resolution linear array multispectral remote-sensing systems. As previously mentioned, Space Imaging’s IKONOS-2 sensor has four multispectral visible and near-infrared bands at 4×4-m spatial resolution. It has both across-track and along-track viewing instruments that enable flexible data acquisition, stereoscopic coverage, and frequent revisit capability: less than 3 days at 1×1-m spatial resolution (for look angles of less than 26°) and 1.5 days at 4×4-m spatial resolution. The four bands of multispectral data have particular interest for transportation-related land use and land cover mapping as well as the extraction of biophysical information such as leaf area index and biomass. A panchromatic 1×1-m image, a normal color composite, and a false-color near-infrared color composite of multispectral data of a railroad yard near Columbia, S.C., are shown in Figure 17a, b, and c, respectively. The near-infrared color composite is draped over an USGS DEM in Figure 17d.
FIGURE 16  Landsat 7 ETM+ color-infrared composite of Palm Springs, Calif., obtained in 1999 (RGB = Bands 4, 3, 2).
ORBIMAGE, Inc., plans to launch OrbView-3 in 2001, with 1×1-m panchromatic data and four visible and near-infrared multispectral bands at 4×4-m spatial resolution. It will have an 8-km swath width. The sensor will revisit each location on Earth in less than 3 days, with an ability to turn 45° from side to side.

Significant advances in the processing of multispectral remote sensing have occurred. For example, there are improved multispectral classification algorithms based on (a) more robust statistical pattern recognition (5), (b) expert systems (e.g., ERDAS’ knowledge classifier), (c) fuzzy logic (e.g., Ji and Jensen, 1999), and (d) neural networks (e.g., Research Systems, Inc., 2000). A graphical user interface associated with a neural network image classification system is shown in Figure 18.

**Advances in Hyperspectral Remote-Sensing and Information-Extraction Methods**

Imaging spectrometry is the simultaneous acquisition of images in many relatively narrow spectral bands throughout the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. Unlike traditional multispectral remote-sensing instruments that record energy in only a few bands, an imaging spectrometer can provide a relatively complete, high-resolution reflectance spectrum for each picture element in the image. For example, hundreds of bands in the spectrum in the region from 0.4–2.5 µm may be used to identify a large range of surface cover materials that cannot be identified with broadband, low-spectral-resolution imaging systems, such as the Landsat multispectral sensor, ETM+, or SPOT (4). Many surface materials (e.g., asphalt and concrete road surface materials and right-of-way land cover, such as vegetation, soil, and rock) have diagnostic absorption features that are often only 20–40-nm wide. Therefore, hyperspectral remote-sensing systems that acquire data in contiguous 10-nm bands may sometimes capture spectral data with sufficient resolution for the direct identification of those materials with diagnostic spectral features.

Two practical approaches to imaging spectrometry are shown in Figures 4e and f. The whiskbroom scanner linear array is analogous to the scanner approach used for the ETM+, except that radiant flux from within the IFOV is passed onto a spectrometer, where it is dispersed and focused onto a linear array of detectors (Figure 4e). Thus, each pixel is simultaneously sensed in as many spectral bands as there are detector elements in the linear array. This is basically how NASA’s Advanced Visible Infrared Imaging Spectrometer (AVIRIS) collects data. In 1998 and 1999, AVIRIS was flown on a NOAA Twin Otter aircraft, acquiring data at an altitude of approximately 12,500 ft above ground level (Figure 19). This resulted in hyperspectral data with a spatial resolution of approximately 3.5×3.5 m.

Ideally, an imaging spectrometer makes use of 2-D area arrays of detectors at the focal plane of the spectrometer. This eliminates the need for the optical-scanning mechanism. In this situation, there is a dedicated column of spectral detector elements for each cross-track pixel in the scene (Figure 4f).

An analysis of hyperspectral data requires the use of sophisticated digital image–processing software. This is because it is usually necessary to calibrate (convert) the raw hyperspectral radiance data to “apparent reflectance” before it can be properly interpreted. This necessitates the removal of atmospheric attenuation, topographic effects (slope, aspect), and any sensor-system electronic anomalies. In addition, to maximize hyperspectral information extraction, it is usually
FIGURE 17 IKONOS-2 imagery of Columbia, S.C., obtained October 29, 2000: (a) IKONOS-2 panchromatic 1×1-m imagery, (b) natural color composites of 1×1-m panchromatic data and 4×4-m multispectral data, (c) near-infrared color composite consisting of 1×1-m panchromatic data and 4×4-m multispectral data, and (d) near-infrared color composite overlaid on USGS DEM.
necessary to use digital image–processing algorithms that allow one to analyze a typical spectra
to determine its constituent materials or to compare the remote-sensing derived spectra with a
library of spectra obtained using handheld spectroradiometers, such as that provided by the
USGS or NASA’s Jet Propulsion Laboratory (JPL). For example, Figure 20 depicts the spectral
signature of healthy and potentially stressed bahia grass on clay-capped hazardous waste sites on
the Savannah River site, derived from an analysis of AVIRIS data.

The only hyperspectral satellite remote-sensing system is the moderate resolution imaging
spectrometer (MODIS) onboard the Terra satellite. It collects data in 36 coregistered spectral bands.
MODIS’ coarse spatial resolution ranges from 250×250 m (Bands 1–2) to 500×500 m (Bands 3–7)
and 1×1 km (Bands 8–36). MODIS obtains simultaneous observations of high-atmospheric (cloud
cover and associated properties), oceanic (sea-surface temperature and chlorophyll), and land-surface
features (land-cover changes, land-surface temperature, and vegetation properties). MODIS has one
of the most comprehensive radiometric calibration systems.

ORBIMAGE, Inc. plans to launch OrbView-4 in the future. It will acquire 1×1-m
panchromatic and 4×4-m multispectral data similar to OrbView-3. In addition, OrbView-4 will
be the first satellite to acquire hyperspectral imagery. It will obtain 200 channels (0.45–2.5 µm)
of 8×8-m hyperspectral imagery, with a swath width of 5 km. It will also have an off-nadir
viewing capability and a revisit cycle of less than 3 days. There is some debate at the present
time as to whether ORBIMAGE, Inc., will be allowed to provide 8×8-m hyperspectral data to the
public.