Recent Improvements to the AVIRIS Sensor: Flight Season 2000

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1.0 INTRODUCTION

The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998) has undergone many modifications and upgrades over the years, resulting in performance far exceeding original expectations. Descriptions of these modifications have appeared periodically in the literature (Chrien et al., 1991, 1992, 1993; Porter et al., 1990; Sarture et al., 1995). This paper describes recent modifications to the instrument over winter maintenance cycles not covered elsewhere, and discusses the rationale leading up to the changes, implementation, and results.

Modifications to focal plane arrays include optimized photodiode arrays in the “A” and “B” focal plane detectors, a new linear-variable blocking filter for the “D” focal plane array (FPA), and new FPA multiplexers. A short history of focal plane multiplexer improvements is also provided for completeness as well as a brief discussion of a multiplexer transient-response anomaly that can cause apparent pixel “smear” for low-light scenes and features. Modifications to spectrometers for improved stability include a new spectrometer thermal stabilization approach, Dewar-to-spectrometer support struts, new Invar-36 cold-finger support structures inside the Dewars, and a switch in the “A” FPA operating temperature from 77 kelvins to room temperature. The results from these changes have also provided evidence which suggests a dominant source of the “bumps and wiggles” spectrometer response variations. A new spectral characterization and calibration capability has been added to on-board calibrator. A dedicated GPS/INS subsystem has been added to AVIRIS to provide sufficiently accurate position and pointing information for image georectification.

2.0 FOCAL PLANES

MULTIPLEXERS

Improvements to the focal planes cover five areas: multiplexer upgrades, modest signal chain noise reductions, photodiode array material optimization, blocking filter improvements, and an operating temperature change for the silicon array.

Multiplexer upgrades are responsible for a major contribution to AVIRIS signal-to-noise ratio (SNR) improvement over the past five years. In 1987, AVIRIS SNR suffered from system noise contributions that were largely mitigated by 1989. In 1990 the FPA signal chains were redesigned, allowing further improvements to be squeezed out of the original Reticon multiplexer-based FPAs over the following few years. From 1990 to 1994 the performance was incrementally teased higher, reaching a practical read noise limit of 1600 electrons for these capacitive discharge mode source-follower multiplexers in 1994.

In 1993 we undertook the development of a new multiplexer, and several candidate designs were fabricated and tested (Niblack et al., 1993). During the 1994-1995 winter maintenance cycle AVIRIS received FPAs with a new Buffered Direct Injection (BOI) multiplexer. These multiplexers offered a read noise floor near 800 electrons, but also came with a transient response artifact. This artifact (called by the term “slew”) was investigated and deemed to be photoelectrons left over from a high-photon-flux integration period’s readout getting collected by subsequent low-photon-flux integration periods, and artificially raising the signal level. Low unit cell amplifier open-loop gain and premature injection field-effect transistors (FET) shutoff were deemed the likely culprits behind this phenomenon. AVIRIS flew in 1995 with this slew artifact mitigated somewhat through careful adjustment of various multiplexer bias voltages.

Further study showed that the effect of the slew artifact could be minimized by adding a small amount of background flux to the spectrometer signals. Hence, in 1996 AVIRIS flew with subminiature tungsten bulbs providing a diffuse polychromatic light field at the FPAs to raise the signal level slightly and keep the injection FET from shutting off at low signal levels and “stranding” photocarriers on the photodiode capacitance. A development effort began in 1995 to address this anomaly using JPL’s very large-scale integration (VLSI) FPA multiplexer design expertise (Pain et al., 1998).

By 1997 we were ready install into AVIRIS FPAs upgraded with the JPL multiplexers. These “muxes” had improved unit cell amplifers and injection FETs. They also exhibited reduced slew so they could be used without the inelegant background flux bulbs, and similar noise performance. Read noise floors were 220e- for both “A” and “C,” 400e- for “B,” and 750e- for “D.” AVIRIS flew with these improved multiplexers in 1997 and 1998 while yet another mux redesign effort was mounted to further reduce slew and improve read noise performance.

In 1999 AVIRIS was retrofitted with FPAs that incorporated improved BDI multiplexers which contained a unit-cell amplifier with much higher open-loop gain [2]. The resulting FPA SNR performance for A and D was approximately 30% better than the previous FPAs, and the transient response showed marked improvement. The SNR performance for C was offset by the inadvertent use of a non-optimal InSb array with the improved multiplexer. Performance for B was vastly improved by a combination of effects described in the next section.

BLOCKING FILTERS

Blocking filter modifications also contributed significantly to overall system SNR improvements in the past decade. In 1993 filters with improved transmission boosted performance for B, C, and D. SNR performance for D received another boost in 1998 for D when a custom linear variable blocking filter (LVBF) was incorporated.

The D blocking filter prior to 1998 had a passband from 1720 to 2570 nm, hence a significant amount of 300-kelvin blackbody flux from the spectrometer fell on the entire array, raising the noise floor from near 220 electrons to 750 electrons. Clearly, if the flux for a given detector pixel could be limited to only the 10 nm FWHM passband required, a significant reduction in read noise could be achieved. Unfortunately, the fast f/1 spectrometer and filter-to-array distance forced specification of a passband wider than the nominal 10 nm spectral bandwidth for D. A custom LVBF was designed and fabricated by OCLI to JPL specifications. Figure 1 shows two representative LVBF passbands superimposed on the previous filter passband.

The noise across the LVBF D FPA varied as anticipated, with the exception of higher background and noise at the 2500 nm end as seen in Figure 2. This is caused by the LVBF passband allowing flux beyond 2570 nm to reach the end pixels of the array, since the LVBF fabrication process cannot make an abrupt stop in the dispersion of the filter. The inclusion of a long wavelength cutoff layer would complicate the design and impact the overall transmission, but could eliminate this unwanted flux. Overall, the improvement provided by the new filter is significant over most of the D spectral range, as seen in Figure 3.

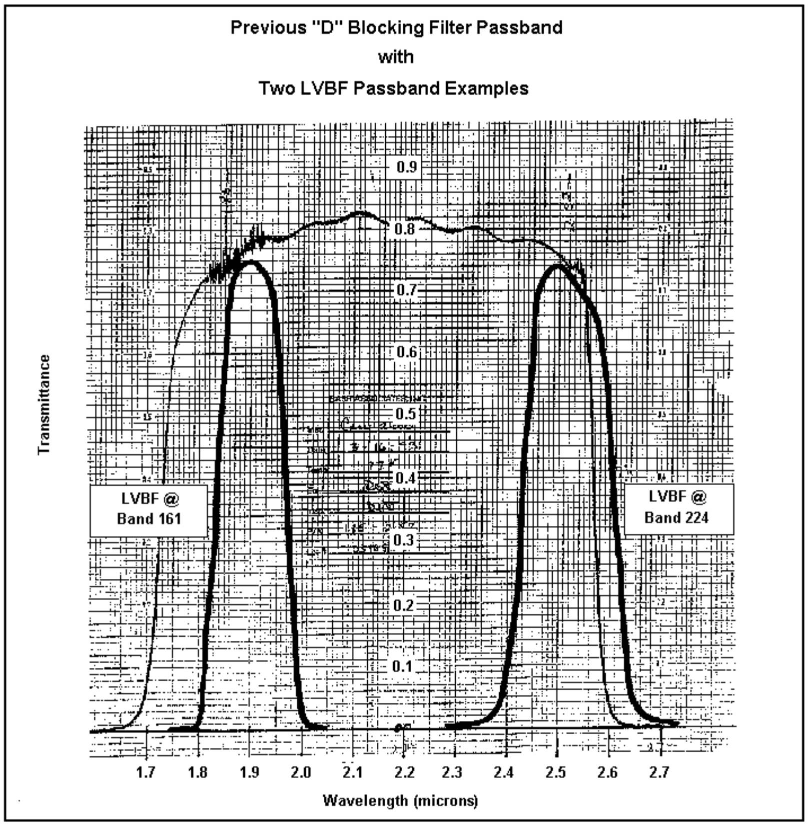

Figure 1. Representative Linear Variable Blocking Filter passbands compared to previous D cold blocking filter passband.

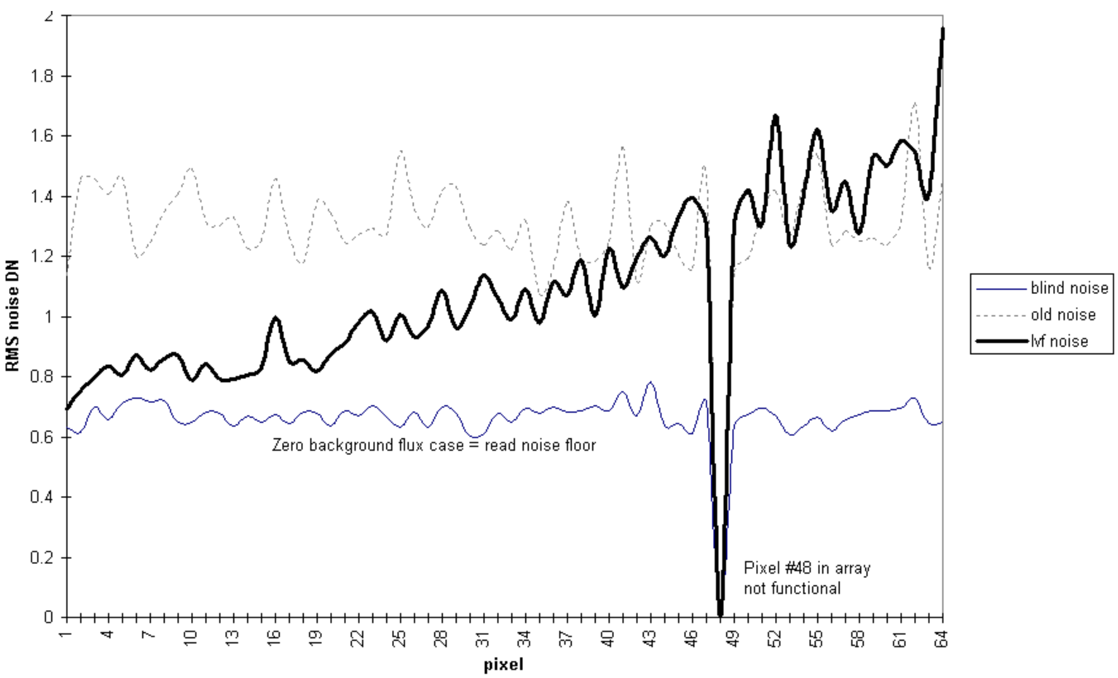

Figure 2. D FPA noise levels for cold-blind case, 1997 passband blocking filter lab bench case (on-AVIRIS noise level 30% higher), and Linear Variable Blocking Filter background-reduced case.

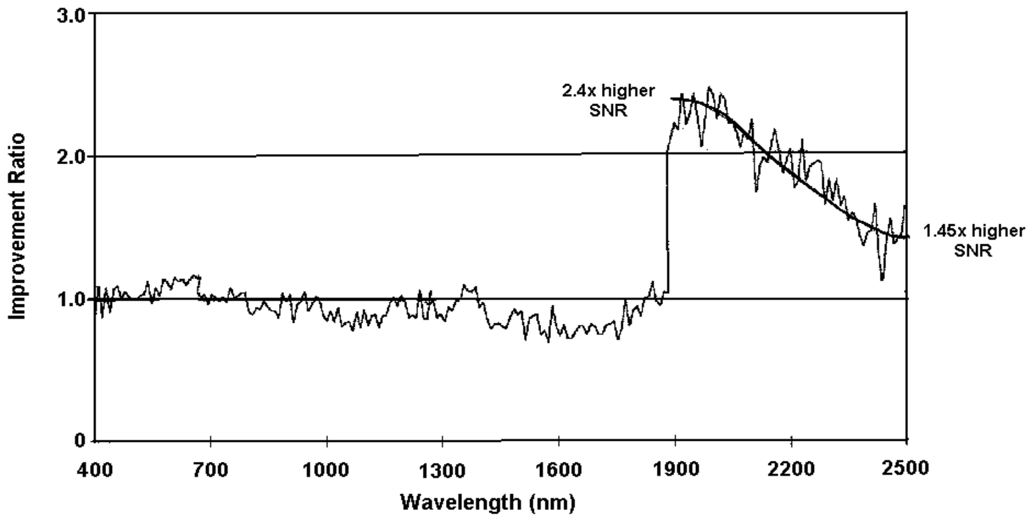

Figure 3. Ratio of 1998 to 1997 AVIRIS pre-season laboratory signal-to-noise performance showing combined effect of new linear variable blocking filter, plus system grounding noise reduction.

PHOTODIODE ARRAY MATERIAL OPTIMIZATION

Both B and D FPA performance had been limited by spectrometer 300 K blackbody background flux. Unlike the D case, the passband spectral range and blocking wavelength range requirements conflicted, and made fabrication of a shorter-cutoff passband filter or a more ambitious LVBF impossible. Since the InSb detector material is sensitive out to 5.5 µm, some form of blocking is imperative. The original AVIRIS design included a KDP filter in the stack, but this material was prone to crack during cooldown so was eliminated early in the program. Until the multiplexer performance improved in the mid-90s, this excess background flux was never noticed.

Switching from a thin-film filter for B to a simple absorbing glass filter combination (1.5 mm thick Schott RG-65 with 1.5 mm thick PK-50) improved the transmission markedly, but did not significantly reduce the background flux. It became clear that the most straightforward way to eliminate the effects of this flux was to switch to a detector material insensitive to it. InGaAs appeared an ideal candidate with a long wavelength cutoff of 1600 nm at 77 K. However, short wavelength response of InGaAs is poor due to absorption of the InP cap layer. Half of the B spectral range is within silicon's spectral range, so a hybrid array of 30 silicon pixels butted to 34 InGaAs pixels would cover the B spectral range with a butting gap in the 940 nm water band. The silicon array was fabricated by UDT Sensors, and the InGaAs array by Sensors Unlimited. They were packaged and wirebonded to the multiplexer by Cincinnati Electronics.

The silicon portion of the "Hybrid B" array had surprisingly high signal response, likely a combination of the optimization of its SiN AR layer for 770 nm and carrier diffusion effects. It appears possible that light previously not collected in the InSb array's active area could now be absorbed by the silicon outside a pixel's active area and still diffuse into the junction region and be collected. We clearly see diffusion effects on the effective FWHM of the spectrometer, and the effect grows with longer wavelength. The photon penetration depth for silicon depends upon wavelength, and the deeper the photon is absorbed, the higher the likelihood it can be collected by an adjacent pixel's junction. The aligned spectrometer exhibited FWHM variation across the silicon array segment from 9.5 nm FWHM at 665 nm up to 11.41nm FWHM at 923 nm. The improvement in the performance of the B spectrometer is shown in Figure 4.

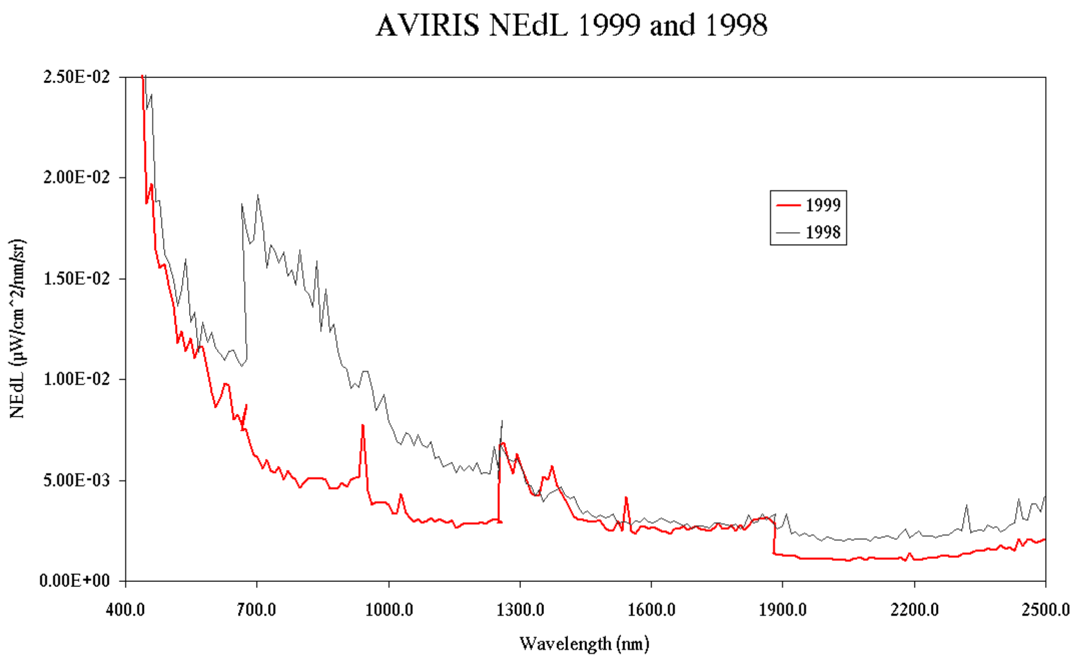

Figure 4. AVIRIS NEdL improved dramatically in the B range due to the combination of an optimized hybrid silicon + InGaAs photodetector array and the improved multiplexer performance. C did not improve due to the inclusion of non-quantum effect (QE)-optimized InSb in the reworked C FPA.

"A" FPA OPERATING TEMPERATURE

The throughput of the AVIRIS optical system is lowest in the spectral region from 370 to 450 nm. Also, the solar flux is decreasing at this end of the sun's blackbody curve. These factors combine to make the blue-end performance of the silicon array in A critical. Operating the silicon array at 77 K sacrifices short-wavelength response, so beginning in 1996 this FPA was operated at ambient temperature, improving response in the blue by 50%. This had the additional benefit of eliminating spectrometer alignment and response variability arising from cryogenic operation. Later sections will discuss this serendipitous benefit in more detail.

Summary of focal plane multiplexer, photodiode array, and cold blocking filter history

1987–1994	Reticon mux FPAs, original blocking filters, all FPAs at 78 K
1993	Upgraded to "blue-enhanced" UDT silicon array
1993	Replaced thin-film B with absorbing glass cold filter: 1.3x to 1.5x improvement
1993	Upgraded to new C thin-film cold filter: 1.05x to 1.3x improvement
1993	Upgraded to new D thin-film cold filter: eliminated light leakage
1994	Read noise floor reduced to approx. 1600 electrons
1995	BDI #1 muxes first flown: read noise floor reduced to approx. 800 electrons
1995	Upgraded to larger rectangular pixel InSb array for D: more flux on pixels, FWHM at 10 nm
1996	Background flux added in spectrometers to minimize slew – this year only
1996	Changed to A operating warm: approx. 1.5x improvement at blue end
1997	JPL BDI #1A mux first flown: read noise floor reduced to 220 electrons, B and D background shot noise limited

1998	Linear Variable Blocking Filter for D: 1.45x to 2.4x improvement
1998	JPL BDI #3A mux first flown: 1.3x improvement, less slew
1999	"Hybrid B" silicon + InGaAs array first flown: 1.3x to 2.6x improvement
2000	400 nm-optimized UDT silicon array: 1.4x to 2.4x improvement at blue end

3.0 SPECTROMETERS

To cover the spectral range from 400 nm to 2500 nm, AVIRIS uses four spectrometers. To obtain high signal throughput the spectrometers are designed with f/1 optics that focus the dispersed light on 200 by 200 µm area detectors. From an alignment perspective, holding the dispersed light on the detectors at the 1-percent level requires spectrometer plus FPA mechanical stability of 2 µm over all time scales up to an AVIRIS flight season of 8 months. This is a difficult requirement that was not fully appreciated when AVIRIS was designed. In 1995 the AVIRIS on-board calibrator was modified to include a silicon diode feedback-stabilized source. Analysis of data from the onboard calibrator revealed perplexing radiometric changes. Figure 5 shows a plot of consecutive spectra from the onboard calibrator ratioed to the first measurement. These "bumps and wiggles" are attributed to not achieving the 2-µm stable mechanical alignment in the AVIRIS spectrometer focal plane subsystem.

Since 1995, the AVIRIS onboard calibrator signal is used to suppress these bumps and wiggles in the data delivered to the investigator. However, it is preferable to not have these artifacts present in the AVIRIS instrument at all. One early hypothesis was that the spectrometer structure was warping and changing with respect to the liquid nitrogen Dewar that holds the AVIRIS detectors. In laboratory tests it was shown that slight pressure on the Dewar could induce bumps and wiggles. In 1996, to address this concern a set of Invar struts were designed and built to tie the top of the Dewar rigidly to the spectrometer structure. This greatly reduced the likelihood that the AVIRIS spectrometers would be bumped out of alignment, but did not significantly reduce the bumps and wiggles artifact.

The next hypothesis was that parts of the spectrometers not connected to the struts could be warping with changes in temperature. Thermal gradients were applied to AVIRIS in the laboratory and bumps and wiggles were induced in the data. In 1998, to address thermal stability, a 32-zone heater controller was purchased for AVIRIS. Eight zones for thermal control where established on each of the four AVIRIS spectrometers. They accurately controlled the thermal state of each spectrometer, but the bumps and wiggles were still present in the data, albeit at an arguably lower level.

At this point the focus shifted to the internal structure of the liquid nitrogen Dewar that holds the detector arrays in place relative to the Dewar/spectrometer interface. The 1992 vintage dewar design used a G-10 fiberglass cylinder to support and thermally isolate the FPA cold finger. It was hypothesized that the G-10 cylinder could shift due to thermal gradients from the inner 77 K LN_2 reservoir to the outside neck of the Dewar. In 1999 the G-10 fiberglass cylinder was replaced with 304 stainless steel. Unfortunately, this did not significantly reduce the bumps and wiggles (but did indeed reduce the LN_2 hold time). Based on subsequent thermal analysis we suspected the thermal gradient profile along the stainless cylinder slowly and continuously changed over time from the moment of cryogen filling, thus imparting a continuous shrinkage of its length. This shrinkage would continuously change the position of the FPA with respect to the spectrometer focus. The expression of AVIRIS bumps and wiggles in 1999 is shown in Figure 6.

Since thermal contraction appeared to be the source of instability, new cylinders were fabricated from Invar-36, which has a coefficient of thermal expansion ten times smaller than

304 stainless. For the 2000 flight season, these Invar-36 components were installed in the Dewars. Figure 7 shows a plot of consecutive data acquisitions from a laboratory light source ratioed to the first. This is a vast improvement to the AVIRIS spectrometer's stability, and promises to allow effective analysis of more subtle phenomena in the future.

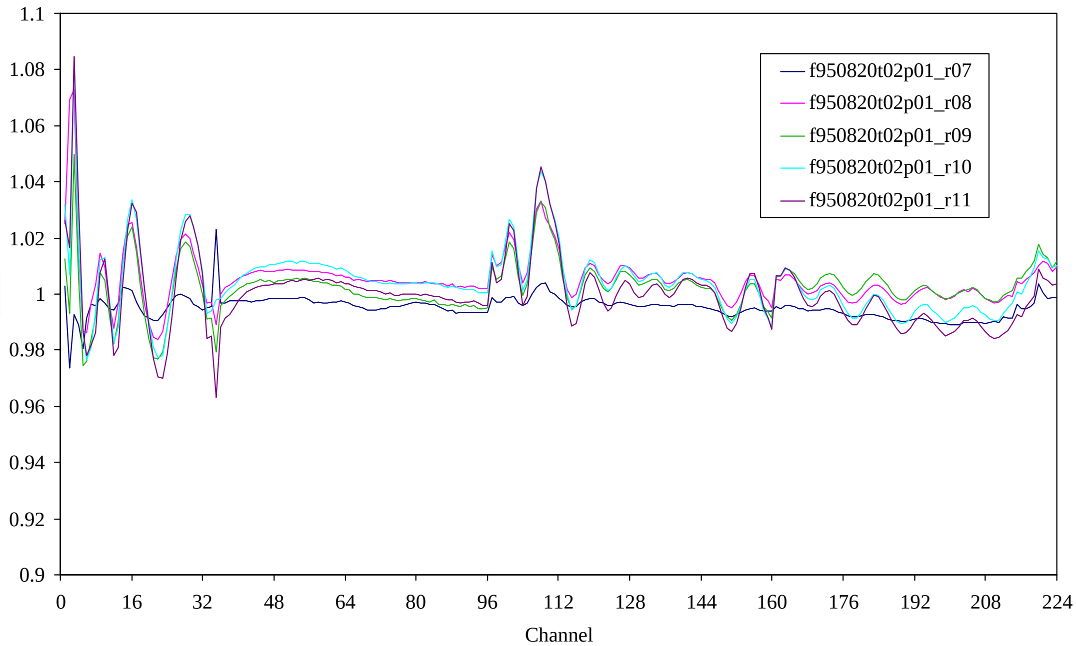

Figure 5. Ratio of consecutive measurement from a stable source to the first measurement for a series of AVIRIS data sets in 1995.

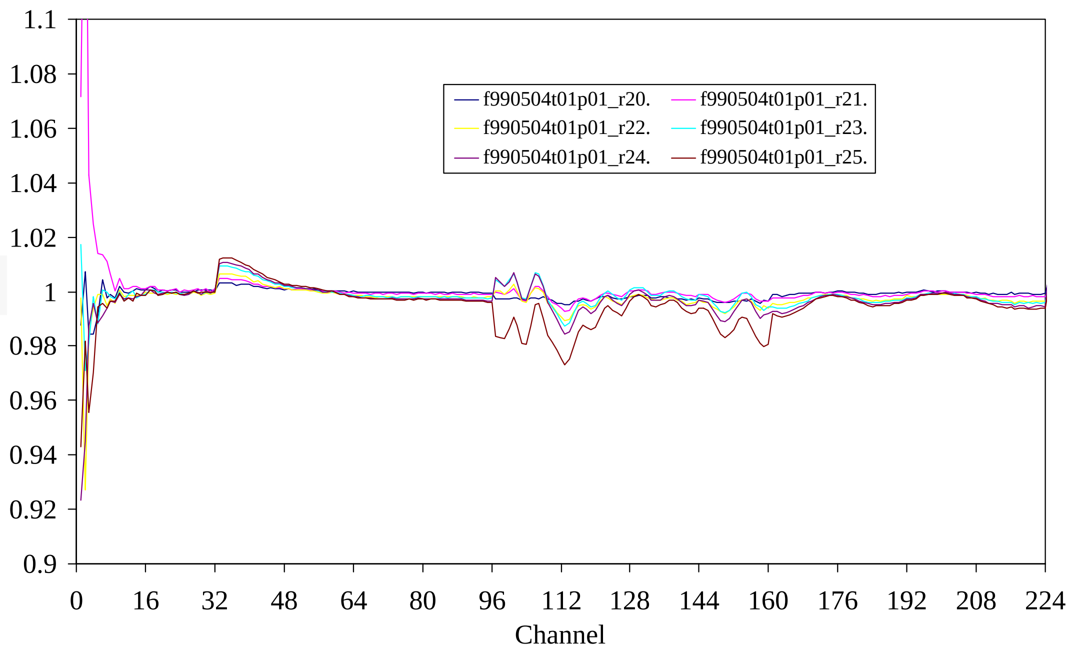

Figure 6. Ratio of consecutive measurement from a stable source to the first measurement for a series of AVIRIS data sets in 1999.

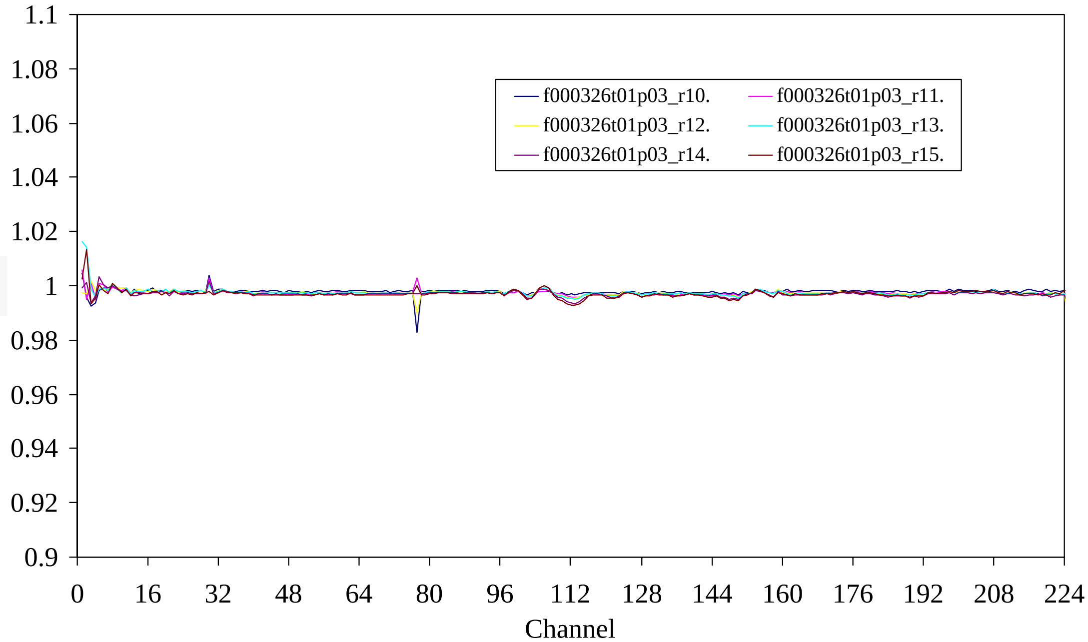

Figure 7. Ratio of consecutive measurement from a stable source to the first measurement for a series of AVIRIS data sets in 2000.

4.0 ON-BOARD CALIBRATOR SPECTRAL SIGNAL

The AVIRIS on-board calibration (OBC) has been designed to have both a radiometric calibration and a spectral calibration capability (Chrien et al., 1995). The spectral filters within the OBC were included to provide a monitor of changes in AVIRIS spectrometer spectral calibration. Actual use of these data has been limited because of incomplete knowledge of the fine structure associated with the thin-film-filter absorption bands, its variation over the solid angle used in the OBC, and how these factors interact with the near-Gaussian bandshapes of AVIRIS' spectral response functions. The current OBC architecture uses the backside of a two-bladed rotating shutter. The stabilized OBC tungsten bulb flux is fed from the OBC to the fiber common end inside the foreoptics, and shines on the backside of the foreoptics shutter during the pre-run and post-run calibration data phase of each collection. The OBC is temperature controlled for stability (Faust et al., 1998). Both sides of the shutter are used for each measurement, and heretofore have been averaged together.

In 1999 a proposal was made to coat the backside of one blade with a spectrally featureful material that would provide a better source of spectral information. Nd_2O_3 powder has numerous spectral features in the AVIRIS spectral range, making it an ideal candidate for an internal reflectance standard. The backside of the foreoptics shutter was painted with a suspension of Nd_2O_3 powder in Nusil Industries CV1144 silicone adhesive. One half of the shutter disc was left uncoated. The ratio of the coated to uncoated sides of the shutter provide a useful spectral calibration signal. Figure 8 shows a plot of this ratio. The stability of the spectral features will be used to track the spectral calibration of AVIRIS through the flight season.

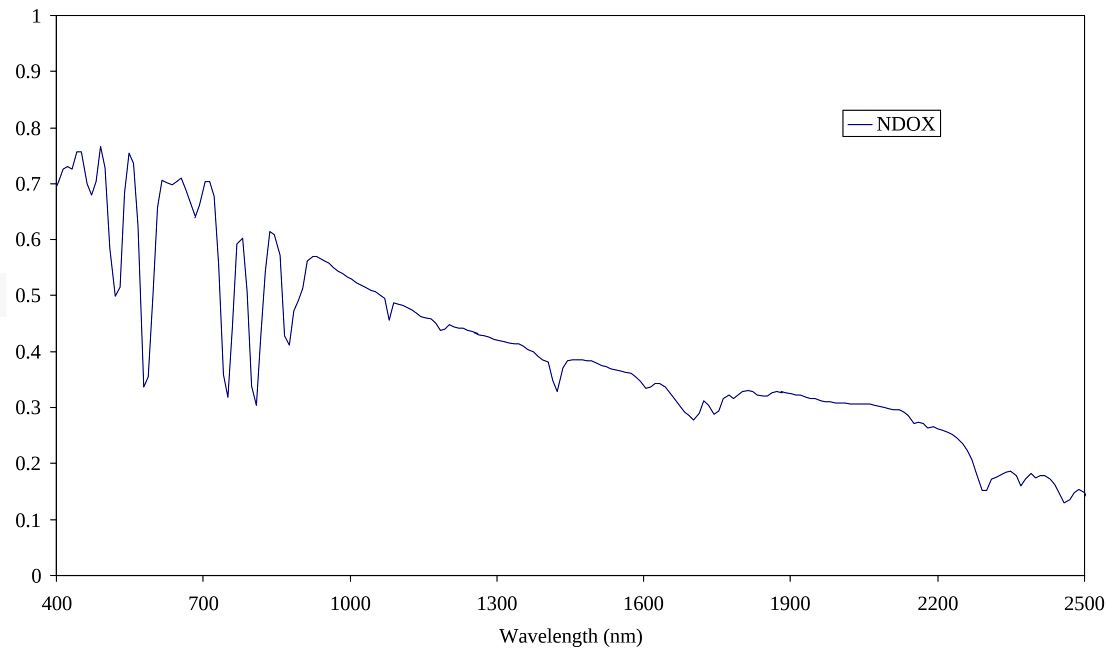

Figure 8. Ratio of the NdOx-coated side of the AVIRIS foreoptics shutter to the uncoated side. This is the spectral calibration signal of the AVIRIS onboard calibrator.

5.0 POSITION AND POINTING KNOWLEDGE

AVIRIS is an imager as well as a spectrometer. The primary focus of the engineering efforts with AVIRIS has been on the spectrometer side of this duality. However, to analyze AVIRIS data, some information is required on where the AVIRIS data were acquired. This information has been provided in the AVIRIS navigation file delivered with every AVIRIS data set. The source for the contents of the navigation file has changed over time. In the period from 1987 to 1998 AVIRIS received aircraft position and pointing information from the ER-2 aircraft. From 1987 to 1994 this information came from a radio updated Inertial Navigation System (INS). From 1995 to 1998 the position and pointing information came from the aircraft INS and Global Positioning System (GPS) data stream. This position and pointing information was provided to the investigator with each AVIRIS data set. A major drawback of this information was that it was the aircraft position and pointing that was reported. The AVIRIS sensor contained an automatic roll correction of ±1.5 degrees for each scan line. This was a fast analog subsystem in AVIRIS and the amount of roll correction applied to each scan line was not recorded. This introduced a ±1.5 degrees roll uncertainty in the position and pointing information. The uncertainty could be greater if the aircraft exceeded ±1.5 degrees and saturated the roll correction subsystem. In 1998 the automatic roll correction subsystem was turned off and an integrated INS/GPS called the CM-2 bolted onto the AVIRIS sensor. The CM-2 provides GPS position updates every 1 second and INS pointing updates every 0.1 seconds. A combined, filtered position and pointing update is provided every 0.1 seconds. The accuracy of the position information was ±100 meters using the GPS civilian mode. The pointing accuracy is better than 2.5 milliradians. In both cases the update-to-update precision is much better than the accuracy. Position and pointing information from CM-2 is now provided with AVIRIS data sets. For AVIRIS data acquired on the low altitude aircraft (Sarture et al., 1998) this CM-2 information is used to provide a georectification of the data. Figure 9 and Figure 10 show the result of use of

CM-2 position and pointing information for georectification of AVIRIS data (Boardman, 1999). For all future AVIRIS data collected both from the high altitude and the low altitude airborne platforms CM-2 data will be provided.

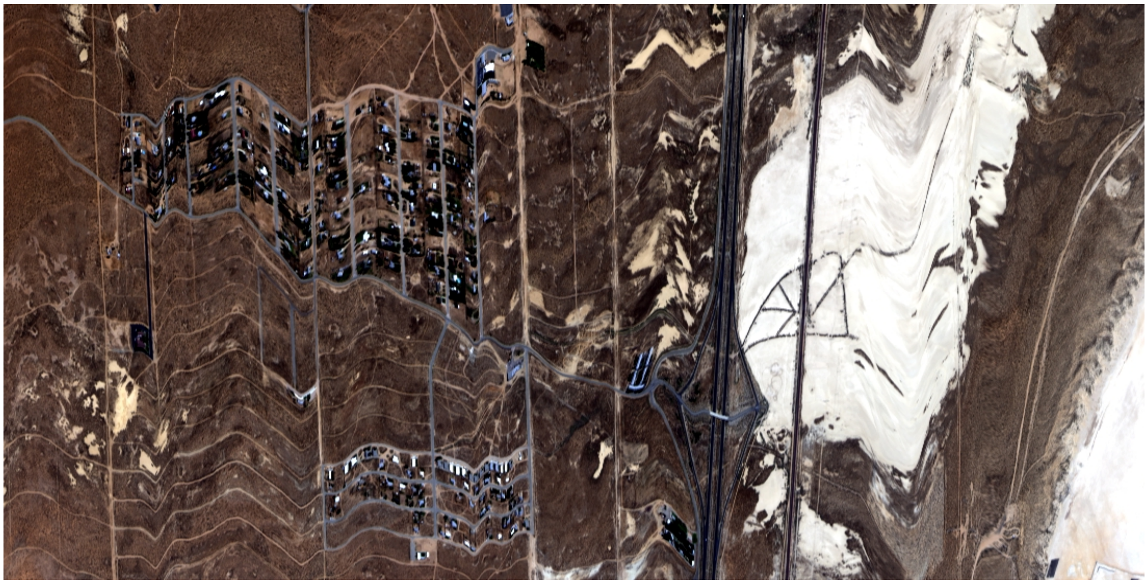

Figure 9. Ungeorectified AVIRIS low-altitude data acquired in 1998.

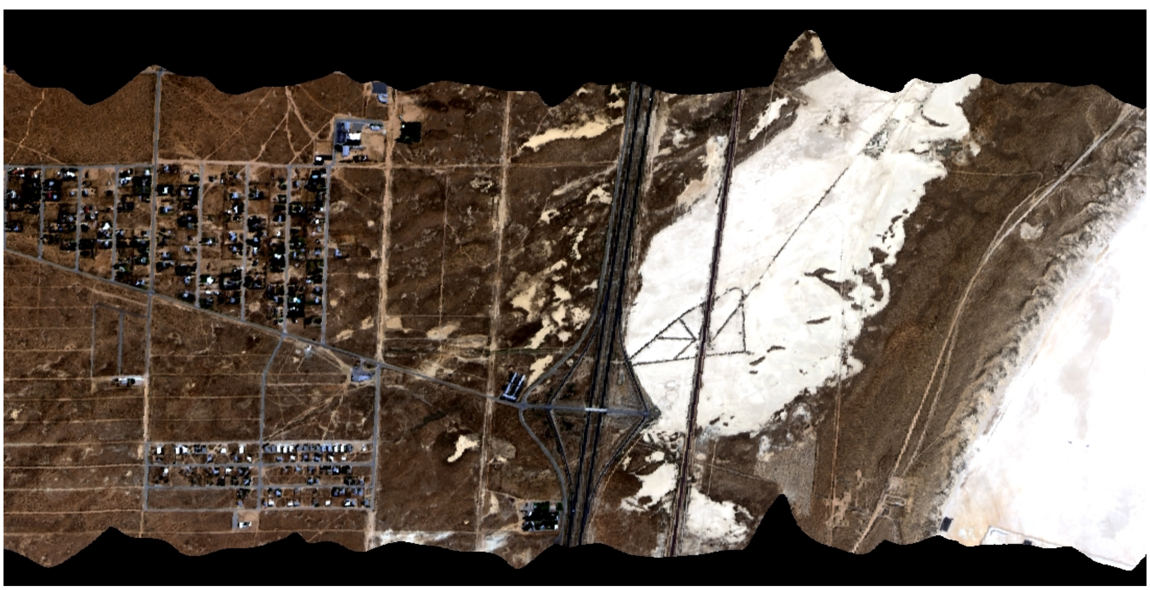

Figure 10. AVIRIS 1998 low-altitude data georectified with CM-2 position and pointing data.

6.0 CONCLUSION

The AVIRIS sensor has been upgraded and improved in every year since the first flight in 1987. This paper has described significant upgrades to the AVIRIS focal planes, spectrometer, onboard calibrator, as well as pointing and position subsystems. Upgrades to the focal planes have improved the AVIRIS SNR. Upgrades to the spectrometers have improved AVIRIS stability at all time scales up to the 8-month AVIRIS flight season. Upgrades to the spectral signal from the on-board calibrator will help monitor and improve AVIRIS spectral calibration. Upgrades to the position and pointing information provided by AVIRIS support advance georectification and geolocation of the AVIRIS data and derived products. The overall results of these upgrades have been improved quality of the data measured by AVIRIS and delivered to investigators. Pushing the performance of AVIRIS forward fulfills two objectives. First, the improved quality of the data enables more advanced science research and applications to be pursued. Second, the improved performance establishes a baseline to which other sensor may be designed to and specified with respect to. Plans are in place for upgrades of the AVIRIS onboard computer and onboard calibration subsystem for the 2001 flight season.

7.0 REFERENCES

Boardman, J. W., "Precision Geocoding of Low-Altitude AVIRIS Data: Lessons Learned in 1998," Proc. Eighth Airborne Earth Science Workshop, Jet Propulsion Laboratory, JPL Pub. 99-17, Vol. 1, 1999.

Chrien, T. G.; M. L. Eastwood, C. M. Sarture, R. O. Green, W. M. Porter, "Current Instrument Status of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," Proc. of the Third AVIRIS Workshop, JPL Pub. 91-28, 1991.

Chrien, T. G., "AVIRIS: Recent Instrument Maintenance, Modifications and 1992 Performance," Summaries of the Third Annual JPL Airborne Geoscience Workshop, JPL: Pasadena, California, 1992.

Chrien, T. G.; R. O. Green, C. M. Sarture, C. Chovit, M. L. Eastwood, B. T. Eng, "Airborne Visible/Infrared Imaging Specrometer (AVIRIS): Recent Improvements to the Sensor," 1993.

Chrien, T. G; M. Eastwood, R. O. Green, C. Sarture, H. Johnson, C. Chovit, P. Hajek, "Airborne Visible Infrared/Visible Imaging Spectrometer (AVIRIS) Onboard Calibration System," Proc. of the Fifth Annual JPL Airborne Earth Science Workshop, Jan 23–26, 1995.

Niblack, C. A., M. A. Blessinger, A. P. Westrick, M. L. Eastwood, C. O. Staller, "Multiplexed focal plane array upgrade for the AVIRIS instrument," SPIE Proceedings Vol. 1946, pp.341–348, 1993.

Faust, J.; M. Eastwood, C. Sarture, O. Williams, "Thermal Stability of the AVIRIS On-Board Calibrator," Proc. Seventh Airborne Earth Science Workshop, Jet Propulsion Laboratory, JPL Pub. 97-21, Vol. 1, 1998.

Green, R. O., M. L. Eastwood, C. M. Sarture, et al., "Imaging spectroscopy and the Airborne Visible Infrared Imaging Spectrometer (AVIRIS)," Remote Sens Environ 65: (3) 227–248 SEP 1998

Pain, B., T. Shaw, M. Eastwood, and R. O. Green, "High Speed Buffered Injection Readout for Airborne Visible and Infrared Imaging Spectrometer (AVIRIS)," presented at SPIE Aerosense Conference 3360, April 1998.

Porter, W. M; T. G. Chrien, E. G. Hansen, C. M Sarture, “Evolution of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Flight and Ground Data Processing System,” Proceedings of the Second Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop., JPL: Pasadena, California, 1990.

Sarture C. M.; T. G. Chrien, R. O. Green, M. L. Eastwood, H. K. Johnson, C. J. Chovit, P. Hajek, J. L. Holbrook, J. J. Raney, M. A. Hernandez, “Airborne Visible/Infrared Imaging Spectrometer (AVIRIS): Sensor Improvements for 1994 and 1995,” Proc. of the Fifth Annual JPL Airborne Earth Science Workshop, Jan 23–26, 1995.

Sarture, C. M.; C. J. Chovit, T. G. Chrien, M. L. Eastwood, R. O. Green, C. G. Kurzweil, “The AVIRIS Low Altitude Option—An Approach to Increase Geometric Resolution and Improve Operational Flexibility Simultaneously,” Proc. Seventh Airborne Earth Science Workshop, Jet Propulsion Laboratory, JPL Pub. 97-21, Vol. 1, 1998

8.0 ACKNOWLEDGMENTS

The majority of this research was carried out at the Jet Propulsion Laboratory, California Institute of technology, under contract with the National Aeronautics and Space Administration. We would like to express our great appreciation for the efforts of the AVIRIS team at the Jet Propulsion Laboratory.