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AVIRIS PERFORMANCE DURING THE 1987 FLIGHT SEASON: AN AVIRIS PROJECT ASSESSMENT AND SUMMARY OF THE NASA-SPONSORED PERFORMANCE EVALUATION

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ABSTRACT

Results are presented of the assessment of AVIRIS performance during the 1987 flight season by the AVIRIS project and the earth scientists who were chartered by NASA to conduct an independent data quality and sensor performance evaluation. The AVIRIS evaluation program began in late June 1987 with the sensor meeting most of its design requirements except for signal-to-noise ratio in the fourth spectrometer, which was about half of the required level. Several events related to parts failures and design flaws further reduced sensor performance over the flight season. Substantial agreement was found between the assessments by the project and the independent investigators of the effects of these various factors. A summary of the engineering work that is being done to raise AVIRIS performance to its required level is given. In spite of degrading data quality over the flight season, several exciting scientific results were obtained from the data. These include the mapping of the spatial variation of atmospheric precipitable water, detection of environmentally-induced shifts in the spectral red edge of stressed vegetation, detection of spectral features related to pigment, leaf water and ligno-cellulose absorptions in plants, and the identification of many diagnostic mineral absorption features in a variety of geological settings.

INTRODUCTION

The AVIRIS Performance Evaluation Workshop held at JPL on June 6, 7, and 8, 1988, was the culmination of an intensive assessment of data quality and sensor performance. The evaluation was sponsored by NASA and conducted by the AVIRIS project and an independent group of NASA-selected scientists. Development of the AVIRIS flight and ground data processing systems began in 1984 in response to an unsolicited proposal to NASA the previous year. Engineering flights were conducted with the sensor in the winter and spring of 1987 in conjunction with extensive laboratory testing of the sensor in the AVIRIS calibration laboratory at JPL. By June 1987, the sensor was performing close to the design goals, meeting most requirements. The notable exception was the signal-to-noise ratio (SNR) in the fourth spectrometer, which was only about half the design requirement. However, because flight data from AVIRIS spectrometer D were shown to be adequate for meeting the original science requirements, i.e., the detection of subtle spectral features such as the OH absorption doublet at 2.2 μm in the spectrum of the clay mineral kaolinite, the decision was made to conduct the data quality and sensor performance evaluation program during the summer of 1987 as planned, and defer further improvements, such as increasing SNR, to the following winter. Flights were begun in late June at the East coast NASA Wallops Island facility on the U-2 aircraft and continued on the West coast at NASA Ames from late July through October when AVIRIS was returned to JPL for post-flight season calibration, checkout and upgrade. During the 4 months of operations aboard the aircraft, several events occurred which compromised the performance of the sensor. These events were related both to parts failures and design flaws that were undetectable through laboratory testing of the sensor. As a result of what was learned during the in-flight testing of AVIRIS, the upgrade program planned for late 1987 was enlarged and extended through 1988.

In this paper, we summarize the performance characteristics of AVIRIS at the beginning of the in-flight assessment program, describe the problems that occurred during the 1987 operations and how they affected data quality, summarize the findings of the independent performance evaluation investigators whose reports are published in these proceedings, and briefly describe the upgrade program that is under way at JPL to bring AVIRIS performance to the required level.

AVIRIS PERFORMANCE DURING THE FIRST FLIGHT SEASON

AVIRIS is a "whisk-broom" imaging spectrometer employing a scanning foreoptic connected by optical fibers to 4 spectrometers, each with a line array of detector elements at its focus. Data encoded at 10 bits are recorded at the rate of 17 Mbps on an on-board tape recorder. Also recorded are data from an on-board calibrator and various engineering data from the sensor. Flight data are subsequently processed at JPL at a dedicated computer facility. The instrument and ground data processing facility are described in detail in a suite of papers by the AVIRIS engineers in Vane (1987a and b). A brief description of the instrument is given in Appendix 1 of these proceedings by Vane et al. (1988).

Figure 1 is an artist's sketch of the flight hardware in the NASA U-2 aircraft (see slide No. 1).

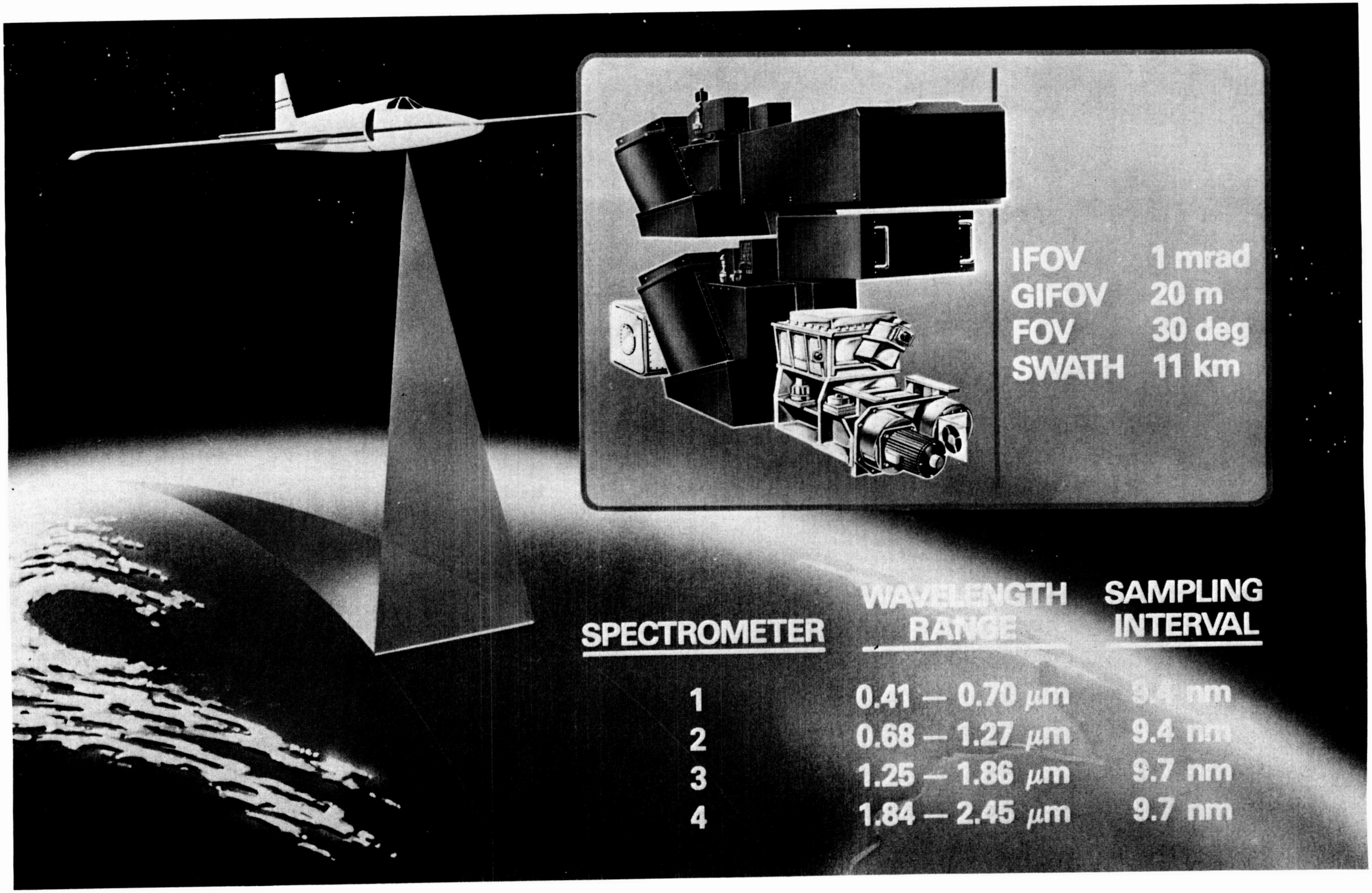
Performance at the Start of the Flight Season

At the start of flight operations in late June, 1987, three engineering flights, including the first field calibration experiment, and 3 laboratory calibrations had been performed on AVIRIS. Table 1 summarizes the sensor performance at the start of flight operations as determined in the laboratory.

Table 1. AVIRIS performance at the start of the 1987 flight season

Parameter	Requirement	Achieved
Spectral Coverage	0.4 to 2.4 μm	0.410 to 2.451 μm
Spectral Sampling	10 nm	9.6 to 10.0 μm
Spectral Bandwidth	10 nm	9.0 to 11.6 μm
SNR (Albedo = 0.5)	100:1 at 0.7 μm	110:1
	50:1 at 2.2 μm	20:1
IFOV	1 mrad	0.95 mrad
Swath from U-2	10 km	10.5 km
Spatial Oversampling	15%	17%
Internal Image Geometry		
Cum. Error over Scan	0.5 mrad	0.26 mrad
Pixel-to-Pixel Error	0.1 mrad	0.06 mrad
Signal Level Stability	3%	2.4 to 7.7%
Calibration		
Spectral	5 nm	0.8 to 2.1 nm
Radiometric (absolute)	10%	7.3%

The areas of sensor performance not meeting the requirements were SNR at 2.2 μm and signal level stability. The required and achieved SNR performance cited in Table 1 is referred to a standard scene radiance determined by an albedo of 0.5 at mid-latitude, mid-summer, with an atmosphere of 23 km visibility with rural aerosols (see Green et al., 1988, for a more detailed description of the AVIRIS reference radiance model). The achieved performance was measured in the laboratory with a calibrated integrating sphere whose radiance output was normalized to the AVIRIS reference radiance. While the SNR requirement of 50:1 was not being met at the start of the flight season, engineering flight data over Cuprite, Nevada showed that the sensor performance at that wavelength was adequate for detecting the kaolinite doublet under the conditions at Cuprite (Vane, 1987c). Signal level stability in Table 1 refers to the stability of the radiometric response function, which is different for



Characteristics of AVIRIS

each spectrometer because of the small differences in their thermal and opto-mechanical configurations. In the pre-flight season laboratory testing of AVIRIS, we found that spectrometer D with a stability of 2.4%, met the requirement, which was derived from the absolute radiometric calibration requirement, while spectrometers A, B and C, at 3.5%, 7.7%, and 4.2% respectively, did not meet the requirement for radiometric response function stability (Vane et al., 1987). Spectral coverage overlap between the spectrometers, plus the on-board calibrator, could be used to tie the radiometry of spectrometers A, B, and C to the more stable spectrometer D if desired, however.

Three other areas affecting data quality and sensor performance were also known at the start of the flight season. Fixed pattern noise was present in the data from all spectrometers and had been studied through a Fourier transform analysis. Only in spectrometer D, however, was its amplitude great enough to be observable to the eye, and there only in highly stretched images of uniform targets such as the interior of the AVIRIS integrating sphere. Spectrometer D was also known to have 2 noisy detector elements in its 64-element line array. Their locations were at spectral channels 181 and 210, or 2.026 and 2.312 μm, respectively. Finally, vignetting was present in the foreoptics of about 8% at the left edge of the field of view. These and the areas discussed above were to be addressed in the upgrade program at the end of the flight season.

Evolution of AVIRIS Performance Over the Flight Season

As a result of the extensive operation of AVIRIS aboard the U-2, coupled with a field calibration experiment at the end of the season, a post-flight season laboratory calibration and the subsequent tear-down of the instrument, a great deal was learned about sensor performance by the AVIRIS project by the time of the Performance Evaluation Workshop. In particular, several additional areas of performance weakness that developed over the flight season were identified, their causes determined and solutions identified. Appendix 1 contains 2 papers that were presented at the Orlando, Florida meeting of the Society of Photo-Optical Instrumentation Engineers (SPIE) April 6, 7, and 8, 1988, that detail what was learned through the field calibration experiment and post-flight season laboratory calibration (Conel et al., 1988a, and Vane et al., 1988, respectively). We summarize the results here as they pertain to radiometric stability, spectral performance and SNR. Details of the engineering work being done to address these problems is discussed in the last section of the paper.

Radiometric stability. Variations of 50% or more were seen in the radiometric response of the sensor relative to the AVIRIS reference radiance model. The causes were (1) an inadequate spectrometer thermal control system, (2) warpage of the AVIRIS instrument rack, (3) detachment of optical fibers to 2 of the spectrometers, (4) failure of a component in the signal chain electronics, and (5) breakage of a blocking filter in one of the spectrometers. Because of the close match between the size of the cone of light falling on the AVIRIS detectors and the detector dimensions, thermal control of the spectrometer bodies is critical to maintaining alignment and, therefore, constant signal level. The thermal control system used during the first flight season held the spectrometer bodies to within 3 degrees C of a pre-set temperature, which resulted in the laboratory stability performance noted earlier. The much colder aircraft environment caused larger fluctuations in temperature, however, and therefore signal levels. Warpage of the instrument rack in the aircraft apparently resulted because of a design deficiency by the manufacturer. The warpage was transmitted to at least spectrometer D, resulting in a degradation of optical alignment. In the post-flight season inspection of the instrument, it was discovered that the optical fibers to spectrometers A and B had become detached because of an epoxy failure. This resulted in both a signal loss in each spectrometer and a degradation of spectral resolution discussed below. During the flight season, sudden shifts in brightness were occasionally noted in the images from the various spectrometers. This was traced to the potentiometers in the preamplifier circuits which null the dark current offset of the detector signal prior to signal processing, in order to keep detector dark current levels on scale. This had the additional effect of making it appear that the output of some detector elements was zero when the offset drift was negative. Table 2 summarizes the spectral channels affected by this problem, which show up in the data as having dark current values of zero. Finally, the breakage of the KH_2PO_4 crystal (KDP) filter in spectrometer B early in the flight season, caused additional fluctuations in the response of that spectrometer. These 5 factors taken together on an individual spectrometer basis are thought to explain most of the instrument response instabilities seen during the 1987 flight season. See Vane et al. (1988) in Appendix 1 for a much more thorough discussion.

Table 2. AVIRIS spectral channels with dark current of zero

Flight	Date	Channel Number
4	6/25	162, 163, 166, 168, 169, 173, 189, 200, 214, 216
5	7/4	162, 168, 173

Table 2. (contd)

Flight	Date	Channel Number
6	7/9	162, 168, 173
7	7/13[a]	162-166, 168, 169, 173-178, 180, 182, 184, 189, 194, 197, 200, 201, 205, 208, 209, 211, 213, 214, 216, 223
9	7/24	162, 168
10	7/30	162, 168
11	8/1	162, 168
12	9/14	20, 24, 26, 28, 32, 162, 163, 168, 169, 173
13	9/18[a]	20, 24, 26, 28, 32, 34, 40, 64, 72, 80,162, 163, 165, 168, 169, 173, 176, 189, 205
15	10/13[b]	none
16	10/14[b]	none
17	10/15[b]	none
18	10/19[b]	none
19	10/21[b]	none

[a]Potentiometers adjusted and/or replaced after these flights.
[b]Although no channels had dark current values of zero, small line-to-line offsets were still occurring.

Spectral performance. Item numbers (2) and (3) above also affected the spectral alignment and bandwidths of the AVIRIS spectrometers. Warpage of spectrometer D induced by distortion of the instrument rack probably accounts for the 3 nm shift in spectral alignment measured in the post-flight season laboratory calibration (Vane et al., 1988) and subsequently measured in the flight data from flight number 10 on July 30, 1987 (Green et al., 1988). Detachment of the optical fibers to spectrometers A and B caused a broadening of the spectral response functions and shifts in the spectral alignments of both spectrometers. Vane et al. (1988) report post-flight season bandwidths of 17 and 14 nm and spectral alignment shifts of 6 and 2 nm toward the blue for spectrometers A and B respectively. Green et al. (1988) report from the flight data of July 30, 1987, spectral bandwidths of 15 and 17 nm and alignment shifts of 0 and 4 nm toward the blue for A and B respectively. We take the discrepancy between these 2 independent determinations to be an indication of the dynamic nature of the spectral response of these two spectrometers because of the detached and therefore moveable optical fibers. A similar disagreement between the in-flight radiometric response and the pre- and post-flight season radiometry is noted by Conel et al. (1988a).

Signal-to-noise performance. All of the factors discussed above which affect instrument output signal levels also affect SNR. In addition, increases in electronic noise were noted over the flight season. One source was the failing potentiometers which by the end of the flight season were causing line-by-line variations in offsets. Additionally, this effect nullifies the gain one would normally get by averaging spatial pixels to enhance SNR by the square root of the number of pixels averaged. We also noted an increase in the Gaussian noise level in spectrometer D, and increases in fixed pattern noise in all spectrometers, but again, especially in spectrometer D. Most of the preamplifier and clock driver boards were reworked several times to improve performance before the flight season began to optimize noise performance. This probably weakened the boards, making them more susceptible to such noise paths as vibration of various electronic components on the boards. As a result of these factors, the SNR of spectrometer D was as low as 10:1 by the end of the flight season, normalized to the AVIRIS reference radiance model.

AVIRIS Ground Data Processing Facility Performance

The AVIRIS Ground Data Processing Facility consists of a dedicated VAX 11-780 computer, an Ampex HBR3000 high density digital tape drive, 2 9-track 6250 bpi tape drives, and dedicated hard disk drives, printers, display devices, terminals, an optical disk drive, a matrix film recorder, and an interlan ethernet interface. The purpose of the facility is to convert flight data on high density tapes (HDTs) to 9-track 6250 bpi archival computer compatible tapes (CCTs) and quick-look hardcopy images (archival processing), to provide engineering data to the instrument team for timely monitoring of instrument performance, to process requested data from the archive through spatial and spectral subsetting and radiometric and geometric rectification (retrieval processing), and to provide analytical processing support for visiting scientists. Also, selected scenes specified by the AVIRIS experiment scientist are archived on optical disk for distribution to anyone who wishes a copy. The system and its functions are described in detail by Reimer et al. (1987). During the 1987 flight season, the AVIRIS Ground Data Processing Facility performed flawlessly.

During 1987, the equivalent of 795 full 6250 bpi CCTs of data were collected and processed as a result of the performance evaluation program and the pre- and post-flight season project engineering evaluation activities. The design goal for the facility was to complete retrieval processing in no more than 3 weeks of elapsed time from receipt of the processing request from the investigator. This goal was achieved. In addition, 10 investigators spent an average of 3 days each analyzing their flight data at the AVIRIS Ground Data Processing Facility. Table 3 summarizes the data processing statistics for 1987. The flow of data from acquisition to distribution of processed products is: (1) Data acquisition aboard the NASA U-2, (2) mailing HDT to AVIRIS Ground Data Processing Facility at JPL, (3) archival processing at JPL, (4) mailing a copy of the quick-look hardcopy images and a retrieval processing request form to the investigator, (5) investigator returns retrieval request form to JPL indicating which data are to be processed and to what level, and (6) JPL mails processed data on 6250 bpi CCT to investigator.

Table 3. AVIRIS 1987 data processing statistics

Data Quantity Collected	33 HDTs
Data Quantity Archived (Archival Processing)	795 CCTs
Data Quantity Processed (Retrieval Processing)	339 CCTs
Number of Investigators Who Received Data	58
Data Processing Times (Average)	
From Acquisition through Archival Processing	6 weeks
From Archival Processing to Receipt of Retrieval Processing Request Form	7 weeks
From Receipt of Request Form to Mailing of Fully Processed Data on CCTs	3 weeks

RESULTS OF THE INDEPENDENT PERFORMANCE EVALUATION OF AVIRIS

In the following section of the paper we summarize the work presented in these proceedings of 15 of the investigations sponsored by NASA to assess AVIRIS data quality and sensor performance. In addition to assessing data quality, many of the investigations attempted to use AVIRIS data to address scientific problems.

Conel et al. (1988b) used AVIRIS data from Mountain Pass, California to assess the potential for recovering atmospheric water abundance in the vertical column below the sensor at the spatial resolution of AVIRIS. Using a band ratio method and the 940 nm atmospheric water band and the 870 nm continuum radiance, they were able to successfully produce a map of the areal distribution of total precipitable water over the region which conforms well to topography. Independent validation of the AVIRIS-derived column abundance at one point in the region was supplied by a calibrated spectral hygrometer. The accuracy of the AVIRIS determination is estimated to be 10%. For average conditions over Mountain Pass, the uncertainty in AVIRIS-derived water column abundance is +/- 0.12 cm. Signal-to-noise was enhanced by averaging spatially 2 by 2 pixels.

Kieffer et al. (1988) analyzed AVIRIS data from several sites to assess instrument stability and response. Although the data were clearly noisy and the instrument response function was unstable at the times of data acquisition, they showed that valuable spectral signatures can still be extracted and analyzed. Two methods are described for extracting spectral information from the Kelso Dunes, California, both of which successfully identified at least three distinct spectral signatures, although positive identification of a specific material was not possible. They also describe their assessment of coherent and random noise and two techniques used for minimizing these and atmospheric effects.

Curran and Dungan (1988) have developed a new procedure for estimating SNR which they call the "geostatistical" method, and have applied it to 5 AVIRIS data sets to illustrate its utility to the investigator for determining where the zones of maximum information lie for a specific ground cover type. They define zones of maximum information as those spectral regions of highest SNR. The procedure is based on removal of periodic noise by "notch filtering" in the frequency domain and the isolation of sensor noise and intra-pixel variability using the semi-variogram.

Clark et al. (1988) used data from several ground calibration sites at Cripple Creek and Canon City, Colorado to reduce their flight data to ground reflectance. SNR performance was computed on selected spectra extracted from the calibrated images. The data were very noisy, although Fourier transform analysis revealed the absence of periodic noise in the data. Random offsets in signal and dark current levels were noted, leading the investigators to drop the standard procedure of the 101 scan line dark current smoothing in favor of a line-by-line correction. Images of spectral absorption band depth selected to be diagnostic of the presence of certain minerals and vegetation were computed. The resulting images showing the presence of goethite, kaolinite and lodgepole pine trees agreed well with field checks of the test sites. Clark et al. point out however, that successful identification of these materials in areas of lower abundance or higher vegetation cover will require higher SNR performance than AVIRIS had in October 1987.

Kruse et al. (1988a) have developed techniques for the automated extraction and characterization of absorption features from reflectance spectra and have successfully applied these techniques to AVIRIS and Geophysical and Environmental Research Imaging Spectrometer (GERIS) data. Maxima in the spectra are identified automatically, and a continuum of straight line segments is fit between these points The continuum is removed from the spectrum by division, the minima of the resulting spectrum are determined, and the 10 strongest features are extracted. From these, the wavelength position, depth, full width at half the maximum depth, and asymmetry for each of the 10 features are determined and tabulated. The routines are written in Fortran and C languages. When applied to AVIRIS data from the Grapevine Mountains of Nevada, many of the strongest features located were noise, but AVIRIS spectra from known areas of sericite and dolomite were also found.

A second study by Kruse et al. (1988b) used the internal average relative (IAR) reflectance approach and a U. S. Geological Survey (Flagstaff) developed analysis program called QLook to analyze the Grapevine Mountains data as well as the Colorado data sets studied by Clark et al. At the Grapevine Mountains both muscovite and carbonate were accurately identified and mapped in the imagery, but low SNR precluded differentiation between calcite and limestone and muscovite and montmorillonite, which had been previously done with AIS. The noise problems with the Colorado data were accentuated by the IAR technique because of the moderate vegetation cover. This approach to information extraction was less successful than that used by Clark et al. described above. The conclusion by Kruse et al. was the same as Clark et al., however: Higher SNR is required if AVIRIS is to be effectively utilized in more challenging geological settings.

Rock et al. (1988) were interested in testing the efficacy of AVIRIS data for detection of environmentally-induced shifts in the spectra of vegetation at the chlorophyll well and red edge. They used radiometrically corrected data from Bishop, California, which were flat field corrected using a grus pit of weathered products from granitic rock and having no vegetation present. A normalization technique was developed and applied to remove the large variations in the height of the near infrared plateau and depth of the chlorophyll well characteristic of the different types of vegetation in the area. Both native and cultivated vegetation sites were studied in areas sufficiently large and uniform that several pixels could be averaged to enhance SNR. When applied to data from fields of green uncut alfalfa and fields of freshly cut green but drying alfalfa, a distinct shift in wavelength toward the blue end of the spectrum was observed in the position of the red edge of the cut alfalfa relative to the red edge position of the uncut alfalfa. The investigators also conclude that AVIRIS spectra may be useful in detecting small amounts (20 to 30% cover) of semi-arid and arid vegetation ground cover.

Elvidge (1988) used laboratory and field reflectance data from 3 large, uniform targets of high, intermediate and low brightness for correcting AVIRIS data from Jasper Ridge, California to percent reflectance. The area studied is a large natural vegetation preserve which contains most of the major plant communities found along the central California coast. Highly linear relationships were found between the digital numbers and reflectance for the 3 calibration targets in the first two spectrometers. However, changes in instrument response in the last 2 spectrometers induced by factors discussed earlier in this paper caused the DN of the bright target at the north end of the flight line to deviate from a linear fit with the other 2 targets further south along the flight line. Spectrometer C and D data were therefore corrected only with the reflectance data from the 2 southern targets. The results of the analysis of the calibrated data showed distinct reflectance spectra from 5 plant communities, including 4 containing green vegetation and 1 containing a dry annual grassland. Spectral features identified in the data were tied to pigment absorption in the visible spectrum, to the red edge, to leaf water absorptions at 0.97 and 1.19 µm, and to ligno-cellulose absorptions at 2.09, 2.26, and 2.33 µm. A ligno-cellulose vegetation index image was produced from the data having very good correlation with known ligno-cellulose concentrations on the ground.

Swanberg (1988) has completed the first phase of a 2 phase study to assess the utility of AVIRIS data for remotely acquiring information on plant chemistry. She assessed the geometric and radiometric properties of data sets from central Oregon for pixel size, swath width, spectral position and SNR. Her in-flight analysis of image geometry compares well with the laboratory measured values for IFOV and FOV, the small differences being due most likely to topographic effects. The LOWTRAN 6 atmospheric modelling code was used to evaluate spectral position by comparing a 50 pixel averaged AVIRIS spectrum with a LOWTRAN spectrum calculated for a mid-latitude, mid-summer, 0.5 albedo model. From the visual inspection of the two radiance curves, agreement was found to within 1 AVIRIS spectral bandwidth or 10 nm, which is the resolution of such an approach. SNR was calculated at two targets by dividing the mean signal level at each by the standard deviation of the signal. Fifty pixels from a bright, relatively homogeneous beach and 9 pixels from a dark forest site were used to determine the upper and lower bounds respectively, of SNR. Swanberg concludes that for the second phase of her study, which is to analyze AVIRIS spectra for plant chemistry signatures, she will use data only from spectrometers A and B since the SNR of spectrometers C and D is too low in the 1987 data.

Bailey et al. (1988) analyzed AVIRIS data from the Drum Mountains, Utah, to assess sensor performance and the utility of the data for geological mapping in an area of well-exposed diverse rock and alteration types. Their assessment of coherent noise and identification of the low output channnels agrees well with results obtained by the AVIRIS project. To avoid contamination by the low output channels, they chose to work with raw data processed without spectral resampling, and a modified dark current subtraction approach was taken to avoid introducing errors due to the offset shifts noted above. Also, a Gaussian notch filter was successfully applied to remove some of the major noise components. SNR was calculated on a bright hardpan target after these corrections and found to be generally lower than those reported by the project at the start of the flight season, which is in agreement with post-flight season laboratory verification of the overall drop in SNR by the end of the summer. To assess the spectral content of the data, several analysis approaches were used including those associated with the JPL-developed Spectral Analysis Manager (SPAM) software, and standard image processing and enhancing techniques such as band ratioing, band averaging, and principal components analysis. Mixed results were obtained: Data from spectrometers A and C were adequate for identifying iron-oxide-bearing rocks, but poor SNR in spectrometer D limited the ability to discriminate and identify hydroxyl-bearing rocks and minerals or differentiate carbonate minerals, although the major absorption features associated with these materials were resolved.

The study by Mustard and Pieters (1988) was limited by the fact that AVIRIS missed the prime area in their test site, although useful field studies were conducted to pave the way for future AVIRIS data collection when the sensor is returned to operations with improved performance. The test area is the Kings-Kaweah ophiolite melange in east-central California, which is thought to be an obducted oceanic fracture zone. The eventual goal of the study is to map the distribution and abundance of key mineral components in the melange with AVIRIS to determine the importance of geological processes which are responsible for the formation of fracture zone crust.

Wetland vegetation near San Francisco was the target of interest to Gross et al. (1988) in their assessment of AVIRIS data utility. Using SPAM to analyze JPL-radiometrically corrected data, they concentrated their efforts in the 0.4 to 1.72 µm region, ignoring the spectral region covered by spectrometer D because of low SNR. Averages of 5 by 5 pixels were generally used in constructing spectral curves from the data. Their results suggest that despite low SNR, it is possible to detect differences in the position of the red edge, and that there may be several narrow spectral regions between 0.4 and 1.72 µm where amplitude and slope variations for various vegetation types are sufficiently different to enable them to be distinguished. These include the 0.76-0.77, 0.80-0.84, 1.04-1.09, 1.29-1.33, 1.50-1.52, and 1.57-1.65 µm regions.

Carrere and Abrams (1988) chose the Goldfield Mining District of western Nevada for their test area because of the large suite of hydrothermal alteration minerals in a well-mapped and well-exposed setting. They worked with raw data, correcting them for dark current variations and detector readout delay with software written for that purpose. Atmospheric correction was achieved by applying the flat field technique using a 9 by 9 pixel average from the spectrally bland and spatially homogeneous Chispa andesite as reference. Unambiguous kaolinite and alunite spectra were obtained from the processed data and verified through field and laboratory work. Poor SNR prohibited the production of mineral and alteration zone maps with the techniques available with SPAM or with ratio or clustering techniques, however. Assessment of several aspects of sensor performance was also conducted, including long-period drift in instrument response over a several minute duration flight line, sudden steps in scene brightness, noise, SNR, and spectral resolution. Their findings on in-flight performance are in good agreement with other results presented at the workshop.

Crowley et al. (1988) studied AVIRIS data quality at the rare-earth-element-bearing carbonatite complex at Mountain Pass, California, a site well-suited for assessment of spectral and radiometric performance because of the presence of minerals with very narrow and deep absorption features, and a large homogeneous, spectrally bland playa and other targets for field calibration. They derived SNR estimates that were in general agreement with the pre-flight season values tabulated earlier in this paper, and characterized periodic noise at several frequencies having strong horizontal and weak vertical, and horizontal only frequency dependencies. Two procedures were used to correct for atmospheric and solar irradiance effects, the flat field and single spectrum techniques. The single spectrum technique consists of dividing a spectrum from a ground target by the corresponding radiometrically calibrated but otherwise uncorrected AVIRIS spectrum, and applying the resulting set of scalars for each spectral channel to the rest of the AVIRIS image. The 3 rare-earth (neodymium) narrow absorption features between 0.7 and 0.94 µm, as well as features due to CO_3 and Al-OH were clearly observable in the processed spectra.

Green et al. (1988), in a parallel but largely independent study of the same area used the rare-earth as well as atmospheric absorption features to qualitatively determine in-flight spectral bandwidths and positions, and used the LOWTRAN 7 atmospheric code in conjunction with measurements of atmospheric optical depth and reflectance of Ivanpah Playa and other ground targets, all obtained near the time of overflight, to assess in-flight SNR. Using field-measured reflectance data from the Playa, an asphalt and a graded soil target, an empirical line correction was applied to the data to compensate for solar, atmospheric and instrumental factors. Using the concurrently acquired surface and atmospheric measurements, an improved spectral calibration was performed. Radiometric calibration was done using LOWTRAN 7 modelled radiance over Ivanpah. From these data, shifts in spectral alignment of spectrometers B, C and D were found respectively, of 4 nm and 1 µm toward the blue, and 3 nm toward the red. The spectral bandwidths of spectrometers A and B were found to have broadened to 15 and 17 nm respectively. SNR over Ivanpah Playa normalized to the AVIRIS reference radiance model was found to be lower for spectrometers A and B than measured in the laboratory pre-flight season calibration, which is consistent with the fact that the optical fibers to these spectrometers were detached at the time of the flight, while the in-flight SNR for spectrometers C and D was roughly equivalent to that measured pre-flight in the laboratory. A comparison of the geometric quality of the AVIRIS imagery was also made relative to a Landsat Thematic Mapper image of the same area. AVIRIS clearly resolves more spatial detail on the surface while showing excellent intra-image geometry. Finally, the neodymium absorption features between 0.7 and 0.94 μm were unambiguously resolved.

SENSOR PERFORMANCE IMPROVEMENTS

Efforts are under way to improve the performance of AVIRIS for the next field season. The 2 major thrusts in performance improvement are (1) increase in SNR and (2) improved radiometric response stability. Table 4 lists the areas of work and the aspect or aspects of performance that are targeted for improvement.

The first 7 items in Table 1 were completed and the instrument was tested in the laboratory over the summer of 1988, and in-flight in early September, 1988. The results were encouraging: The instrument radiometric response functions were significantly more stable than during the 1987 flights, although anomalies were observed which it is hoped may be partially mitigated by item number 9; signal levels generally were the highest yet achieved from the instrument and matched the modelled levels for all but spectrometer D which, because of the aberrations inherent in its design, has a larger spot size than the other spectrometers, resulting in signal loss off the detectors; and, there was a general improvement in noise, especially coherent noise, which was

Table 4. AVIRIS project activities directed at improving sensor performance.

	Engineering Activity Undertaken	Performance Issue(s) Addressed
1.	Improve spectrometer thermal controllers	Stabilize radiometric response function and spectral alignment
2.	Kinematically mount spectrometers to rack	Reduce heat flow and vibrations from rack and mitigate effects of rack warpage on alignment
3.	Improve optical fiber package	Minimize chance of future defocus of instrument
4.	Implement new fiber positioners	Facilitate optical alignment - maximize signal levels

Table 4. (contd)

	Engineering Activity Undertaken	Performance Issue(s) Addressed
5.	Remove KDP filter from spectrometer B	Stabilize radiometric response function
6.	Realign foreoptics	Minimize vignetting
7.	Build new pre-amplifier and clock driver boards	Stabilize signal chain performance and reduce noise
8.	Repackage detector drive logic	Reduce signal chain noise
9.	Remove delrin rod between dewar mount and spectrom.	Stabilize spectrometer alignment

greatly reduced from the levels seen early in the 1987 flight season. However, overall, there was only a modest improvement in SNR as a result of reduced coherent noise and much more stable signal chain electronics performance. After the in-flight testing in September 1988, additional experiments were conducted in the laboratory which showed that (1) signal chain packaging was responsible for much of the remaining system noise, and (2) the delrin rod that is the mechanical interface between each dewar mounting assembly and the spectrometer body is not sufficiently rigid for that application, allowing some movement of the dewar under various conditions that exist in both the lab and flight environments. These rods are being replaced with aluminum. The signal chain packaging was implicated as a noise source through substitution testing of each spectrometer with the breadboard electronics, which when substituted for the flight electronics on the instrument rack, gave noise levels that were 2 to 4 times lower. As a weight saving strategy to meet the requirements for flying on the NASA U-2 aircraft, the detector drive logic was originally packaged in the same box with other logic circuitry using a common power supply and master clock. Moreover, because of its size, the box is located at the other end of the AVIRIS rack from the spectrometers, requiring long electrical cables which are susceptible to noise pick up. The weight constraints of the U-2 have been relieved now that the last of the U-2s has been retired and replaced with the more capable ER-2, so the detector drive logic is being repackaged with its own power supply and clock and located much closer to the spectrometers to minimize cable length. It is hoped that this will result in a significant noise improvement. The engineering team plans to finish the work in the Spring of 1989 and verify in-flight performance with another field calibration experiment.

SUMMARY

Judged by most criteria, the 1987 flight season and performance evaluation effort were successful in meeting the objectives of assessing data quality and sensor performance. The results of the evaluation by the AVIRIS project and the independent performance evaluation investigators provided the engineering team with a great deal of information needed to bring AVIRIS performance to its desired levels. In spite of degraded data quality over the course of the summer, some exciting scientific results were also obtained from the program, which bodes well for the future of imaging spectroscopy. If the AVIRIS engineering team is successful in its work over the next few months, the enhanced performance of the sensor and the knowledge gained by the members of the earth science community who participated in the 1987 evaluation program should allow us to launch a vigorous and exciting new phase of earth remote sensing.

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