Chapter 11: Visible-Infrared Sensors and Case Studies

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11.1 Introduction

This chapter of the earth sciences volume of the Manual of Remote Sensing is intended as a survey of selected available visible-infrared sensors and their applicability to earth sciences. Because of the author's background, the focus is necessarily on geological applications; however, the principles presented are equally applicable to other areas of terrestrial remote sensing.

The chapter is organized into two complementary sections. The first outlines the basic characteristics of selected sensors ranging from operational satellite systems, through both operational and experimental aircraft systems to planned satellite systems. The information in this section is a summary of the latest data available for the selected instruments at the time, described as of June 1998). Information is compiled from published material, commercial brochures, the Manual of Remote Sensing, 3rd Edition "Earth Observing Platforms and Sensors" CD-ROM (Morain and Budge, 1996), Lillesand and Kiefer (1987), Pease (1990), and from Kramer (1994). In the second section, we provide several case studies that compare and contrast the capabilities of selected sensors, with particular emphasis on the impact of spatial and spectral resolution on their utility for mapping of Earth surface features and properties.

11.2 Sensor Characteristics

In this section we describe the characteristics of selected remote sensing systems that are generally useful for remote sensing of the land surface. No attempt has been made to document all available sensors; only a representative sampling has been included (see Kramer, 1994; Morain and Budge, 1996; ASPRS, 1996 for more comprehensive sensor information). References and contacts are provided for obtaining additional information about the sensor systems described.

11.2.1 Satellite Systems

The launch of Landsat in 1972 was a landmark in the use of remote sensing technology for earth observation. Researchers and operational users alike quickly recognized the advantages of imaging from satellite platforms. Remote sensing instruments in earth orbit provide platform stability; a synoptic view; and repetitive, worldwide, multitemporal coverage. The following instrument descriptions outline the basic characteristics of selected satellite sensors and their applicability to geologic remote sensing. Examples are given for some of these sensors in the case histories in Section 11.3.

11.2.1.1 AVHRR. The Advanced Very High Resolution Radiometer (AVHRR), launched in 1978 as TIROS-N (later, NOAA-6), provides regional-scale coverage (2800 to 4000 km swath width) at 1- and 4-km spatial resolutions (Kidwell, 1991; ASPRS, 1996). AVHRR uses silicon (Si), indium-antimonide (InSb), and mercury-cadmium-telluride (HgCdTe) detectors to provide four or five spectral bands (depending on sensor version) covering the ranges 0.55 to 0.68 μm, 0.725 to 1.1 μm, 3.55 to 3.93 μm, 10.3 to 11.3 μm, and 11.5 to 12.5 μm (NOAA-7 through NOAA 14). Although its principal use is currently for measuring cloud cover and vegetation indices, it is also valuable for providing basic surface geologic information over truly regional scales. Table 11-1 summarizes the AVHRR satellites:

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Sioux Falls, SD 57198, USA
Phone: (605) 594-6151
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E-Mail (Internet): custserv@edcmail.cr.usgs.gov
URL: http://edcwww.cr.usgs.gov/eros-home.html

Additional Detailed Information: http://edcwww.cr.usgs.gov/glis/hyper/guide/avhrr

11.2.1.2 IRS. India's IRS-1A and IRS-1B, launched in 1988 and 1991,provide spectral and spatial coverage similar to the Landsat MSS system (ASPRS, 1996). The Linear Imaging Self Scanning Sensor (LISS) provides spectral coverage in four bands with 72.5-m spatial resolution (IRS-1A/LISS I) and 36.25-m resolution (IRS-1B/LISS II). IRS-1C, the first of the second generation of IRS series satellites, was launched on December 28 1995. IRS 1-C includes a high-resolution 5.8-m panchromatic band with a 70-km swath and stereo capabilities resulting from ±26° across-track steering. The LISS III multispectral sensor includes bands equivalent to Landsat TM bands 2, 3, 4, and 5 with a visible and near-infrared (VNIR) ground resolution of 23.5-m, shortwave infrared

(SWIR) resolution of 70-m, and an approximate 140-km swath. IRS-1C also includes the two-band (0.62 to 0.68 µm, and 0.77 to 0.86 µm) Wide Image Field Sensor (WiFS) with 188-m spatial resolution and approximate 800-km-wide swath. IRS-1D, identical to the IRS-1C sensor, was launched on 29 September 1997. The IRS series of satellites provides basic mapping capabilities similar to those of Landsat MSS and TM, with significant spatial enhancement provided by the IRS-1C 5.8-m panchromatic band.

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11.2.1.3 JERS-1 OPS. The Japanese Earth Resources Satellite Optical Sensor [JERS-1 (OPS)], launched in February 1992, provides eight spectral bands covering the VNIR and SWIR regions of the spectrum (ASPRS, 1996). Bands 1 to 4 are similar to Landsat TM bands 1 to 3 covering the ranges 0.52 to 0.60 µm (band 1), 0.63 to 0.69 µm (band 2), and 0.76 to 0.86 µm (bands 3 and 4). Bands 3 and 4 provide stereoscopic capabilities. JERS-1 (OPS) bands 5 to 7 cover critical regions in the SWIR, 1.60 to 1.71 µm (band 5), 2.01

to 2.12 µm (band 6), 2.13 to 2.25 µm (band 7), and 2.27 to 2.40 µm (band 8) (ASPRS, 1996). JERS-1 (OPS) provides approximately 18-m x 24-m spatial resolution over a swath width of approximately 75 km. The SWIR bands are of particular interest to geologists because they cover key regions critical to mineralogical discrimination (Yamaguchi, 1987).

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Minato-ku, Tokyo, 106 Japan
URL: http://hdsn.eoc.nasda.go.jp/guide/guide/satellite/satdata/jers_e.html
URL: http://hdsn.eoc.nasda.go.jp/guide/guide/satellite/sendata/ops_e.html

Additional Contact: National Space Development Agency of Japan (NASDA)
World Trade Center Bldg., 2-4-1,
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Telex: J28424 (AAB: NASDA J28424)
Phone: 81-3-3438-6000 Fax: 81-3-5402-6512
URL: http://yyy.tksc.nasda.go.jp/Home/This/This-e/jers_e.html

11.2.1.4 Landsat MSS. Landsat was originally launched with two sensor systems, the three-channel Return Beam Vidicon (RBV) and the four-channel Multispectral Scanner (MSS) (Lillesand and Kiefer, 1987). The RBV bands were designated as bands 1, 2, and 3, while the MSS bands were designated as 4, 5, 6, and 7. While the RBV was part of the payload on Landsats 1 to 3, the MSS quickly became the primary data source for most users because it was the first system capable of producing multispectral digital data on a global basis. The MSS system has been flown on board all five Landsat missions (MSS bands were redesignated as 1 to 4 on Landsats 4 and 5). An oscillating scan mirror covering 11.56 degrees scans six contiguous image lines simultaneously every 33-ms. Four arrays of six detectors each acquire spectral images in the ranges 0.5 to 0.6 µm (band 1), 0.6 to 0.7 µm (band 2), 0.7 to 0.87 µm (band 3), and 0.8 to 1.1 µm (band 7). The MSS scans six contiguous lines simultaneously from west to east, with the motion of the spacecraft building the along-track image. The instantaneous field of view (IFOV) of the scanner is approximately 79 m on a side. The swath is 185 km wide and images are typically provided in “framed” format of 185 km x 185 km with 10% endlap between successive scenes. The dynamic range of the data is 6 bits. MSS data are generally useful for mapping earth surface features. Typically the data are used to produce color composites that discriminate spectral differences between surface cover types. The use of band 7 (band 4 on Landsats 4 and 5) with bands 4 and 5 (bands 1 and 2 on Landsats 4 and 5) provides an excellent means of discriminating vegetation from other materials. Landsat MSS’s utility for geologic mapping is well documented, ranging from early efforts at alteration mapping (Rowan et al., 1974) to a variety of geologic uses (Goetz and Rowan, 1981; Legg, 1991; Prost, 1994). While long the workhorse of the earth science community because of its global coverage and continuous acquisition since 1972, the MSS sensors’ 79-m spatial resolution and the selection of spectral bands are not sufficient for many geologic application’s requirements. MSS is most useful for environmental studies that map the general distribution of surface vegetation and geologic characteristics such as iron oxides over long time periods. The MSS does not provide the spectral coverage or resolution required for many geologic applications.

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11.2.1.5 Landsat TM. The Thematic Mapper (TM) sensor was included on Landsat beginning with Landsat 4 launched in 1982. The Landsat MSS bands were also included, but renumbered from 4 to 7 to 1 to 4. The Thematic Mapper includes seven spectral bands covering the region from the visible to the thermal infrared (Table 11-2) (ASPRS, 1996). The IFOV is 28.5 m for bands 1 to 5 and 7, and 120 m for band 6. The total field of view of the sensor is 15.4° (approximately 185 km x 185 km at 705 km altitude). The TM sensor has sixteen detectors per band (four for the thermal infrared). Bands 1 to 4 utilize silicon detectors, while bands 5 to 7 use passively cooled indium antimonide (InSb). Band 6 utilizes mercury-cadmium-telluride (HgCdTe) detectors. The TM sensor uses bidirectional scanning (both west to east, and east- to west) to minimize scan mirror oscillation and increase detector dwell time (Lillesand and Kiefer, 1987). The dynamic range of the TM data is 8 bits, providing increased sensitivity over MSS data. Landsat 7, scheduled for launch in 1998 will include an additional 15-m-resolution panchromatic band covering the rnge 0.50 to 0.90 μm. Landsat TM presents an order-of-magnitude improvement over MSS for Earth-surface mapping because of the increased number of spectral bands and improved spatial resolution. Color composites are still commonly used for analysis of TM data. Color infrared composites using bands 4, 3, and 2 (RGB) and true color composites (not available using Landsat MSS) utilizing bands 3, 2, and 1 (RGB) have proven extremely useful. Color-ratio-composites have been used successfully for spectral mapping of a variety of surface materials (Rowan et al., 1974; Goetz et al., 1983; Kruse, 1984a; Paylor et al., 1985; Lang et al., 1987, Prost, 1994). These commonly utilize the 5/7 ratio to discriminate areas of clays, carbonates, and vegetation, and the 3/1 ratio to map areas of iron oxides (Sabins, 1997). The third ratio is often the 3/4 or 4/5, which also helps discriminate vegetation. The relatively high spatial and spectral resolution of the TM data also provide improved opportunities for detailed digital analysis. A wide variety of digital techniques, including contrast enhancements, spectral ratioing, principal components, and both unsupervised and supervised classification, have been used to produce image-maps of surface materials (Sabins, 1997).

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URL: http://www.spaceimage.com

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URL: http://edcwww.cr.usgs.gov/webglis

11.2.1.6 SPOT. The System Pour l'Observation de la Terre (SPOT) designates a series of high-spatial-resolution imaging satellites designed by the Centre National d'Etudes Spatiales (CNES), France. SPOT 1 was launched in February 1986, SPOT 2 in January 1990, SPOT 3 in December 1993, and SPOT-4 in March 1998 (see http://www.spotimage.fr/). SPOT utilizes a linear array sensor and push-broom scanning techniques along with pointable optics (ASPRS, 1996). Its repeat period is 26 days; however, off-nadir pointing allows shorter revisit periods as well as stereoscopic imaging. SPOT's payload is a high-resolution visible (HRV) imaging system operating in either panchromatic (PAN) or multispectral (XS) mode. The PAN sensor on SPOT 1 to 3 operates at 10-m spatial resolution from 0.51 to 0.73 µm. The multispectral mode provides 20-m spatial resolution in three spectral bands covering the ranges 0.50 to 0.59 µm, 0 .61 to 0.68 µm, and 0.79 to 0.89 µm. SPOT-4 makes slight adjustments to the spectral configuration, including changing the 10-m panchromatic band coverage to 0.61 to 0.68 µm, and adding an additional band operating in the short-wave infrared portion of the spectrum (SWIR) from 1.5 to 1.75 µm. SPOT-4 also offers a "Vegetation Instrument" operating in the four spectral bands with a resolution of 1-km, with a swath width of 2,250 km. The HRV instrument's field of view is 4.13°, providing a swath width of 60 km for nadir pointing. Two identical HRV sensors provide the capability to image a total swath of 117 km in either PAN or XS mode. Data dynamic range is 8 bits. The high spatial resolution of the SPOT system provides capabilities not available with either the Landsat MSS or TM systems. Photogeologic mapping using either single PAN images or stereoscopic PAN coverage allows mapping at 1:24,000-scale. The multispectral mode images are useful for vegetation mapping and general lithologic mapping, but do not really provide the spectral resolution or spectral coverage required for detailed geologic work. SPOT/Landsat merges provide one means of overcoming SPOT's spectral shortcoming and Landsat TM's relatively poor spectral resolution.

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11.2.2 Aircraft Sensors

Aircraft remote sensing provides both advantages and disadvantages over satellite, spaceborne remote sensing. The platforms are less stable and the spatial coverage is smaller, however, greater spatial resolutions can be obtained, and the user can maintain closer control over when and how the data are collected. In this section we provide an overview of selected aircraft sensors, with particular emphasis on hyperspectral systems. No attempt has been made to document all available sensors; only a representative sampling has been included (see ASPRS, 1996, for more comprehensive sensor information). References and contacts are provided for obtaining additional information about the sensor systems described.

11.2.2.1 AVIRIS. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is a 224-channel imaging spectrometer built by Jet Propulsion Laboratory (JPL) and first flown in engineering tests during 1987. The system became fully operational in 1989. AVIRIS covers the range 0.4 to 2.5 μm in 224 approximately 10-nm-wide contiguous bands (Porter and Enmark, 1987; Vane et al., 1993). The sensor is a whiskbroom system utilizing scanning foreoptics to acquire cross-track data. The IFOV is 1 milliradian. Four off-axis double-pass Schmidt spectrometers receive incoming illumination from the foreoptics using optical fibers. Four linear arrays, one for each spectrometer, provide high sensitivity in the 0.4 to 0.7 μm, 0.7 to 1.2 μm, 1.2 to 1.8 μm, and 1.8 to 2.5 μm regions respectively. AVIRIS is flown as a research instrument on the NASA ER-2 aircraft at an altitude of approximately 20 km, resulting in approximately 20-m pixels and a 10.5-km swath width. AVIRIS is easily the best-calibrated aircraft imaging system flown today. Routine calibration consists of spectral and radiometric calibration utilizing both laboratory and field measurements (Vane et al., 1987, 1993; Chrien et al.; Green et al., 1996). Spectral calibration consists of calibration of a laboratory monochromator using standard line emission sources and then recording the response of AVIRIS detectors to specific narrow spectral bandwidths of light from the monochromator. Radiometric calibration consists of using a calibrated laboratory spectroradiometer and a 100-cm-diameter integrating sphere to generate a calibration file to convert AVIRIS data numbers to units of radiance. These calibrations are accomplished before and after each flight season. Additionally, JPL conducts in-flight calibration experiments before, during, and after each flight season to verify the laboratory measurements and monitor in-flight instrument performance. AVIRIS is particularly well suited to use for mineralogic and lithologic mapping. Its spectral resolution of 10 nm makes direct mineral identification possible (unique to imaging spectrometers), while its 20-m spatial resolution allows mapping of igneous, metamorphic, and sedimentary features at scales suitable for 1:24,000-scale maps (Kruse et al., 1993a; Vane and Goetz, 1993).

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11.2.2.2 CASI. The Compact Airborne Spectrographic Imager (CASI) is a pushbroom charge coupled device (CCD) imager operating over a 545-nm spectral range between 0.4 and 1.0 μm in up to 288 programmable spectral channels (see CASI marketing literature and http://www.itres.com). CASI uses a 578 x 288 CCD Si detector array. Quantization is 12 bits. The IFOV is 1.25 mrad. The instrument configuration is fully programmable to operate in any of three modes. In spatial mode, the full cross-track resolution of 512 pixels is obtained for up to 19 nonoverlapping spectral bands with programmable center wavelengths and bandwidths. In spectral mode, a 288-point spectrum is measured at 1.9-nm intervals for each of a limited number of points across the swath. A programmable monochromatic image at the full spatial resolution (scene recovery channel) is also acquired. Alternatively, a maximum of 101 adjacent pixels can be configured to record 288 spectral bands. Full frame mode provides for digitization of the entire 512 x 288 pixel array. Because of the data quantities involved, however, this mode is used primarily for laboratory and ground-based studies and the collection of data for instrument calibration. The CASI sensor has been operated since 1988 on light aircraft and helicopter platforms, with spatial resolution ranging from 0.5 to 10 m, depending on flight altitude. CASI's use for geology is limited because of its spectral coverage, which does not include the SWIR wavelengths. The majority of geologic material's unique spectral characteristics occur outside this range. CASI has found widespread use in vegetation mapping and environmental studies, as it is well suited to mapping subtle difference in vegetation reflectance spectra.

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11.2.2.3 GEOSCAN MkII Airborne Multspectral Scanner. The GEOSCAN MkII sensor, flown on a light aircraft, was a commercial airborne system that acquired up to 24 spectral channels selected from 46 available bands. Though currently not flying, significant archival data are available. GEOSCAN covered the range from 0.45 to 12.0 μm using grating dispersive optics and three sets of linear array detectors (Lyon and Honey, 1989). A typical data acquisition for geology resulted in ten bands in the visible/near infrared (VNIR, 0.52 to 0.96 μm), eight bands in the shortwave infrared (SWIR, 2.04 to 2.35 μm), and six bands in the thermal infrared (TIR, 8.64 to 11.28 μm) regions (Lyon and Honey, 1990). The instantaneous field of view was 3.0 mrad with a field of view of 45° from nadir. Radiometeric calibration was accomplished using separate calibration sources for each of the spectral regions. The spatial resolution varied depending on flight altitude, but typically ranged from 3- to 5-m. The sensor was stabilized for pitch and yaw and the data corrected for roll. Resampling was applied to the data to produce a constant pixel size and the data were quantized to 8 bits, with gain and offset applied to adjust for different brightness terrains. Data were recorded directly on optical media and displayed in real time in the aircraft. GEOSCAN's high spatial resolution makes it suitable for detailed geologic mapping (Hook et al., 1991). The relatively low number of spectral bands and, low spectral resolution limit mineralogic mapping capabilities to a few groups of minerals in the absence of ground information.

Strategic placement of the SWIR bands, however, does provide more mineralogic information than would intuitively be expected based on the spectral resolution limitations.

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URL: http://www.agarss.com.au/MAIN.HTM

11.2.2.4 GER 63 Channel Scanner (GERIS). Geophysical and Environmental Research Inc. (GER) has been developing and operating high-spectral-resolution sensors since the late 1970s. The GER 63-channel airborne scanner (also known as GERIS) has been operational since approximately 1987. This instrument is a Kennedy-type scanner consisting of three grating spectrometers with three individual linear detector arrays (Kruse et al., 1990). The IFOV is selectable at 5.0 and 3.3 mrad, covering a scan angle of 90°. The visible/near infrared (VNIR) spectrometer covers the range 0.4 to 1.0 µm with up to 27 bands, 25 nm wide. The first short wave infrared (SWIR 1) spectrometer covers the range 1.5 to 2.0 µm with one band. The second SWIR spectrometer covers the 2.0 to 2.5 µm region with 29 bands with 17.5-nm widths. One additional band is used to record gyroscopic information. The current version includes an additional spectrometer covering the thermal infrared (TIR) region from 8 to 12.5 µm. A total of 63 bands are selectable out of the available 72 bands. The GER64 swath width and spatial resolution are variable, depending on flight altitude; typical resolutions average about 5 to 15 m. Radiometric calibration includes band/channel position and bandwidth using calibrated light sources, signal-to-noise determinations, and radiometric tests to determine transfer coefficients to radiance. The data are processed for roll utilizing the gyroscope channel with accuracies to 1 pixel. Several related sensors built by GER are also currently operational. The Digital Airborne Imaging Spectrometer series (DAIS-2815, 3715, 7915) provides similar capabilities but with different channels and bandwidths. Current instrument specifications are available from GER. The GER63 data are generally suitable for mineralogic and lithologic mapping, and spatial resolution can be tailored to requirements. Despite good placement of spectral bands, the relatively low number of bands and the spectral resolution of these bands limits mineral identification to a few groups of minerals (Kruse et al., 1990).

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11.2.2.5 HYDICE. The Hyperspectral Digital Imagery Collection Experiment (HYDICE), developed by Hughes Danbury Optical Systems and operational since 1994, was designed specifically to determine the utility of hyperspectral technology for intelligence, military, and civil applications (Basedow et al., 1995). Hydice is a pushbroom imaging spectroradiometer covering the 0.4 to 2.5 μm range in 210 nominally 10-nm-wide channels utilizing a 320 x 210 element InSb focal plane. Spatial resolution ranges from 1 to 4 meters depending on aircraft altitude. Typical ground swath is 308 pixels covering on the order of 1 km, based on the design flight altitude of six km. Calibration information provided includes linear correction coefficients, measured laboratory response of the calibration unit, center wavelength position for each band, and a bad detector element list. Goetz and Kindel (1996) and Resmini et al. (1996) have demonstated that HYDICE can map mineralogy successfully at high spatial resolution. The trade-off for this capability, however, is the relatively small spatial coverage.

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11.2.2.6 MIVIS. The Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) built by Daedalus for CNR, Italy and flown since 1993 is a modular system consisting of four spectrometers that provide 102 spectral channels (Bianchi et al., 1996). MIVIS covers the ranges of 0.43 to 0.83 μm in 20 bands (20-nm-resolution), 1.15 to 1.55 μm in eight spectral bands (50-nm resolution), 1.985 to 2.479 μm in 64 spectral bands (8-nm resolution), and 8.21 to 12.70 μm in 10 bands (400- to 500-nm resolution). Quantization is 12 bits. MIVIS is flown on CNR's CASA C200/212. The IFOV is 2.0 mrads with a digitized FOV of 71° covering 755 pixels per line. Ground resolution varies with flight altitude. The system includes an integrated GPS receiver, and roll, pitch, and heading sensors. Two blackbody sources are used as thermal reference sources. MIVIS has been flown extensively in Europe; however, few geologic data have been collected. The layout and spectral resolution of the instrument indicate that it should be very useful for geological applications.

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URL: http://ntserver.iia.mlib.cnr.it/index.htm

11.2.2.7 SFSI. The Short Wavelength Infrared (SWIR) Full Spectrum Imager (SFSI) developed by the Canadian Center for Remote Sensing (CCRS) and flown since 1994 covers the range 1.2 to 2.4 μm range in 120 bands with a nominal full-width-half-max (FWHM) of approximately 10 nm. The instrument utilizes a 488 x 512 PtSi detector array, refractive optics, and a transmission grating with one order separating filter

(Rowlands and Neville, 1994). In practice, 480 lines x 496 columns are used. Adjacent lines are summed together on-chip, resulting in 240 spectral bands (lines) x 496 cross-track pixels. Quantization is 12 bits; however, adjacent bands are again summed, giving 120 bands in the final output data. The cross-track pixel field of view is 0.33 mrad, resulting in a total swath of 9.4°. Ground resolutions are typically better than 10 m. Significant post processing is required to calibrate the data to reflectance. SFSI has been flown in Canada by CCRS and by a consortium of mining companies in the southwestern United States during 1995 (Hauff et al., 1996).

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11.2.2.8 TIMS. The Thermal Infrared Multispectral Scanner (TIMS), designed by the Jet Propulsion Laboratory and operational since 1982, collects thermal infrared data in six channels between 8.2 and 12.6 µm utilizing a six-element HgCdTe detector array (Kahle and Goetz, 1983; Palluconi and Meeks, 1985). Approximate spectral coverage is band 1 (8.2 to 8.6 µm), band 2 (8.6 to 9.0 µm), band 3 (9.0 to 9.4 µm), band 4 (9.4 to 10.2 µm), band 5 (10.2 to 11.2 µm), and band 6 (11.2 to 12.2 µm). The sensor's IFOV is 2.5 mrad, providing spatial resolutions of 8 to 20 m at elevations above terrain of approximately 3000 to 8000 m. A typical data set consists of 638 pixels per line, covering an approximately 5- to12-km swath at the foregoing spatial resolutions. TIMS is well suited to geologic mapping because of its coverage of the thermal infrared portion of the spectrum, where primary rock-forming minerals have their fundamental absorption features. The presence of fundamental absorption features in this region theoretically makes possible direct detection and mapping of silicate mineralogy. The relatively broad spectral resolution of TIMS, however, reduces this capability to the mapping and detection of silica, regardless of origin and mineralogy (Kahle and Goetz, 1983; Kruse and Kierein Young, 1990; Watson et al., 1990; Rowan et al., 1992). TIMS has been demonstrated as a valuable tool for geological mapping. The ASTER instrument (Abrams and Hook, 1995), scheduled for launch on EOS Platform AM-1 in 1998, will provide TIMS-like capabilities from orbit.

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Phone: (605) 594-6116
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E-mail: edc@eos.nasa.gov
URL: http://edcwww.cr.usgs.gov/landdaac/landdaac.html

Contact (new acquisitions): NASA Dryden Flight Research Center
Edwards Airforce Base, CA 93523

Phone: (805) 258-3311

URL: http://www.dfrc.nasa.gov/Projects/airsci/general

11.2.3 Planned Systems: U. S. Government

In this section we provide a brief overview of two US government-planned remote sensing systems. The sensors described here serve to illustrate some of the research activities under way that may lead to future commercial systems with similar capabilities.

11.2.3.1 ASTER. The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) is a planned instrument scheduled to fly on NASA's Earth Observing System (EOS) AM-1 platform in 1998 (Abrams and Hook, 1995). ASTER is a cooperative effort between NASA and Japan's Ministry of International Trade and Industry, with the collaboration of scientific and industry organizations in both countries. The ASTER instrument consists of three separate instrument subsystems. Each subsystem operates in a different spectral region, has its own telescope(s), and is built by a different Japanese company. The three subsystems combined will collect data in 14 spectral bands in the visible and near-infrared (VNIR), short-wavelength infrared (SWIR), and thermal infrared spectral regions (TIR). The VNIR subsystem operates using a Si detector in three spectral bands, with a resolution of 15 m. A backward-looking telescope provides a second view of the target area in band 3 for stereo observations. The individual spectral bands are separated through a combination of dichroic elements and interference filters. The SWIR subsystem uses PtSi-Si detectors in six spectral bands at 30-m resolution. The TIR subsystem uses HgCdTe for five bands in the thermal infrared region at 90-m spatial resolution. Quantization is 8 bits for bands 1 to 9 and 12 bits for bands 10 to 14. ASTER is particularly well suited to geologic mapping. The combination of VNIR/SWIR/TIR capabilities will provide the ability to produce detailed maps of mineralogy and alteration (Abrams and Hook, 1995). Table 11.3 lists the band characteristics for ASTER.

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11.2.3.2 MODIS. The Moderate Resolution Imaging Spectrometer (MODIS) is an imaging spectrometer designed primarily for the measurement of biological and physical processes on regional scales (NASA, 1986; Asrar and Greenstone, 1995). MODIS will have 36 bands covering the visible through thermal infrared ranges at from 250-m to 1-km spatial resolution. Bands 1 and 2 will have 250-m spatial resolution with band centers at approximately 0.645 and 0.858 µm respectively. Bands 3 through 7 will provide 500-m spatial resolution covering the approximate region 0.46 to 2.16 µm in five strategically placed spectral bands. Bands 8 to 16 cover the approximate range 0.4 to 0.88 µm in nine spectral bands designed primarily for ocean color mapping, providing 1-

km spatial resolution. Bands 17 to 19, again with 1-km resolution, are placed between 0.89 to 0.965 µm for mapping of clouds and atmospheric properties. Bands 20 to 36 cover the thermal infrared range 3 to 5 µm and 11to 14 µm in 17 bands at 1-km resolution. The MODIS swath width will be approximately 2330 km, thus providing regional overview coverage.

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11.2.4 Planned Systems: Commercial

Within the next few years, at least three U.S. organizations will launch high-spatial-resolution remote sensing systems. Many other domestic and international systems are currently under design. Companies designing these satellites expect that the high-resolution sensors will supplement or replace orthophotography as a data source for Geographic Information Systems (GISs) because of reduced costs, timeliness, frequent revisit, global availability, regional coverage, and the digital nature of the data. In this section we provide a brief overview of selected planned commercial remote sensing systems.

11.2.4.1 EarthWatch. One of several U.S. commercial satellites, EarthWatch's EarlyBird satellite was launched in December 1997, but lost contact with earth receiving stations several days after launch. Earlybird was designed to provide high-spatial-resolution imagery with 3-m panchromatic (0.45 to 0.80 μm) and 15-m multispectral [0.50 to 0.59 μm (green), 0.61 to 0.68 μm (red), and 0.79 to 0.89 μm (near-IR) coverage] (ASPRS, 1996). The panchromatic sensor was to have used a 4 mega-pixel staring focal plane array to cover a frame size of approximately 36 km^2 (6 km x 6 km) per exposure, while the multispectral sensor would have used three 4 mega-pixel staring focal plane arrays to cover an area of approximately 900 km^2 (30 km x 30 km) per exposure in three spectral bands. A second mission, the QuickBird scheduled for launch in late 1999 will carry a 0.82-m panchromatic band [0.45 to 0.90 μm) and a 3.28-m multispectral sensor with four bands (0.45 to 0.52 μm (blue), 0.52 to 0.60 μm (green), 0.63 to 0.69 μm (red), and 0.76 to 0.90 μm (near-IR)]. Nominal image size will be 22 km x 22 km. Quantization will be 11 bits. Two QuickBird satellites are planned. EarthWatch plans to create a digital global imagery archive and distribution network for data distribution.

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11.2.4.2 Orbview. Orbital Imaging Corporation (ORBIMAGE) plans to provide a series of low-cost, high-spatial-resolution satellites in support of mapping and surveying, natural resources exploration, governmental functions, and news gathering. ORBIMAGE has already launched OrbView-1, a weather information satellite, and OrbView-2, carrying the SeaWiFs sensor with six visible channels and two NIR channels. Two additional Orbview sensors are planned. Orbview-3 will consist of a 1-m resolution panchromatic system (0.45 to 0.90 μm) as well as a 4-m multispectral (0.45 to 0.52 μm (blue), 0.52 to 0.62 μm (green), 0.63 to 0.69 μm (red), and 0.76 to 0.90 μm (near-IR)) system, both with a standard swath width of 8 km. Orbview-4 will have the same 1-m and 4- pancromatic and multispectral configuration as Orbview-3; however, it will also carry a 280-channel hyperspectral imaging instrument. This instrument will combine 8-m spatial accuracy with high spectral accuracy over a 5 km swath. Several imaging modes are available to obtain larger, contiguous swaths.

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11.2.4.3 Space Imaging/EOSAT. Space Imaging/EOSAT plans to provide geometrically corrected and digital orthophoto products combining the properties of imagery with the geometric accuracy of large-scale maps. The IKONOS 1 satellite will carry a sensor with a 1-m panchromatic sensor (0.45 to 0.90 µm) and a 4-m multispectral sensor with coverage similar to Landsat's spectral ranges [0.45 to 0.52 µm (blue), 0.52 to 0.60 µm (green), 0.63 to 0.69 µm (red), and 0.76 to 0.90 µm (near-IR)] (ASPRS, 1996). Repeat coverage will be approximately every eleven days. Both fore-aft and cross-track stereoscopic capabilities are provided by ±45° tilt capabilities. Individual scenes will be approximately 11 km x 11 km, with swaths possible up to 100 km in length. Quantization will be 11 bits. IKONOS 1 is scheduled for 1998 launch.

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11.2.4.4 ARIES. The Australian Resource Information and Environmental Satellite (ARIES) is designed as a commercially sustainable resource information satellite using the latest hyperspectral sensing technology. The ARIES-1 satellite will deliver detailed geological and mineral information to the international mining industry, anywhere in the world and on demand. Because of its hyperspectral approach, ARIES-1 will also be capable of providing improved environmental and agricultural resource information. ARIES-1 will have on the order of 60+ spectral bands, with approximately 32 contiguous bands in the visible and near-infrared (0.4 to 1.1 µm) with approximately 20-nm spectral resolution, and 32 contiguous bands in the shortwave infrared (SWIR) (2.0 to 2.5 µm) with approximately 16-nm spectral resolution. Additionally, several bands will be provided for the 0.94 and 1.14 µm regions to assist with atmospheric correction. Optional contiguous coverage from 1.05 to 2.0 µm with 32-nm spectral resolution is also being considered. Spatial resolution is planned to be 30-m and a 10-m-resolution panchromatic sharpening band is also planned. Several simulation studies have been performed, and examples are available (see URL below). Launch is planned for 1999 to be fully operational in early 2000.

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11.3 Case Studies

In this section we provide several case studies that illustrate the capabilities of selected sensors and analysis strategies. The first example compares the effect of both spatial and spectral resolution on visual interpretation of satellite and airborne sensors (Landsat MSS, Landsat TM, SPOT, and AVIRIS). The second case history compares spectra from Landsat TM, GEOSCAN, GER63, and AVIRIS data to spectral library measurements and contrasts image expression of spectral characteristics in a simple spectral matching algorithm. The final case history is an end-to-end example of state-of-the-art analysis of hyperspectral imagery using AVIRIS data.

11.3.1 Case Study: Landsat MSS and TM/SPOT/AVIRIS, Northern Grapevine Mountains, Nevada

A coregistered Landsat MSS, Landsat TM, SPOT Panchromatic, and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data set of a portion of the northern Grapevine Mountains, Nevada, provides the basis for comparison of sensor characteristics and capabilities, including spatial and spectral resolution (Kruse, 1988; Kruse and Dietz, 1991). Figure 11.1 (see the color insert) shows Landsat color composites, a SPOT panchromatic image, and an AVIRIS spectral classification. The area covered by the images is approximately 7 km x 9 km. The Landsat MSS false-color composite of bands 7, 5, and 4, the equivalent of a color infrared photograph (Figure 11.1a), illustrates the 79-m MSS spatial resolution, which limits effective mapping using MSS to scales smaller than about 1:250,000. Compare the MSS image to the Landsat

TM image (Figure 11.1b) and the SPOT panchromatic image (Figure 11.1c) with 30- and 10-m spatial resolution, respectively. The Landsat TM bands 4, 3, and 2 color composite, again comparable to a color infrared photograph, allows effective mapping at scales as large as 1:24,000. Key landmarks, topographic features, and lithologic information can be seen. The apparent gain in going from TM to SPOT 10-m resolution is less dramatic than the MSS-to-TM changes. Most of the features visible in the SPOT data (Figure 11.1c) are also visible in the TM data (Figure 11.1b). Note the sharpening of spatial details associated with the improved 10-m resolution SPOT data, but the loss of lithologic information caused by SPOT's limited spectral coverage and inability to make color composites (note that SPOT XS does allow making color composites at 20-m resolution). Figures 11.1d, 11.1e, and 11.1f illustrate the effects of both spatial and spectral resolution on lithologic mapping capabilities. Band ratioing is a well-established method for extracting spectral information from multispectral data sets (Rowan et al., 1974). Figure 11.1d shows a color-ratio-composite (CRC) image of Landsat MSS ratios 4/5, 6/7, and 5/6 for the northern Grapevine Mountains, Nevada site. Note first how topography is suppressed and how this makes the relatively low spatial resolution nature of the data more apparent. The green areas in the image represent occurrences of iron oxide minerals (Rowan et al., 1974, Kruse, 1984a). Little can be said, however, about other important rock-forming and weathering minerals. Because of its additional spectral bands, the Landsat TM color-ratio-composite image provides significant amounts of additional mineralogic information. The 5/7, 3/1, 3/4 CRC was designed to emphasize occurrences of iron oxides, clays/carbonates, and vegetation, respectively (Kruse, 1984b). The effect of improved spatial and spectral resolution is readily apparent (Figure 11.1e). The 3/1 ratio emphasizes the distribution of iron oxides by indicating locations where the characteristic UV-Visible Fe^{+3} absorption feature occurs. The 5/7 ratio emphasizes occurrences of both clays and carbonates based on characteristic absorption features near 2.2 and 2.3 µm, respectively, as well as some vegetation, which has absorption features at wavelengths greater than 2.0 µm caused by molecular water. The 3/4 ratio suppresses the effect of vegetation, by de-emphasizing areas that have the characteristic infrared vegetation peak near 0.80 µm. When combined in a CRC image, these band combinations allow interpretation of areas that appear in various shades of green as iron oxides, red areas on the image typically have either clay or carbonate (although they may also have vegetation), and yellow areas on the image are combinations of iron oxides and clays/carbonates. Note in Figure 11.1e how this combination greatly enhances the ability to map the distribution of these minerals over the capabilities provided by the MSS. In addition to the effects of spectral resolution and coverage, also note how the improved (30-m) TM spatial resolution allows better mapping of smaller occurrences of specific materials. For example, the areas of iron oxide are much more spatially coherent and easier to observe. Additionally, structurally controlled alteration areas only a few pixels wide (yellow bands in the center of Figure 11.11e marked by white arrow) are easily resolved by the TM data. Figures 11.1e and 11.1f illustrate the difference between <u>discrimination</u> of mineralogy and <u>identification</u> of mineralogy made possible by high spectral resolution. The TM data shown in Figure 11.1e can only be used to determine broad groups of minerals, because the six visible-infrared bands undersample the available reflectance spectrum (Figure 11.2). A true absorption-feature-based spectral classification is not possible and the CRC image and related multispectral digital classification methods are the only option. These approaches use spectral slopes between widely spaced spectral bands rather than actual spectral features to discriminate areas of similar mineralogy, but do not allow identification of individual materials. Imaging spectrometer or Hyperspectral data, on the other hand, collect continuous spectra in narrow contiguous bands (Goetz et al., 1985), and thus allow direct comparison to laboratory reflectance spectra and the use of individual spectral features for identification and classification. Figure 11.1f shows the results of a Spectral Angle Mapper (SAM) classification of AVIRIS data of the northern Grapevine Mountains, Nevada site. SAM determines the similarity of the AVIRIS reflectance spectrum at every pixel to a library of reference materials (J.W. Boardman, unpublished data; Kruse et al., 1993b, also explanation in section 2.3.10). Compare the yellow regions on the TM CRC to the red, yellow, and green areas on the AVIRIS image. Where Landsat TM could only be used to map the occurrence of iron oxides with clays and/or carbonates (yellow areas on Figure 11.1e), the AVIRIS data allows the analyst to assign specific mineral names and can be used to tell the difference not only between clays and carbonates, but to discriminate mineral variation within groups, for example, between the two carbonates calcite (red on Figure 11.1f) and dolomite (yellow on Figure 11.1f).

11.3.2 Case Study: Landsat TM, AVIRIS, GEOSCAN, GER63, Cuprite, Nevada

11.3.2.1 Background. This example is provided to illustrate the effects of spatial and spectral resolution on information extraction from multispectral/hyperspectral data. Several images of the Cuprite, Nevada, USA, area acquired with a variety of spectral and spatial resolutions serve as the basis for discussions on the effect of these parameters on mineralogic mapping using remote sensing techniques. These images have not been georeferenced, but image subsets covering approximately the same spatial areas are shown. Cuprite has been used extensively as a test site for remote sensing instrument validation (Abrams et al., 1978; Kahle and Goetz, 1983; Kruse et al., 1990; Hook et al., 1991; Swayze, 1997). A generalized alteration map (Figure 11.3) is provided for comparison with the images. Examples from Landsat TM, GEOSCAN MkII, GER63, and AVIRIS illustrate both spatial and spectral aspects. All of these data sets have been corrected to reflectance and processed by extracting selected spectral endmembers using averages for regions of interest. The data were then classified using the Spectral Angle Mapper (SAM) algorithm (J. W. Boardman, unpublished data; CSES, 1992; Kruse et al., 1993b). SAM is a simple classification technique that determines similarity to reference spectra. Only three of the numerous materials present at the Cuprite site were used for the purposes of this comparison. Average kaolinite, alunite, and buddingtonite image spectra were selected from known occurrences at Cuprite. The SAM processing was applied to illustrate the similarities and differences between data acquired by various sensors; there are numerous other processing strategies that might produce similar or superior results for each specific sensor. Laboratory spectra from the US Geological Survey spectral library (Clark et al., 1990) of the three selected minerals are provided for comparison to the image spectra (Figure 11.4). The following is a synopsis of selected instrument characteristics and a discussion of the images and spectra obtained with each sensor. Refer to Section 11.1 for additional instrument specifics.

11.3.2.2 Landsat TM. The Cuprite TM data were acquired on October 4 1984 and are in the public domain. Figure 11.5 (upper left) shows TM band 3 (0.66 µm) for spatial reference (30-m resolution). The areas A, B, and C indicate the approximate locations of the reference materials buddingtonite, alunite, and kaolinite, respectively. Figure 11.6 is a plot of the region of interest (ROI) average spectra for these three materials. The small squares indicate the TM band 7 (2.21 µm) center point. The lines indicate the slope from TM band 5 (1.65 µm). Note the similarity of all the "spectra" and how it is not possible to discriminate between the three endmembers shown in Figure 11.4. Because TM only had one band in the critical region at 2.0 to 2.5 µm, the full six-band TM spectrum, which includes visible/near-IR bands, was used in the SAM classification, even though the classifications for the other sensors compared here only used the SWIR region. Figure 11.5 (upper right, lower left, lower right) shows the results of the SAM classification. Compare these images to the alteration map shown in Figure 11.3. Note that the "Kaolinite" endmember seems to outline the circular alteration pattern observed for the site, but that the other two endmember images seem totally unrelated to the known alteration pattern.

11.3.2.3 GEOSCAN MkII Airborne Multispectral Scanner. The GEOSCAN data were acquired in June 1989. Figure 11.7 (upper left) shows GEOSCAN band 3 (0.645 µm) for spatial reference (6-m resolution). The areas A, B, and C indicate the approximate locations of the reference materials buddingtonite, alunite, and kaolinite. Figure 11.8 is a plot of the ROI average spectra for these three materials. Compare these to Figure 11.4 and note that the three minerals appear quite different in the GEOSCAN data, even with the relatively widely spaced spectral bands. Figure 11.7 (upper right, lower left, lower right) shows the results of the SAM classification. Compare these images to the alteration map shown in Figure 11.3 and the TM classifications shown in Figure 11.5. Note the circular nature of the Kaolinite and Alunite distributions mapped using the GEOSCAN data, which generally corresponds to the known alteration pattern observed at Cuprite. Also note the small discrete, spatially-coherent areas on the buddingtonite endmember map. This distribution generally corresponds to known occurrences of buddingtonite at Cuprite (Goetz et al., 1985, Kruse et al., 1990).

11.3.2.4 GER 63 Channel Scanner. The GER63 data described here were acquired during August 1987. Selected analysis results were previously published in Kruse et al. (1990). Figure 11.9 (upper left) shows GER63 band 11 (0.67 µm) for spatial reference (12- to 22-m spatial resolution).). The areas A, B, and C indicate the approximate locations of the reference materials buddingtonite, alunite, and kaolinite. Figure 11.10 is a plot of the ROI average spectra for these three materials. Note that the GER63 adequately discriminates the alunite and buddingtonite but do not fully resolve the kaolinite “doublet” near 2.2 µm shown in the laboratory reflectance data (Figure 11.4). Figure 11.9 (upper right, lower left, lower right) shows the results of the SAM classification. Compare these images to the alteration map shown in Figure 11.3, the TM classifications shown in Figure 11.5, and the GEOSCAN classifications shown in Figure 11.7. Again note the circular distribution of the kaolinite and alunite alteration endmembers, which generally match the known alteration pattern, and the discrete distribution of the buddingtonite endmember.

11.3.2.5 AVIRIS. The AVIRIS data shown here were acquired during July 1995 as part of an AVIRIS Group Shoot (Kruse and Huntington, 1996). Figure 11.11 (upper left) shows AVIRIS band 30 (0.67 µm) for spatial reference (20-m spatial resolution). The areas A, B, and C indicate the approximate locations of the reference materials buddingtonite, alunite, and kaolinite. Figure 11.12 is a plot of the ROI average spectra for these three materials. Compare these to the laboratory spectra in Figure 11.4 and note the high quality and nearly identical signatures. Figure 11.11 (upper right, lower left, lower right) shows the results of the AVIRIS SAM classification. Compare these images to the alteration map shown in Figure 11.3, the TM classifications shown in Figure 11.5, the GEOSCAN classifications shown in Figure 11.7, and the GER63 classifications shown in Figure 11.9. Note that the AVIRIS data resolve the three alteration minerals into three distinct, spatially coherent zones and that the extracted spectra closely match the laboratory spectra (Figure 11.4) allowing positive identification.

11.3.2.6 Discussion. There are two aspects emphasized by comparison of these data. The first obvious difference is in the spatial resolution of the various sensors and aspects of the geology that can be observed. The GEOSCAN data have the highest spatial resolution at about 6 m, followed by the GER63 data with approximately 12-m cross-track and 22-m down-track resolution, AVIRIS data with about 20-m resolution, and the TM data with 28.5-m resolution. The GEOSCAN data allow observation of the fine details of the geology and prospecting activities, including individual stratigraphic layers, prospect pits, and minor access roads. The GER63 data have lower spatial resolution and significant geometric (scanning-induced) distortion, and some lithologic information and the distribution of prospect pits cannot be seen. The AVIRIS data appear quite blocky and again, the prospect information is obscured as well as individual stratigraphic layers which are typically thinner than 20 m. The TM data are extremely blocky, and altered areas are lumped together into grossly observable light versus dark areas. Individual beds and prospect pits are not observed, and none of the minor access roads are visible. Spectrally, it is actually surprising how much information can be obtained from the lower-spectral-resolution instruments in the 2.0 to 2.5 µm region, in particular, the GEOSCAN data. The spectral resolution ranges from greater than 50 nm for TM through approximately 40 nm for GEOSCAN, to 17 nm for GER63, to 10 nm for AVIRIS. While the TM data can not be used to identify individual minerals, the altered areas do have the expected characteristic low band 7 signature. The single 2.21µm TM band cannot be used for SAM classification or other multispectral classification techniques, and a density slice of the single band is unlikely to produce usable mineralogic information. All six TM bands (excluding the thermal band) were used for the SAM classification, including information from the visible/near-infrared, so it is not surprising that the TM SAM images do not match the known alteration mineralogy very well. The GEOSCAN spectra show distinct minima for the three minerals buddingtonite, alunite, and kaolinite, yet they do not fully resolve the band shapes, particularly for kaolinite. The GER63 data do a better job of showing the mineral spectra band positions and shapes, but the kaolinite doublet is still not resolved. AVIRIS fully resolves the major mineral absorption features, including subtle features in both alunite and kaolinite. Comparison of the GEOSCAN, GER63, and AVIRIS SAM results show that if one already knows what mineral one wishes to map, similar results can be achieved using any of these three sensors. If one wants to identify minerals without a priori knowledge, however, higher spectral resolution is required. Of the sensors shown here, only AVIRIS allows unambiguous identification of all three test minerals by comparison to the laboratory spectra in Figure 11.4. This is a direct result of the high spectral resolution, a convincing argument for the use of hyperspectral sensors similar to AVIRIS for detailed mineralogic mapping. While AVIRIS is currently the only fully operational imaging spectrometer, many other sensors are under development, and high spectral resolution data will soon be widely available.

11.3.3 Case Study: AVIRIS Data Analysis, Goldfield, Nevada

11.3.3.1 Introduction. This case study describes AVIRIS processing and results for Goldfield, Nevada, for Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data collected during an AVIRIS group shoot conducted during summer 1995. At the time of this flight, AVIRIS was the only available instrument with sufficient spectral resolution for direct mineral mapping. AVIRIS is the standard by which future hyperspectral systems will be judged, and the processing described here is one model for processing of other hyperspectral data types. High-quality AVIRIS data were collected during this mission for sites in Arizona, Nevada, California, Utah, Wyoming, and Colorado, USA. The Goldfield site described here consists of two approximately 10 km x 12 km AVIRIS scenes (Figure 11.13). The Goldfield area was chosen as the shared group site for the 1995 AVIRIS Group Shoot because considerable previous remote sensing and ground information exist for the area. The Goldfield mining district is a volcanic center thought to be a resurgent caldera (Ashley, 1974, 1979; Sabins, 1997). At least two periods of volcanism occurred and the hydrothermal alteration present in the district was caused by convective circulation of hydrothermal solutions along a zone of ring fractures and their linear extensions. Rocks exposed at the surface include air-fall and ash-flow tuffs, flows, and intrusive bodies. Hydrothermal alteration is extensive (Ashley, 1974, 1979; Rowan et al., 1974; Sabins 1997). The district exhibits a zoned alteration pattern. The rocks in the area have extensive exposures of alteration minerals including alunite, kaolinite, microcrystalline silica, illite, and montrmorillonite**.** The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an imaging spectrometer that simultaneously acquires 224 spectral images at 20-m spatial resolution and 10-nm spectral resolution. Each “scene” covers an approximately 10 km x 12 km area. Although imaging spectrometers collect images, in addition they collect a complete spectrum for each picture element (pixel) of the image, thus allowing detailed mapping based on the spectroscopic characteristics of minerals (Goetz et al., 1985, Boardman et al., 1995). Despite major revisions to the instrument prior to the 1995 flight season, AVIRIS operated without problems during the group shoot flights. Whereas some minor irregularities were observed with the data, the order of magnitude of these is near the noise level in the data (R. O. Green, personal communication). Problems encountered with the data included (1) dropped bits in individual pixels, resulting in anomalous spectra, and (2) multiplexer lag in the instrument, resulting in spatial shifting between bands (bands 13 and 35 were discarded because of a shift of 1 pixel or more). According to Rob Green at Jet Propulsion Laboratory (JPL), “the multiplexer lag artifact is similar to the detector-readout-delay that has been in all AVIRIS data before 1995. The artifact expresses itself very close to the level of the AVIRIS noise.” What this means is that the size of the instantaneous field of view (IFOV) of AVIRIS varies slightly as a function of the intensity of the signal. According to Green, the AVIRIS calibration without any correction is still at the 96% level. Based on preview processing, the AVIRIS data were judged to be satisfactory for the purposes of flight sponsors. In general, the data appeared to be of high quality in both the spatial and spectral domains. A standardized processing and analysis approach has been developed based on nearly 10 years of processing experience with AVIRIS data. While many other approaches are possible; this one is favored by the author and associates. Table 11.4 outlines this approach. In the following sections we describe this approach in more detail.

11.3.3.2 Download Quicklook Data. JPL processing to AVIRIS quicklooks was completed within two weeks. Quicklook data were obtained via anonymous FTP from JPL online at: “makalu.jpl.nasa.gov” in the directory “/pub/95qlook.” The quicklook data were downloaded for the Goldfield site, spatial coverage was reviewed, and hard-copy output produced. Standard processed, full AVIRIS scenes for each site were ordered from JPL following the preview. Calibrated radiance data (Green et al., 1996) arrived from JPL within two months of the flights. The Goldfield data were processed using the steps discussed below.

11.3.3.3 Preview Data and Assess Quality. Calibrated radiance data were both spatially and spectrally previewed. The spatial coverage of the site was good and the geometry and coverage of the data were excellent. Spatial browsing of different bands indicated that bands 13 and 35 were spatially offset from the rest of the bands (by one pixel horizontally). Another apparent anomaly was that some pixels exhibited what appeared to be dropped bits in one or more spectral bands. This was only for about 10 to 30 pixels per 614 x 1024 scene, well less than 1% of the data. These pixels were not used in subsequent processing.

11.3.3.4 ATREM Correction. The Goldfield AVIRIS data were corrected to apparent reflectance using the ATREM software available from the Center for the Study of Earth from Space (CSES) at the University of Colorado, Boulder. This software can be obtained via anonymous FTP from "cses.colorado.edu" in the directory "pub/atrem. Get the readme file for download instructions. ATREM is an atmospheric model-based correction routine and requires input of data parameters such as the acquisition date and time, the latitude and longitude of the scene, and the average elevation, along with atmospheric model parameters (CSES, 1992). ATREM version 1.31 was used for the Goldfield atmospheric correction. The output of the ATREM procedure is apparent reflectance data and a water vapor image for each scene. Typically, the water vapor image mimics topographic expression. Higher water vapor concentrations occur in the valleys, and lower water vapor concentrations occur over the higher elevations. In the Goldfield case, however, it appears as if there may have been some modulation by clouds. No clouds were visible in the images, however, and based upon review of spectra in areas apparently modulated by clouds, the ATREM apparent reflectance correction appears to have adequately removed water vapor contributions from the spectra.

11.3.3.5 Adjustments to ATREM Corrected Data. Residual atmospheric features and minor systematic noise in the apparent reflectance corrected data indicate that the quality of the AVIRIS data is better than the models we are currently using to calibrate the data. Empirical models can be used effectively to improve the apparent reflectance data. One means of doing this is a new method called the Empirical Flat Field Optimized Reflectance Transformation (EFFORT) which uses the characteristics of the data themselves without external spectral information (Boardman and Huntington, 1996). This method automatically finds the "flat" spectra in an AVIRIS scene, calculates the least-squares fit between these spectra and a low-order polynomial derived from the spectra, and uses a gain factor to remove the systematic noise. Small systematic noise and atmospheric absorptions present in every spectrum are effectively removed, resulting in smooth spectra without channel averaging. These spectra are comparable to high-signal-to-noise laboratory spectra.

11.3.3.6 Evaluation of Apparent Reflectance Data. Spectral browsing through the apparent reflectance corrected Goldfield data set was used to get an idea of the success of the correction as well as to identify specific minerals. This procedure indicated that the spectral quality of the data was excellent and the apparent reflectance correction adequate, however, several bands were dropped from further analysis. As previously noted, bands at 0.5001 µm (band 13) and 0.6824 µm (band 35) had spatial misregistrations. Additionally, the overlap regions between spectrometers in bands 32 to34 (0.67 µm) and in bands 97 to 98 (1.26 µm), as well as the spectral regions between approximately 1.3 to 1.4 µm and 1.84 and 1.96 µm, corresponding to the major atmospheric water bands, were masked out during subsequent processing. Individual spectra that contained absorption features attributable to kaolinite, alunite, buddingtonite, muscovite, and calcite could be recognized in the apparent reflectance corrected data.

11.3.3.7 MNF Transformation. The next step of the processing was to perform a “Minimum Noise Fraction” (MNF) Transform to reduce the number of spectral dimensions to be analyzed. The MNF transformation is used to determine the inherent dimensionality of the data, to segregate noise in the data, and to reduce the computational requirements for subsequent processing (Green et al., 1988; Boardman and Kruse, 1994). The MNF transformation is similar to Principal Components (PCs), but orders the data according to decreasing signal-to-noise-ratio (SNR) rather than decreasing variance as in PCs (Green et al., 1988). The MNF transformation can be used to partition the data space into two parts: one associated with large eigenvalues and coherent eigenimages, and a second with near-unity eigenvalues and noise-dominated images. By using only the coherent portions in subsequent processing, the noise is separated from the data, thus improving spectral processing results. For the Goldfield data, the eigenvalue plots fall sharply for the first 10 eigenvalues and then flatten out for the rest of the data. Examination of the eigenimages shows that while the first 10 images contain most of the information, images 11 through 20 still contain coherent spatial detail. The higher numbered MNF bands contain progressively lower signal-to-noise.

11.3.3.8 Pixel Purity Index (PPI). Based on the MNF results above, the lower-order MNF bands were discarded and the first 20 MNF bands were selected for further processing. These were used in the “Pixel Purity Index” (PPI), processing designed to locate the most spectrally extreme (unique or different or “pure”) pixels (Boardman et al., 1995). The most spectrally pure pixels typically correspond to mixing endmembers (unique materials). The PPI is computed by repeatedly projecting N-dimensional scatterplots back to two dimensions. The extreme pixels in each projection are recorded and the total number of times each pixel is marked as extreme is noted. A PPI image is created in which the digital number of each pixel corresponds to the number of times that pixel was recorded as extreme. A histogram of these images shows the distribution of “hits” by the PPI. A threshold was interactively selected using the histogram and used to select only the purest pixels in order to keep the number of pixels to be analyzed to a minimum. These pixels were used as input to an interactive visualization procedure for separation of specific endmembers.

11.3.3.9 N-Dimensional Visualization. Spectra can be thought of as points in an N-dimensional scatterplot, where N is the number of bands (Boardman, 1993; Boardman et al., 1995). The coordinates of the points in N-space consist of N values that are simply the spectral reflectance values in each band for a given pixel. The distribution of these points in n-space can be used to estimate the number of spectral endmembers and their pure spectral signatures. This geometric model provides an intuitive means to understand the spectral characteristics of materials. In two dimensions, if only two endmembers mix, the mixed pixels will fall in a line in the histogram. The pure endmembers will fall at the two ends of the mixing line. If three endmembers mix, the mixed pixels will fall inside a triangle, four inside a tetrahedron, and so on. Mixtures of endmembers "fill in" between the endmembers. All mixed spectra are "interior" to the pure endmembers, inside the simplex formed by the endmember vertices, because all the abundances are positive and sum to unity. This convex set of mixed pixels can be used to determine how many endmembers are present and to estimate their spectra. The Goldfield AVIRIS data set was analyzed using these geometric techniques. The thresholded pixels from the MNF images above were loaded into an N-dimensional scatterplot and rotated in real time on the computer screen until points or extremities on the scatterplot were exposed. These projections were “painted” using region-of-interest (ROI) definition procedures and then rotated again in three or more dimensions (three or more bands) to determine if their signatures were unique in the AVIRIS MNF data. Once a set of unique pixels were defined, then each separate projection on the scatterplot (corresponding to a pure endmember) was exported to a ROI in the image. Mean spectra were then extracted for each ROI to act as endmembers for spectral unmixing. Using the SWIR data only from 2.0 to 2.4 µm, and the procedure described above, several endmembers were defined for the Goldfield AVIRIS data. These include the minerals calcite, kaolinite, illite/muscovite, an additional unknown clay, alunite, and opaline silica (Figure 11.14). Another mineral, with an “unknown 2.2-µm absorption feature,” was also located. Based on the spatial distribution of spectra matching this endmember and known information about the sites, this endmember was identified as representing opaline silica. Unfortunately, similar spectra also occur on alluvial fans away from the altered areas, probably because of weathering and/or spectral mixing. Finally, both “light” and “dark” relatively aspectral endmembers were defined. These endmembers or a subset of these endmembers were used for subsequent classification and other processing.

11.3.3.10 Spectral Angle Mapper (SAM) Classification. The Spectral Angle Mapper (SAM) is an automated method for comparing image spectra to individual reference spectra (J. W. Boardman, unpublished data; Kruse et al., 1993b). The algorithm determines the similarity between two spectra by calculating the angle in N-dimensions (the spectral angle) between them, treating them as vectors in a space with dimensionality equal to the number of bands. Because this method uses only the vector "direction" of the spectra and not their vector "length", the method is insensitive to illumination. The result of the SAM classification (not shown) is an image showing the best SAM match at each pixel. Additionally, rule images are calculated that show the actual angular distance (in radians) between each spectrum in the image and each reference or endmember spectrum. Darker pixels in the rule images represent smaller spectral angles and thus spectra that are more similar to the endmember spectra. For the purposes of display, the dark pixels are inverted, so that the best matches appear bright. These images present a good first cut of the mineralogy at the sites.

11.3.3.11 Spectral Unmixing. While the SAM algorithm does provide a means of identifying and spatially mapping minerals, it only picks the best match to a spectrum. Natural surfaces are rarely composed of a single uniform material, thus it is necessary to use mixture modeling to determine what materials cause a particular spectral "signature" in imaging spectrometer data. Spectral mixing is a consequence of the mixing of materials having different spectral properties within a single image pixel. If the scale of the mixing is large (macroscopic), the mixing occurs in a linear fashion. A simple additive linear model can be used to estimate the abundances of the materials measured by the imaging spectrometer (Boardman, 1991). Each mixed spectrum is a linear combination of the "pure" spectra, each weighted by their fractional abundance within the pixel, a simple averaging. While some intimate non-linear mixing does occur for natural surfaces (eg: soil development resulting in mixing at the scale of mineral grains), the linear model is a good first order approximation in most cases. To determine the abundances, we must first determine what materials are mixing together to give us the spectral signature measured by the instrument. Selection of endmembers is the most difficult part of linear spectral unmixing. The N-dimensional visualizer approach described above provides one method for using the data themselves to determine endmembers. The ideal spectral library used for unmixing consists of endmembers that, when linearly combined, can form all other observed spectra. This can be presented as a simple mathematical model in which the observed spectrum (a vector) is the result of a multiplication of the mixing library of pure endmember spectra (a matrix) by the endmember abundances (a vector). An inverse of the original spectral library matrix is formed by multiplying together the transposes of the orthogonal matrices and the reciprocal values of the diagonal matrix (Boardman, 1989). A simple vector-matrix multiplication between the inverse library matrix and an observed mixed spectrum gives an estimate of the abundance of the library endmembers for the unknown spectrum. Linear Spectral Unmixing was used as the final step in producing mineral maps for the Goldfield AVIRIS data. The endmember library defined using the N-dimensional visualization procedure (Figure 11.14) was used in the unmixing process and abundance estimates were made for each mineral. These results can be presented in two ways. First, a set of gray-scale images stretched from 0 to 50% (black to white) provides a means of estimating relative mineral abundances. Selected grayscale abundance image results for a few of the minerals occurring at Goldfield are shown in Figure 11.15. Second, color composite images can be used to highlight specific minerals and mineral assemblages. Pure colors in these images represent areas where the mineralogy is relatively pure. Mixed colors indicate spectral mixing, with the resultant colors indicating how much mixing is taking place and the relative contributions of each endmember. For example, in a color composite of selected unmixing results for Goldfield (Figure 11.16; see the color insert), the minerals kaolinite, alunite, and muscovite when assigned to red, green, and blue in the color output result in distinctive image colors. These areas were extracted and overlain on a gray-scale image for improved location purposes. Areas that are pure red in this image correspond to areas where kaolinite is the spectrally dominant (most abundant) mineral. Areas that are green are dominated by alunite. Areas that are blue contain primarily muscovite. The yellow pixels are an example of mixed pixels, where the contribution of red from kaolinite and of green from alunite results in the mixed yellow color. The color image described above provides an example of how color information can be used to highlight selected minerals. To produce useful mineralogical maps for specific applications, however, these color images, the individual mineral abundance images, and reflectance spectra must be used together to determine the locations and distribution of minerals characterizing specific geologic processes important to those applications.

11.3.3.12 Discussion. This case study summarizes a standardized processing and analysis approach and results for AVIRIS data of the Goldfield, Nevada site flown during the 1995 AVIRIS geology group shoot. This demonstrates the utility of imaging spectrometers such as AVIRIS to produce detailed, high-quality mineral maps without supporting ground measurements. The group shoot effort demonstrated that a cooperative industry/NASA effort can provide an efficient means for organizations to share some of the costs and apparent risks of using a new technology while getting data specific to their needs.

11.4 Conclusions

This chapter has shown the current state of technology with respect to selected airborne and spaceborne sensors. There is a wide variety of data available including numerous sensors with varying spatial, spectral, and radiometric resolutions. Aircraft sensors described in this chapter act as both operational systems used in a variety of disciplines, and as prototypes for satellite systems. Numerous new systems are planned for the near future. Two trends appear to be developing: (1) sensors with improved spatial resolution (EarthWatch, OrbView, Space Imaging), and (2) sensors with improved spectral resolution (hyperspectral sensors/imaging spectrometers such as Orbview-4 and ARIES-1). These technologies are not mutually exclusive. The future probably holds hybrid sensors that use high spatial resolution bands to sharpen data from hyperspectral sensors, as well as hyperspectral sensors with better spatial resolution. These systems will provide near-laboratory-quality spectral information and improved spatial detail.

11.5 References

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Table 11.1. AVHRR Satellite Information

Number	Dates
TIROS-N	10/19/78 - 01/30/80
NOAA-6	06/27/79 - 11/16/86
NOAA-7	08/24/81 - 06/07/86
NOAA-8	05/03/83 - 10/31/85
NOAA-9	02/25/85 - Present
NOAA-10	11/17/86 - Present
NOAA-11	11/08/88 - 09/13/94
NOAA-12	05/14/91 - Present
NOAA-14	12/30/94 - Present

Table 11.2. Landsat Thematic Mapper Bands

Band	Wavelengths (μm)
1	0.45-0.52
2	0.52-0.60
3	0.63-0.69
4	0.76-0.90
5	1.55-1.75
6	10.40-12.50
7	2.08-2.35

Table 11.3. ASTER Instrument Characteristics

A) VNIR

Band	Spectral Range (µm)
1	0.52-0.60
2	0.63-0.69
3	0.76-0.86

B) SWIR

Band	Spectral Range (µm)
4	1.60-1.70
5	2.145-2.185
6	2.185-2.225
7	2.235-2.285
8	2.295-2.360
9	2.360-2.430

C) TIR

Band	Spectral Range (µm)
Band 10	8.125-8.475
Band 11	8.475-8.825
Band 12	8.925-9.275
Band 13	10.25-10.95
Band 14	10.95-11.65

Table 11.4. Standardized AVIRIS Processing Methodology

1. Download quicklook data
2. Review spatial coverage
3. Perform preliminary assessment of spatial data quality
4. Define areas for further processing
5. Order AVIRIS radiance data for selected scenes
6. Download radiance data from tape
7. Perform data quality assessment
a. Spatial browsing
b. Spectral browsing
c. SNR calculations
8. Correct to apparent reflectance
ATREM
Empirical line correction if ground information available
“Effort” correction if no ground information available
Spectral browsing
9. Report data problems to JPL
10. Perform MNF Transform (spectral compression)
11. Calculate Pixel Purity Index Image (limited iterations for identification of bad pixels)
12. Perform masking of bad pixels
13. Calculate Pixel Purity Index Image (maximum iterations for endmember determination)
14. Conduct N-Dimensional Visualization (Endmember Definition)
15. Compare of endmembers to spectral library for identification
16. Run Spectral Angle Mapper (SAM)
17. Perform Spectral unmixing and/or Matched Filtering or other advanced mapping methods
18. Add annotation and create output, and report

Figure Captions

Figure 11.1. Comparison of images from Landsat MSS, Landsat TM, SPOT, and AVIRIS for the northern Grapevine Mountains, Nevada site.

Figure 11.2. Comparison of a library, AVIRIS, and TM spectrum for the mineral kaolinite.

Figure 11.3. Generalized alteration map of the Cuprite, Nevada, site (From Kruse et al., 1990. After Abrams et al., 1978).

Figure 11.4. Laboratory spectra of kaolinite, alunite, and buddingtonite. Spectra are from the USGS Spectral Library (Clark et al., 1990).

Figure 11.5. Cuprite, Nevada TM images. (Upper Left) TM Band 3 (0.66 μm). The remaining images are the results of SAM classification using image endmembers: (upper right) “kaolinite”, (lower left) “alunite”, (lower right) “buddingtonite”. The full TM spectral range was used for these classifications, so these distributions are not limited to areas with the IR signatures of kaolinite, alunite, and buddingtonite, but to areas that have similar full-range TM spectra.

Figure 11.6. Cuprite, Nevada, TM spectra. The squares mark the single TM band 7 reflectance values. The lines connecting the left edge of the plot to the squares indicate the spectral slope from TM band 5 to TM band 7.

Figure 11.7. Cuprite, Nevada, GEOSCAN images. (upper left) GEOSCAN Band 3 (0.645 μm). The remaining images are the results of SAM classification using image endmembers: (upper right) “Kaolinite”, (lower left) “Alunite”, (lower right) “Buddingtonite”.

Figure 11.8. Cuprite, Nevada, GEOSCAN spectra for buddingtonite, alunite, and kaolinite. The squares mark the band centers of the GEOSCAN image bands.

Figure 11.9. Cuprite, Nevada, GER63 images. (upper left) GER63 band 11 (0.67 μm). The remaining images are the results of SAM classification using image endmembers: (upper right) “Kaolinite”, (lower left) “Alunite”, (lower right) “Buddingtonite”.

Figure 11.10. Cuprite, Nevada, GER 63 spectra for buddingtonite, alunite, and kaolinite. The squares mark the band centers of the 30 GER63 image bands used in the analysis.

Figure 11.11. Cuprite, Nevada, AVIRIS images. (upper left) AVIRIS band 30 (0.67 μm). The remaining images are the results of SAM classification using image endmembers: (upper right) “Kaolinite”, (lower left) “Alunite”, (lower right) “Buddingtonite”.

Figure 11.12. Cuprite, Nevada, AVIRIS spectra for buddingtonite, alunite, and kaolinite. The AVIRIS band-centers are too close together (10 nm) to mark on the plot.

Figure 11.13. Goldfield, Nevada, Location Map and Generalized Geology/Alteration Map (after Sabins, 1997.)

Figure 11.14. Goldfield, Nevada, AVIRIS Endmember spectra. Spectra are offset for clarity. Identifications are based on the USGS Spectral Library (Clark et al., 1993.)

Figure 11.15. Selected 1995 Goldfield, Nevada, AVIRIS unmixing results. Bright pixels represent higher abundances stretched from 0 to 50% (black to white). Representative endmember spectra for kaolinite and alunite are compared to USGS spectral library spectra.

Figure 11.16. AVIRIS true-color composite for reference (left) and overlay of color composite of Goldfield unmixing results on AVIRIS band 30 (0.67 μm)

(right). Red areas are predominantly kaolinite, green areas are predominantly alunite, and blue areas are predominantly illite/muscovite. Mineral mixtures appear as intermediate colors (e.g. yellow = red + green = kaolinite + alunite).