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AVIRIS: a New Approach to Earth Rmte Sensing

By Robert O. Green, Charles M. Sarture, Christopher J. Chovit, Jessica A. Faust, Pavel Hajek, and H. Ian Novak

An imaging spectrometer measures a contiguous spectrum of light for each spatial element of an image. From these spectra, the constituents of the Earth's surface and atmosphere are identified and measured quantitatively based on the fundamental molecular absorption features and particle scattering characteristics. The imaging spectrometry concept is depicted in Figure 1. Spectra measured in the range of 400 to 2500 nm contain molecular absorption features for many constituents of the Earth's surface and atmosphere. Scientific investigations are ongoing using imaging spectrometry data in the disciplines of ecology, oceanography, coastal and inland waters. geology and soils, and snow hydrology, to name a few.

The approach of imaging spectrometry to fully measure molecular absorption is revolutionarily different from all previous multispectral remote sensing. For example, Figure 2 (page 32) shows the contrast in approach between the multispectral Landsat Thematic Mapper and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS).

AVIRIS is the first, and currently the only, imaging spectrometer that measures light from the Earth over the entire solar reflected wavelength range from 400 to 2500 nm at 10 nm spectral resolution. Spatial images of 11 km by up to 1000 km with 20 m spatial resolution are collected. AVIRIS was designed and built at NASA's Jet Propulsion Laboratory (JPL). It is currently operated by JPL and flown on the NASA ER-2 aircraft. In this article, we present an overview of the sensor, the flight operations, the data system, calibration, and scientific research.

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The AVIRIS sensor

Light enters AVIRIS *from* a 10 cm × 20 cm scan mirror driven by a 70% efficient whiskbroom scan drive at a rate of 12 scans pcr second, This scan drive is unique in its ability to sweep linearly across the 30 degree (11 km) fidd+f-view and then fly back at nearly twice the speed to start the next imaging scan. The instantaneous field-of-view of AVIRIS is 1 mrad (20 m) and translates to 614 crosstrack spatial elements per scan. In the foreoptics, the energy reflected from the scan mirror is magnified and focused on four 200 μm diameter optical fibers. The fibers transmit the light from the foreoptics to one each of four spectrometers. Silica glass fibers with numerical apertures of 0.55 are used to cover the spectral range from 400 to 1200 nm. Zirconium fluoride glass fibers with a beryllium fluoride cladding with a 0.55 numerical aperture arc used from 1200 to 2500 nm. These high numerical aperture zirconium fluoride fibers were specifically developed for AVIRIS and were the first of their kind. Initial difficulties, due to the hydroscopic nature of these fibers, were overcome. The use of fibers was essential to allow independent alignment of the foreoptics and spectrometers as well as meet the compact sensor packaging requirements,

AVIRIS uses four off-axis Schmidt spectrometers (A, B, C, and D) to measure the light across the wavelength range at maximum grating efficiencies. Light enters the spectrometers from the optical fibers. A spherical mirror collimates and directs the beam co a diffraction grating where the light is dispersed into its spectral components. The dispersed light is refocused by the spherical mirror onto the detector focal plane, For the range 400 to 700 nm, a linear silicon detector array of 32 elements is used in Spectrometer A. Spectrometers B, C, and D usc 64 element arrays of iridium antimonide. The signal measured by each detector in the array is multiplexed in the focal plane and then amplified. The amplified signal is then digitized at 12 bits. The digital signal is buffered and then merged with engineering, navigation, and dark signal data. Data is recorded on a 10.4 Gbyte digital high density tape at a rate of 20.4 MB per second.

An on-board calibrator is an additional component of the AVIRIS sensor. This subsystem contains a stabilized quartz halogen lamp that provides light to the foreoptics end of the optical fibers. AVIRIS data are collected from the on-board calibrator before and after each flight line. A silicon detector feedback circuit has been specifically developed to maintain the stability of the light from the on-board calibrator. In addition, light from the on-board calibrator is sent sequentially through eight different filters providing both radiometric and spectral calibration sources.

The AVIRIS sensor and on-board calibrator system arc calibrated in the laboratory preceding and following each flight season. During laboratory calibration the spectral, radiometric, and geometric characteristics of AVIRIS are determined with respect to laboratory standards.

When AVIRIS is not collecting airborne data, the sensor is maintained and improved at JPL. Since its first flight in 1986, almost every subsystem of AVIRIS has been upgraded. For example, this winter new detectors will be installed to further improve AVIRIS signal-to. noise and stability (Fig. 3). Through these improvements, AVIRIS has continued to incorporate new technology and remain a unique state-of-the-art imaging spectrometer.

AVIRIS flight operations

AVIRIS first flew in December of 1986 and collected initial evaluation data in the summer of 1987. Based on these data, a series of improvements and upgrades were incorporated into AVIRIS to support a full flight season in 1989. These modifications included increased spectrometer stability, improved signal-[o-noise, a new on-board calibrator design, and reduced sensitivity to background humidity. In 1989 and each subsequent year, AVIRIS has typically flown on the ER-2 for six months of the year collecting data from bases throughout the U. S. and in Europe. Because each flight exposes AVIRIS to the accelerations of takeoff and landing and extreme gradients in temperature, humidity, and pressure, the performance of AVIRIS is evaluated on the ground before and after each flight. Through the six-month flight season, AVIRIS may fly up tcr 45 times for as many as SO different investigators spanning 300 regional sites.

On a single flight, data sets covering more than 11,000 sq km for five or more investigators may be acquired. This poses a significant challenge to p-e-flight planning and in flight acquisition by the pilot. Furthermore, most science investigators require their data to be acquired under cloud free conditions. For this reason, most flight schedules arc finalized on the day of the flight, often only three hours before takeoff. To keep investigators informed of their acquisition, the AVIRIS Experiment Coordinator communicares intensively with every investigator prior to and *following each* flight. Following each flight, the Experiment Coordinator debriefs the pilot to determine the exact flight lines acquired and weather conditions. The flight tape and an accurate flight line record are then transmitted to the data facility at JPL.

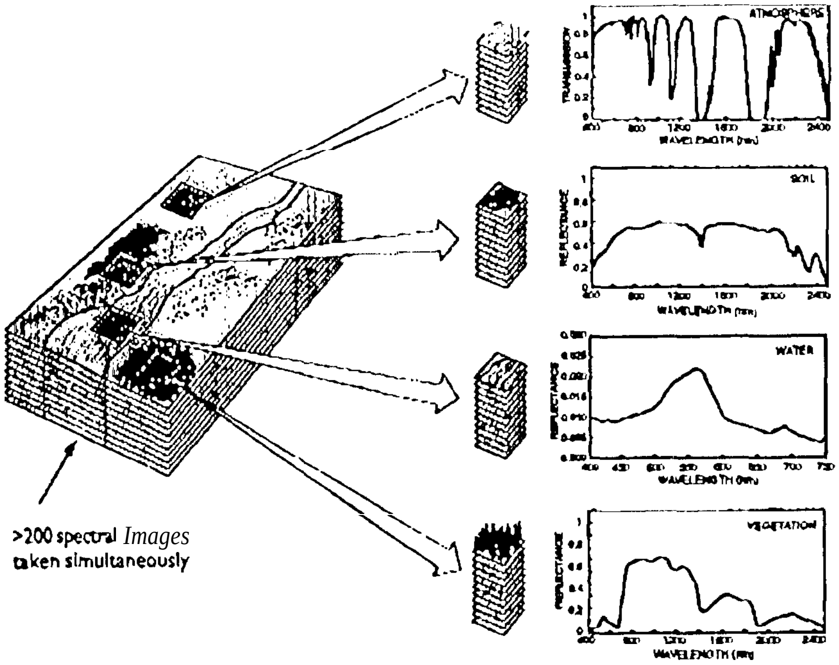

Figure 1. Imaging spectrometer concept showing measurement of a contiguous spectrum for each spatial element in the image.

AVIRIS data facility

As each flight tape arrives in the data facility, a rapid performance check of AVIRIS is made based on the on-board calibrator and engineering data encoded in each flight tape. Results of this check arc automatically e-mailed to the AVIRIS sensor, calibration, and data system engineers for real-time evaluation. Upon passing the evaluation, the flight tape is then placed in the archiving queue, After a flight line is archived, a single AVIRIS band image is generated and placed on-line in an anonymous ftp directory (ophelia.jpl.nasa. gov). The investigator is informed by e-mail that the quicklook images from their site are available on-line. The investigator then places an order for calibrated data for the portions of the flight line of interest and the AVIRIS data are calibrated. Calibration transforms the data from images of digitized number per band to images of spectral radiance pcr wavelength. ~~The calibrated images are passed through a rapid quality evaluation and then distributed to the investigator.~~ Procedures, algorithms, and processes of the Data Facility have evolved both incrementally and through three major upgrades since 1986. The current AVIRIS archive of flight and calibration data exceeds 1.5 'I'bytes,

Inflight calibration and compensation for the atmosphere

To pursue quantitative research and applications with AVIRIS, the data must be calibrated stnd the accuracy of the calibration known. On the first day of each flight season, an AVIRIS inflight calibration experiment is held to determine the calibration of AVIRIS as it is acquiring data from the ER-2 platform. During this experiment, the characteristics of surface and atmosphere at a homogeneous calibration target are measured on the ground at the same time AWNS overflies the target, The surface based measurements are used to constrain a radiative transfer code (RTC) and independently predict the upwelling radi-

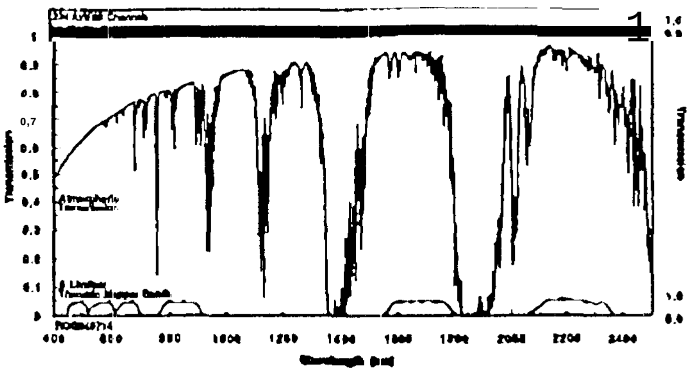

Figure 2. This plot shows the 224 bands of AVIRIS in contrast to the 6 broad multispectral bands of the Landsat Thematic Mapper. A typical transmission spectrum of the atmosphere is also shown.

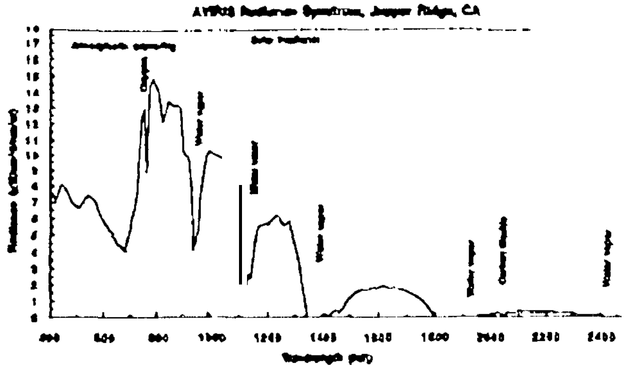

Figure 5. AVIRIS calibrated upwelling radiance for a vegetated target on the San Francisco Peninsula. The region of strong atmospheric scattering as well as dominant atmospheric absorbers are shown.

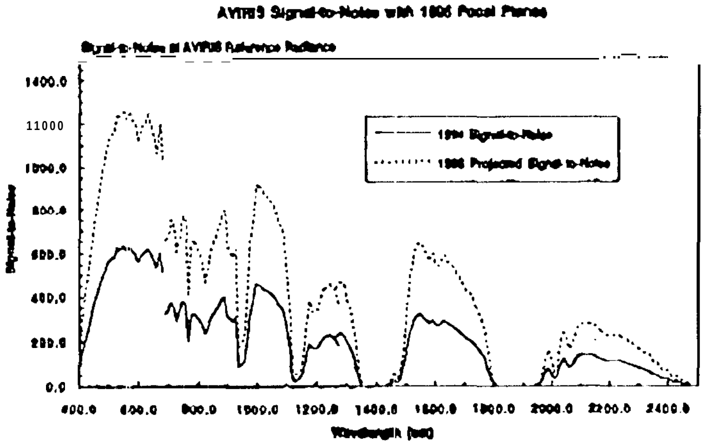

Figure 3. AVIRIS inflight signal-to-noise performance during the inflight calibration experiment at Lunar Lake, NV on the 5th of April 1994. The projected signal-to-noise for 1995 is shown based on installation of new focal planes.

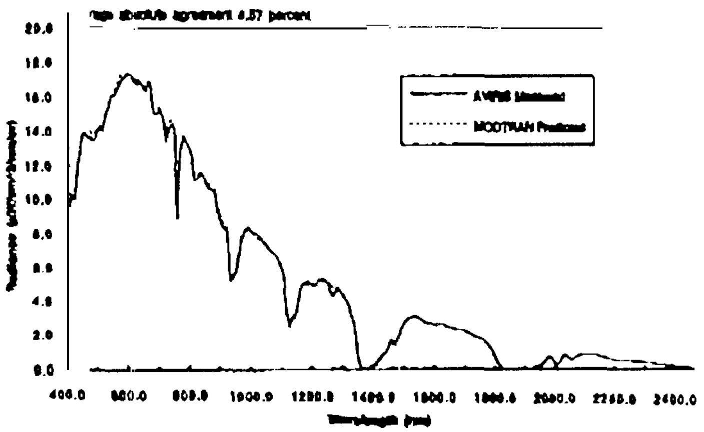

Figure 4. Radiometric calibration results of the AVIRIS inflight calibration experiment at Lunar Lake, NV on the 5th of April 1994. A calibration greater than 95% is shown.

ante at AVIRIS. The RTC-predicted and AVIRIS-measured radiance are compared to determine the accuracy of the AVIRIS inflight calibration. Figure 4 shows results from the AVIRIS calibration experiment at the beginning of the 1994 flight season, In 1994, inflight calibration accuracy of AVIRIS was better than 95%. The inflight signal-to-noise is also determined ~~through~~ experiment and shown in Figure ~~4. Overall, the signal-to-noise of AVIRIS is high with low values occurring only where there is little measurable signal due to strong absorption of light by the atmosphere.~~

Research and Applications

Research spanning a range of scientific disciplines is ongoing with AVIRIS. ~~In each of these research investigations, accurate AVIRIS calibration as well as characterization and compensation for the atmosphere have been required.~~

- Measurements by AVIRIS of the molecular absorption due to the plant molecules of chlorophyll, leaf water, and cellulose are used by ecologists today. Recent research with AVIRIS has shown the measurement of absorptions due to lignin and nitrogen compounds in forest canopies. Differential expression of light scattering across the spectrum is giving insight into the structural geometry of plant canopies.
- Geologists have identified and mapped more than 100 different minerals with AVIRIS in a range of geological environments. The ability to accurately map small mineralogical difference with AVIRIS has lead to detection of subtle previously unknown earthquake faults, in another AVRIS application, mapping the distribution of tailings washing out from an abandoned mine in Colorado allows researchers to track movement of associated toxic mine wastes.
- Coastal and inland waters oceanographers use AVIRIS data to measure phytoplankton, organic matter, water plants-, coral, sediments, and shallow water depth.
- Atmospheric researchers measure water vapor, cloud properties, aerosols, and smoke. In the AVIRIS spectral range, the absorption scattering properties of

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ice, liquid water, and soot particles are used to study issues of importance to snow hydrology.

- AVIRIS has been used to fly beneath an orbiting satellite and reestablish the calibration of the satellite sensor following launch.

Conclusion

Numerous engineering and technological challenges have been overcome to develop AVIRIS—a new class of remote sensing sensor. This instrument routinely acquires imaging spectrometer data for research in a wide range of scientific disciplines. The measurement of contiguous spectra that are calibrated allows quantitative measurement of the Earth's land, water, and atmosphere. It is hoped AVIRIS will continue to operate and be improved as the growing imaging spectrometer community waits for the launch of a spaceborne imaging spectrometer.

Acknowledgments

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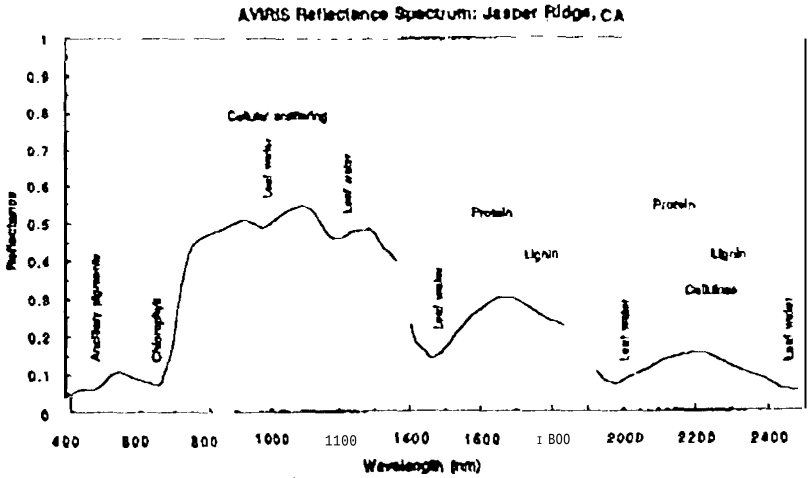

Figure 6. Derived surface reflectance spectrum following AVIRIS based compensation for the atmosphere. The regions of absorption from vegetation compounds are shown.

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