AVIRIS Inflight Calibration Experiment Measurements, Analyses, and Results in 2000

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INTRODUCTION

The NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998a) measures spectra from 370 to 2500 nm with nominally 10-nm sampling and resolution. The spectra are acquired as images with an 11 km width and up to 800 km length from the ER-2 platform or 2.1 km width and 160 km length from the Twin Otter platform. AVIRIS measurements are used for a range of Earth science research and application objectives. The molecular absorption and particle scattering properties expressed in the calibrated AVIRIS measurements are used. For both science research and application objectives, calibration of the AVIRIS spectra is required to produce useful results. Each year prior to the flight season AVIRIS is calibrated in the laboratory (Chrien et al., 1990, 1995, 1996, 2000). However, the temperature, pressure, vibration, and observational geometry, as well as mechanical, electrical and operational interfaces of the laboratory are different than the environment on board the airborne platform. To validate the calibration of AVIRIS in the flight environment, an inflight calibration experiment is orchestrated at the beginning of each flight season (Conel et al., 1988; Green et al., 1990, 1992, 1993, 1995, 1996, 1998b, 1999). In most years additional inflight calibration experiments occur towards the middle and end of the flight season as well. For an inflight calibration experiment, AVIRIS acquires airborne data over a designated calibration target. In concert with the airborne data acquisition, surface and atmospheric properties at the calibration target are measured in situ. These in situ measurements are used to constrain a radiative transfer code and predict the radiance incident at the AVIRIS instrument from the calibration target. This prediction is compared with the AVIRIS-measured radiance to validate the calibration of AVIRIS in the flight environment. Additional properties (such as the AVIRIS inflight measurement precision) are determined as well. This paper presents measurements, analyses, and results from the inflight calibration experiment held on the dry lake bed surface of Rogers Dry Lake, California, on June 5, 2000.

IN SITU MEASUREMENTS

In order to predict the radiance at AVIRIS, in situ measurements of surface and atmospheric properties at the time of the overflight are required. For the experiment of June 5, 2000, a calibration target was designated on the surface of Rogers Dry Lake, California. Rogers Dry Lake is located on Edwards Airforce Base about 120 km north of Los Angeles, California. The target was located near north latitude 34.985 and west longitude 117.833 and was selected as a visually homogeneous portion of dry lake bed surface measuring 40 by 120 m. At each end of the calibration target, blue demarcation tarps were position and staked to the surface. In the period from 30 minutes before to 30 minutes after the AVIRIS over flight, surface reflectance measurements were acquired between the demarcation tarps. A portable field spectrometer that covers the range from 350 nm to 2500 nm with approximately 10 nm resolution and 1 nm sampling was used. The field of view of the spectrometer was 8 degrees or 14 cm diameter for a 1-m observation distance. Sets of spectra were acquired along transects at 0, ±10, and ±20 m of the central line between the demarcation tarps. At the beginning, middle, and end of each transect, a reflectance standard was measured.

Following acquisition, the surface measurements were converted to surface reflectance using the interspersed reflectance standard measurements. The absolute reflectance of the reflectance standard and the corresponding bidirectional reflectance distribution function (BRDF) for the average 20-degree solar zenith angle were used for this reflectance calculation. Figure 1 shows the calculated average reflectance of the calibration target from the 890 surface measurements. Also shown is the standard deviation of the measurements that is roughly ±1 percent reflectance across the spectrum. The standard deviation of the mean (Taylor, 1982) calculated as the standard deviation divided by the square root of the number of samples is less than 0.1 percent across the spectrum. The statistical uncertainty in knowledge of the average reflectance of the reflectance measurements of this calibration target is best characterized by the standard deviation of the mean and is excellent based on the 890 measurements. This average surface reflectance provides the basis for constraining the surface reflectance used in the radiative transfer code prediction of the radiance incident at AVIRIS.

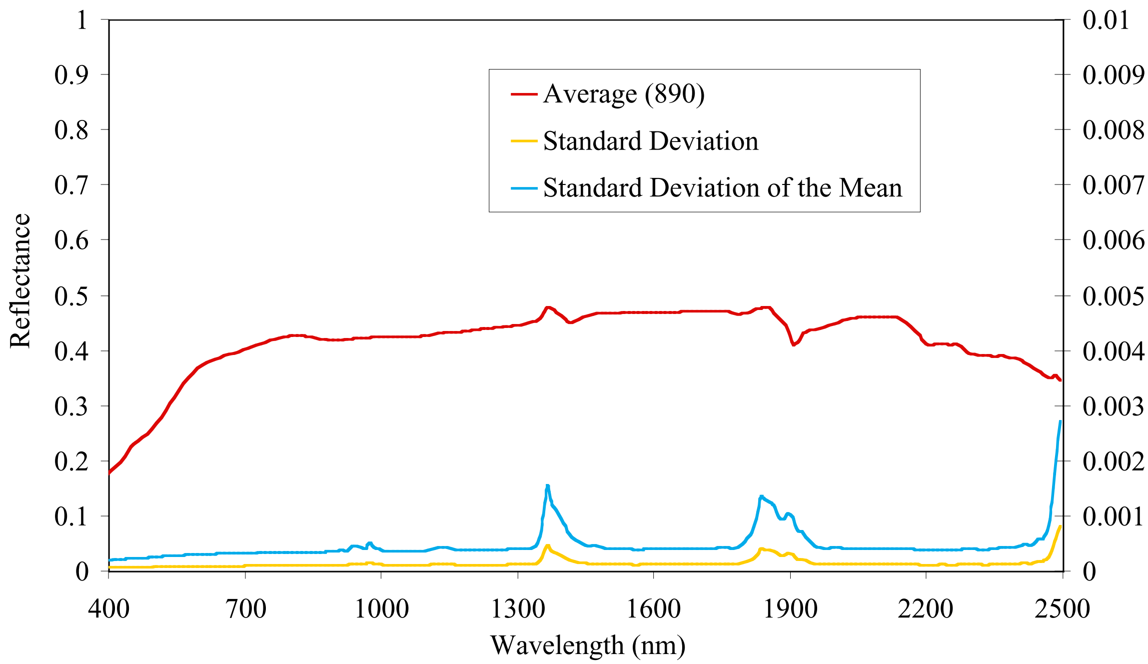

Figure 1. Average, standard deviation, and standard deviation of the mean, for measured surface reflectance at the time of the AVIRIS over flight of Rogers Dry Lake, California, on June 5, 2000.

In addition to surface reflectance, the atmospheric properties were measured at a site adjacent to the surface calibration target. These atmospheric measurements were acquired by a sun-tracking solar radiometer. The radiometer has 10 spectral channels located at 370, 400, 440, 520, 620, 670, 780, 870, 940, and 1030 nm in the solar reflected spectrum. This instrument records voltage output as a function of time. On June 5, 2000 the solar radiometer was operated from 7:53 to 13:18 local time with measurements every 5 minutes. Figure 2 shows the voltage output of the solar radiometer over this period. The measurements are used to calculate the average optical depth of the atmosphere in each channel (Liou, 1980). Also, with an absolute calibration estimate for the spectral channels, the attenuation of the atmosphere for each measurement may be calculated. The calculated instantaneous optical depths for this experiment are plotted in Figure 3. The optical depths at the time of the over flight are required to constrain the radiative transfer code to predict radiance at AVIRIS.

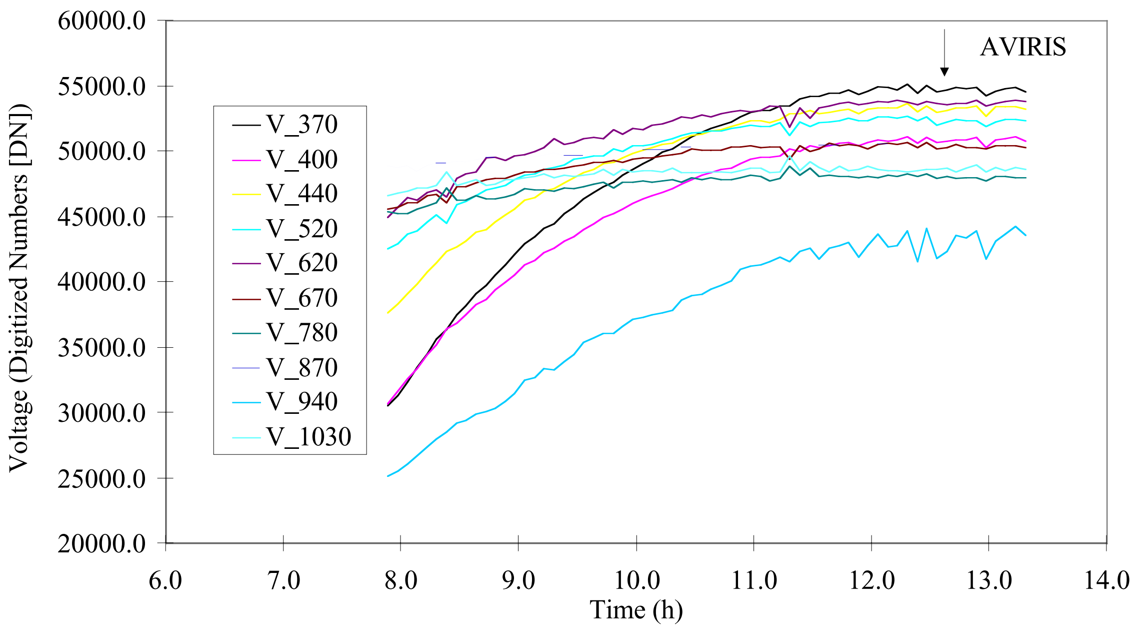

Figure 2. Measured voltages of the sun photometer for derivation of atmospheric optical depths at designated wavelengths at Rogers Dry Lake, California, June 5, 2000.

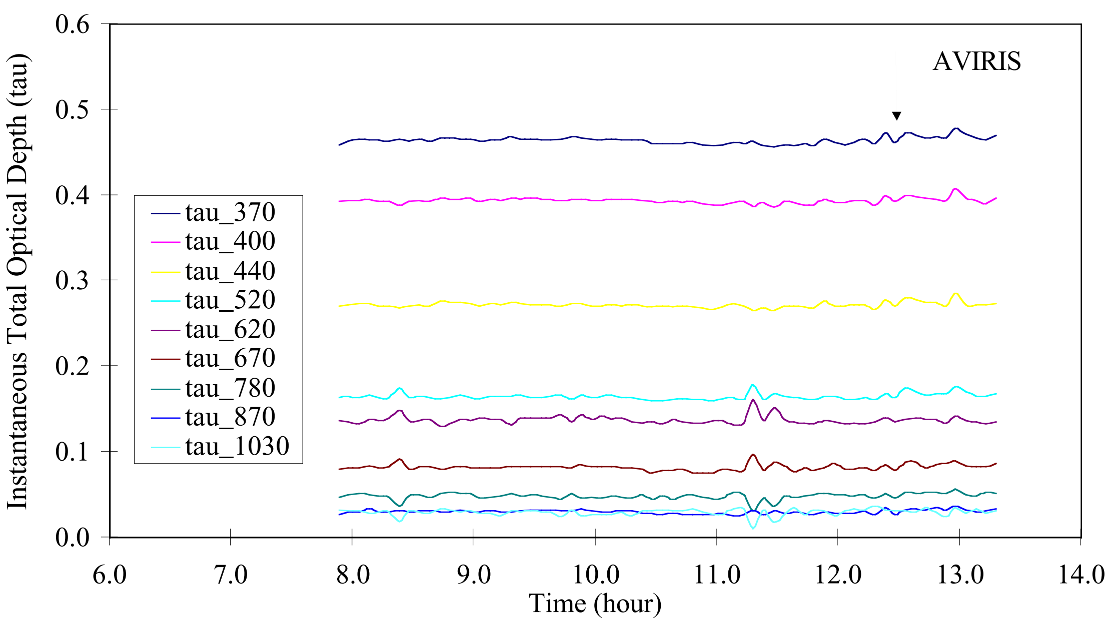

Figure 3. Derived instantaneous optical depths for the calibration experiment on June 5, 2000, at Rogers Dry Lake, California.

In addition to determination of atmospheric optical depth, the sun tracking solar radiometer has a spectral channel at 940 nm. This channel is centered in a moderately strong atmospheric water vapor absorption band. With the voltage measurements over the range of air mass observations the water vapor abundance may be calculated (Reagan et al., 1987; Bruegge et al., 1992). With an absolute calibration estimate for the solar radiometer water vapor channel, the water vapor abundance may be calculated for each measurement. Figure 4 shows the water vapor calculated over the period of measurements with a range from 4.1 to 3.8 precipitable mm. A value of 3.9 mm is estimated for the time of the AVIRIS over flight. This value, in conjunction with the surface reflectance and atmospheric optical depths, is the in situ parameter required to constrain the radiative transfer code to predict the radiance at the AVIRIS instrument.

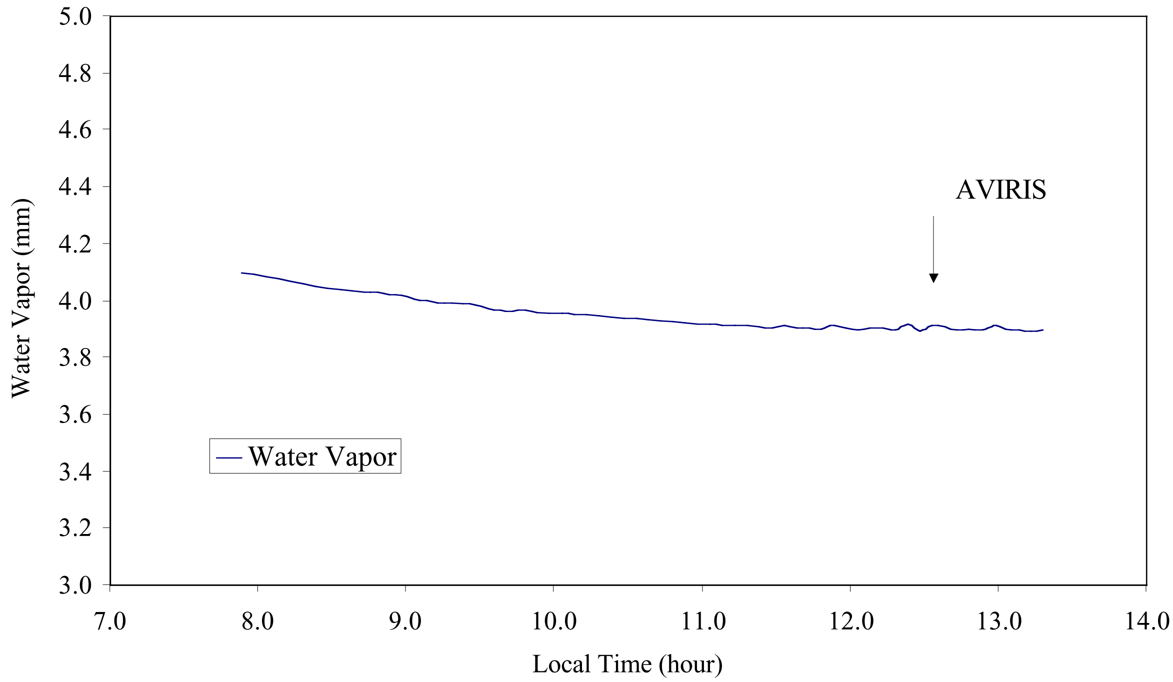

Figure 4. Derived instantaneous water vapor abundance from the 940-nm channel of the solar radiometer data set.

AVIRIS MEASURED RADIANCE

The essential measurements of the calibration target for the inflight calibration experiment are data acquired by AVIRIS onboard the ER-2 aircraft flying at 19.6 km altitude. The corresponding AVIRIS image of Rogers Dry Lake, California, for these measurements is shown in Figure 5. The area of the calibration target is towards the top center of the image. On the surface, blue demarcation tarps were placed at either end of the calibration target. The spectral reflectance contrast between these tarps and the surface allows unambiguous identification of the location of the calibration target. Figure 6 shows a spectrum of the blue tarps and of the lake bed surface. A ratio of the 600 nm over the 450 nm AVIRIS image generates low values for the tarp spectral signature in contrast to the lake bed reflectance. Figure 7 shows an extracted portion of this ratio image with the demarcation tarps clearly evident. The calibration target is the lake bed surface between the tarps. The time of acquisition of this calibration target was recorded in the AVIRIS ephemeris data stream as 18:39:43 UTC.

Figure 5. AVIRIS image of Rogers Dry Lake, California, acquired on June 5, 2000. (North is up.)

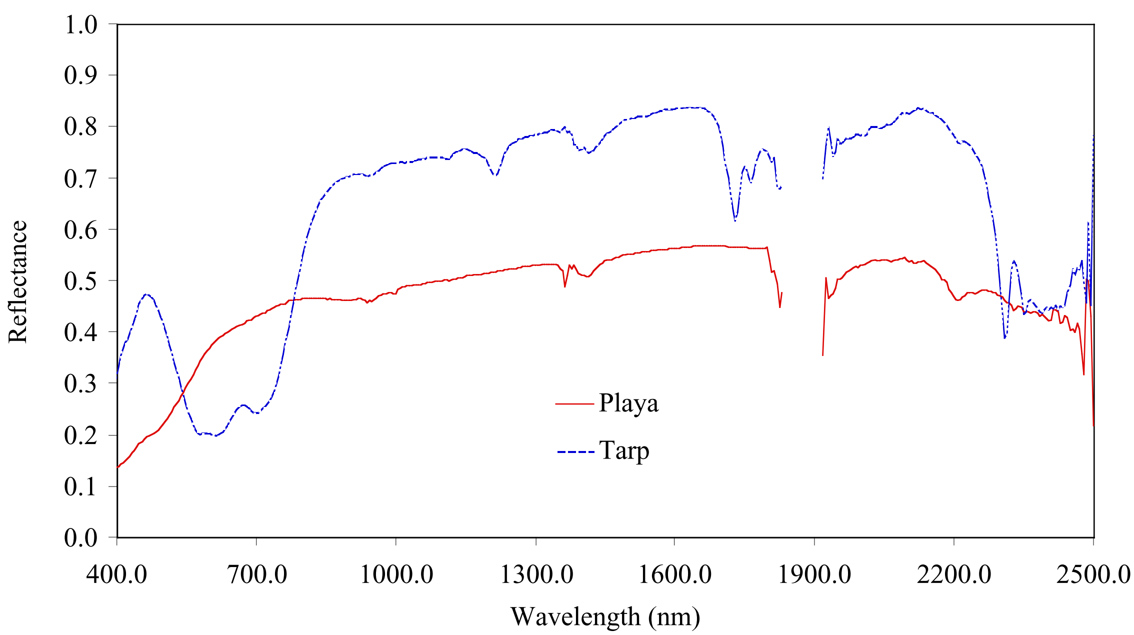

Figure 6. Spectra of blue demarcation tarps used to identify the calibration target surface.

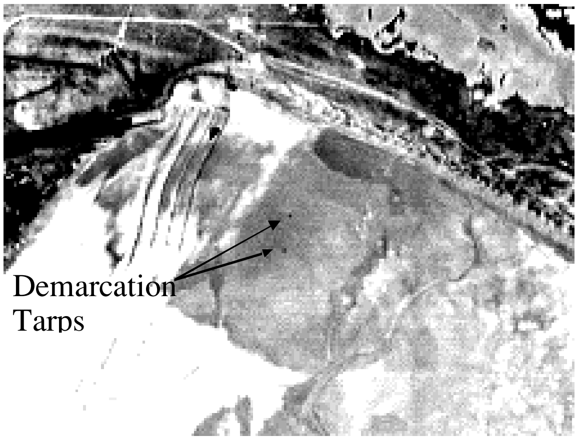

Figure 7. AVIRIS inflight calibration target on the surface of Rogers Dry Lake, California, on June 5, 2000.

With the identification of the calibration target in the AVIRIS data set, the average spectrum for the target is extracted. Figure 8 shows the extracted average uncalibrated data for calibration target. The total signal, dark signal, and total minus dark signal are plotted. The dark is measured as the average of 64 spectra at the end of each scan line with the AVIRIS primary shutter closed. These uncalibrated data are calibrated with the radiometric calibration coefficients and the spectral calibration file and data from the AVIRIS onboard calibrator (Green et al., 1991; Green, 1993). Figure 9 shows the average calibrated AVIRIS spectrum for the calibration target. This is the measured AVIRIS spectrum to be validated with respected to the radiative transfer code predicted radiance for the calibration target.

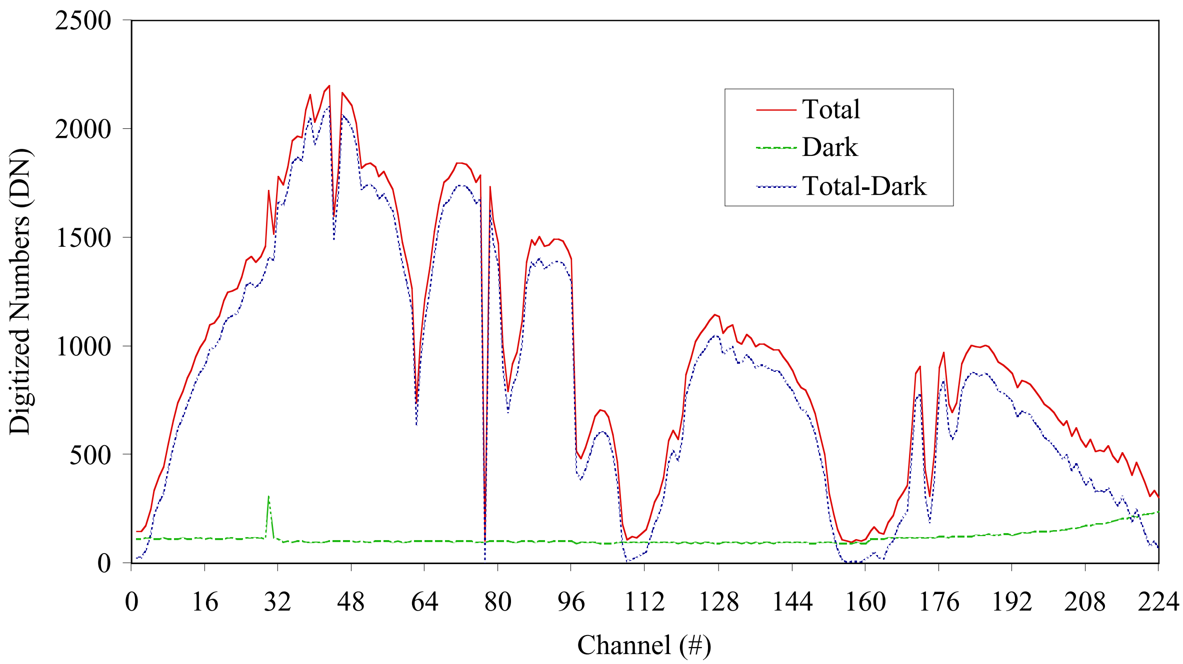

Figure 8. AVIRIS average measured data for the calibration surface.

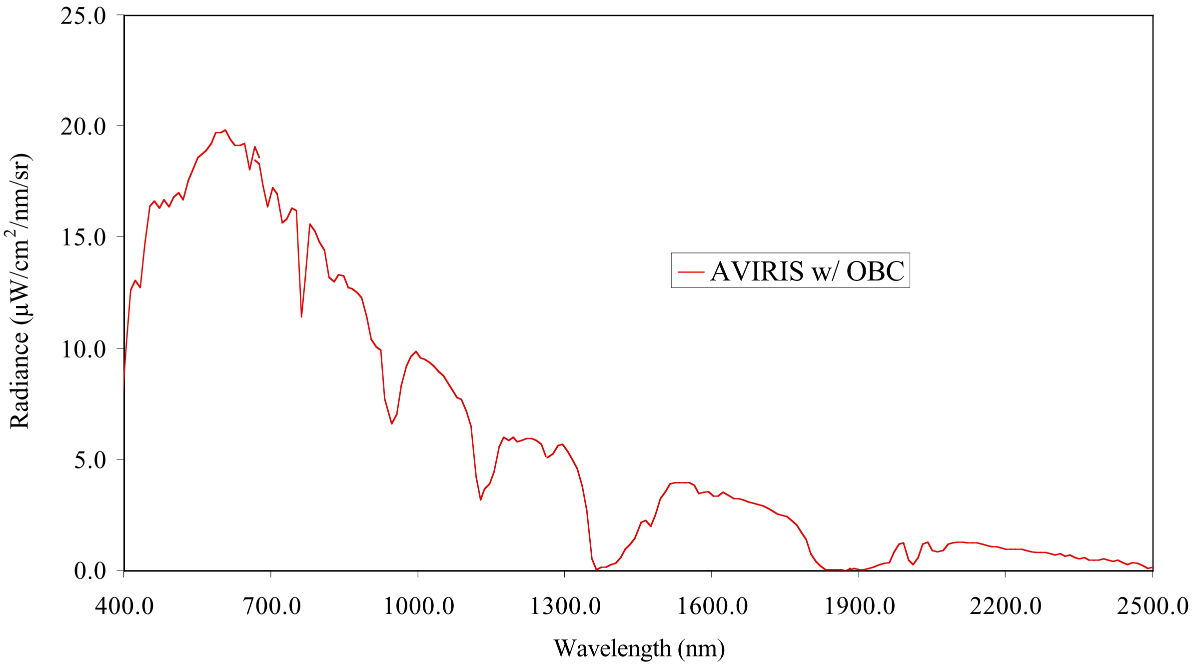

Figure 9. AVIRIS calibrated radiance for the calibration surface with corrections of the onboard calibrator (OBC).

MODTRAN PREDICTED RADIANCE

The radiance incident at the AVIRIS instrument is predicted with a radiative transfer code constrained by the in situ surface and atmospheric measurements acquired at the calibration target site. The MODTRAN radiative transfer code (Berk et al., 1989; Anderson et al., 1995, 2000) was used for the analysis. MODTRAN constraint parameters were set for the time, location, and observation geometry of the AVIRIS measurements based on ephemeris information. Through adjustment of the visibility parameter, the mid-latitude summer atmospheric model was constrained to closely match the measured atmospheric optical depths. A comparison between the measured optical depths and those of MODTRAN are shown in Figure 10. This level of agreement was achieved with an atmospheric visibility of 150 km. Both the in situ measured surface reflectance and water vapor abundance were included in the MODTRAN constraint parameter. The amount of carbon dioxide in the MODTRAN model was adjusted to a 370 ppm mixing ratio for the year 2000 (Keeling et al., 2001). Ozone was constrained by the total ozone mapping spectrometer (TOMS) (McPeters, 2001) derived value of 310 dobsin units for June 5, 2000. With this complete set of constraints, a predicted radiance spectrum was calculated at full MODTRAN spectral resolution. This spectrum with a 1 wavenumber sampling interval and 2 wavenumber resolution is shown in Figure 11. For comparison with AVIRIS, the high resolution output was convolved to the AVIRIS spectral response functions determined in the laboratory. Figure 12 shows the resulting MODTRAN predicted radiance for the calibration target on Rogers Dry Lake at 18:39:43 on June 5, 2000. This predicted radiance spectrum forms the basis for validating the inflight calibration of AVIRIS for the 2000 flight season.

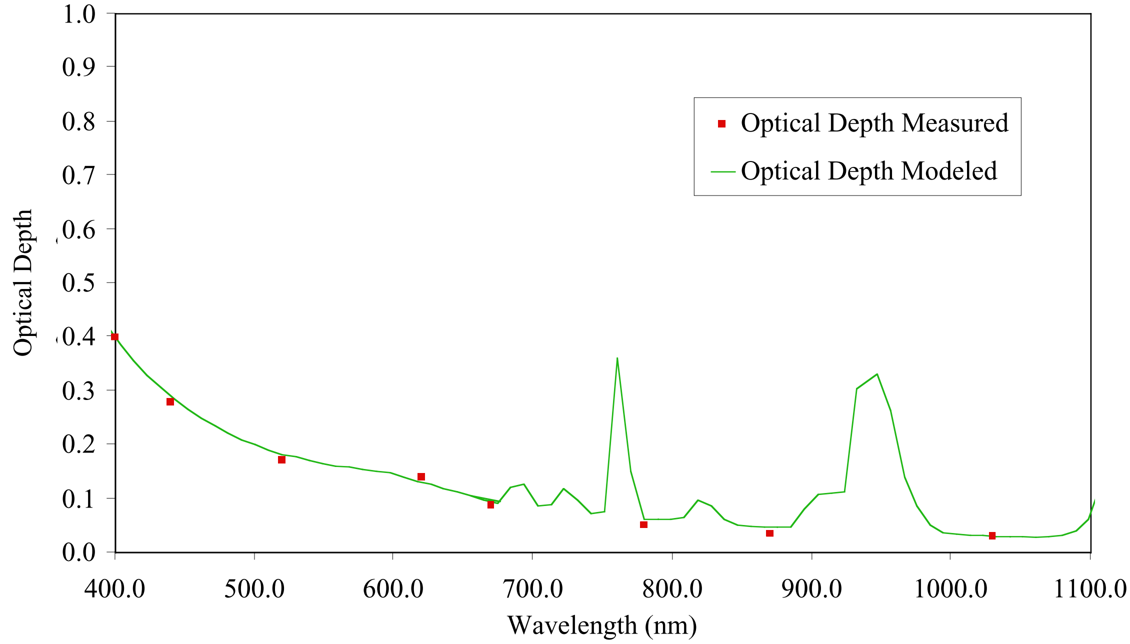

Figure 10. In situ measured optical depths for the time of the AVIRIS over flight and corresponding MODTRAN optical depths for a 150-km visibility mid-latitude summer atmosphere model.

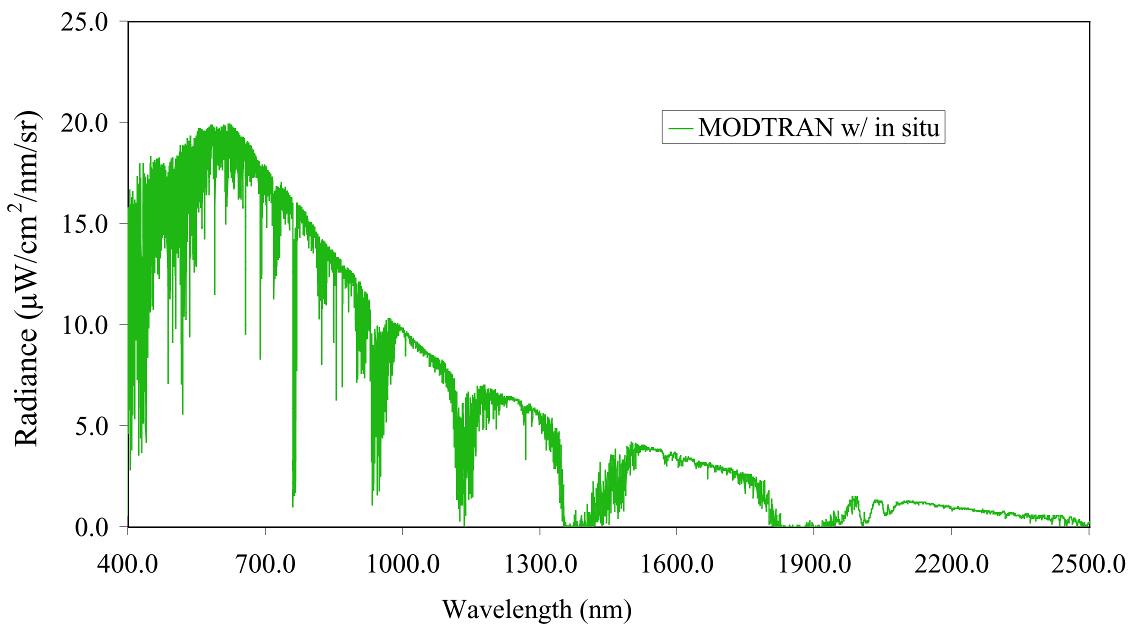

Figure 11. MODTRAN modeled radiance for the inflight calibration experiment calculated with in situ constraints.

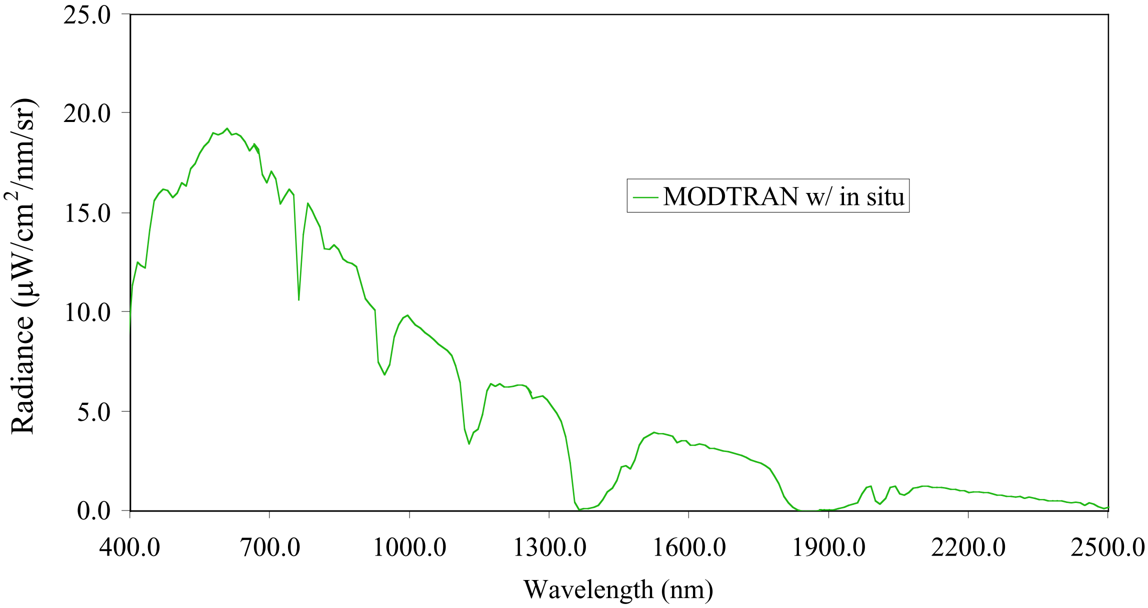

Figure 12. MODTRAN-predicted radiance convolved to the AVIRIS spectral characteristics calculated with in situ restraints.

COMPARISON ANALYSIS

With the AVIRIS measured spectrum and the MODTRAN predicted radiance spectrum, a simple comparison analysis was performed to validate the calibration of AVIRIS in the flight environment. Figure 13 shows a combined plot of the measured and predicted radiance spectra. The AVIRIS spectrum has been calibrated with the laboratory-generated radiometric calibration coefficients and onboard calibrator measurements. The MODTRAN spectrum was generated with the surface reflectance, atmospheric optical depths, and water vapor abundance measured at the calibration target site. The absolute average agreement between the AVIRIS and MODTRAN spectra is 96.2 percent. This agreement is calculated excluding the regions of strong atmospheric absorption where the radiance levels approach zero. A comparison ratio of these two spectra is shown in Figure 14. In several regions of the spectrum there are areas of disagreement. These disagreements may result from either or both AVIRIS and MODTRAN uncertainty factors. The slightly higher values of AVIRIS in the 400- to 700-nm region of the spectrum are likely do to changes in the throughput performance of the first AVIRIS instrument spectrometer. The sharp deviations near 760, 940, and 1150 nm probably relate to small shifts (on the order of 1 nm) in the in flight spectral calibration of AVIRIS with respect to the spectral calibration of AVIRIS in the laboratory. Other factors (such as the absolute calibration standards of AVIRIS and changes in AVIRIS performance through time) may contribute to these absolute uncertainties. For MODTRAN, factors (such as the solar irradiance and parameterization of the atmosphere) may contribute to uncertainties. In addition, uncertainties in the in situ measurements and derived parameters will contribute to uncertainty in the MODTRAN predicted radiance. However, the primary result of this inflight calibration experiment is a baseline validation of AVIRIS inflight calibration at the 96 percent level for the 2000 flight season.

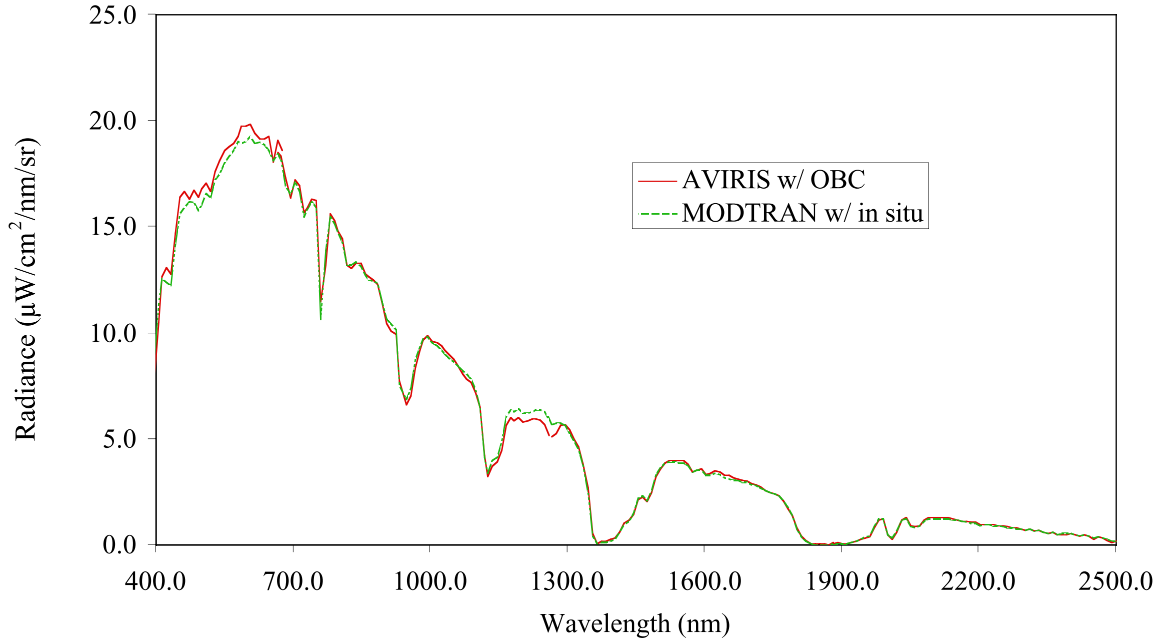

Figure 13. Comparison of the AVIRIS-measured radiance and the MODTRAN-predicted radiance from the inflight calibration experiment on June 5, 2000.

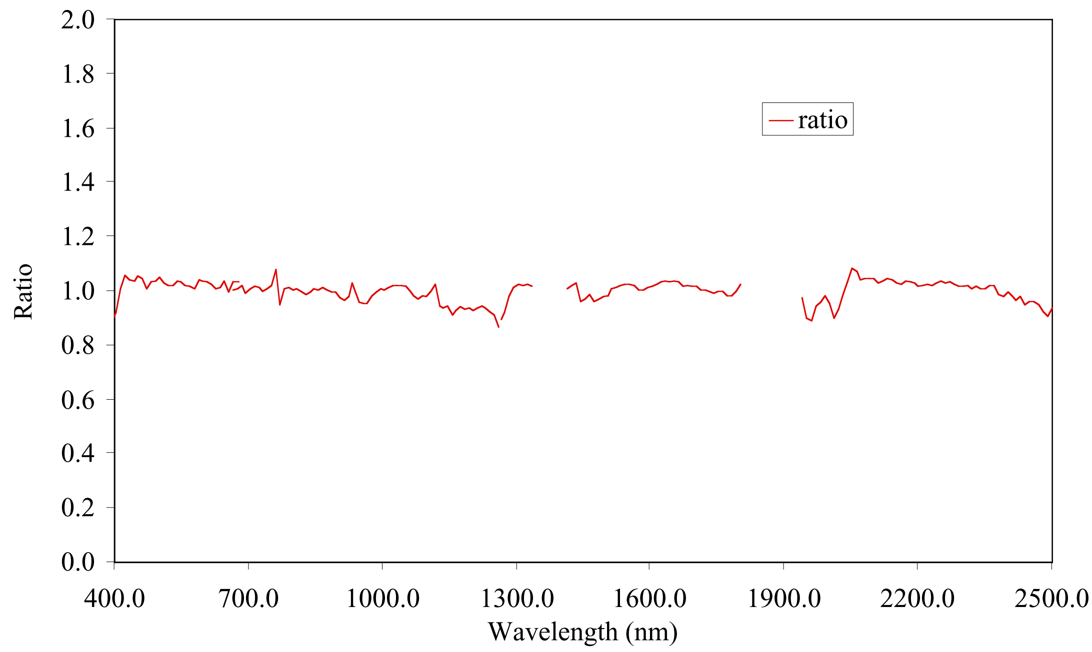

Figure 14. Ratio of AVIRIS-measured to MODTRAN-predicted radiance.

AVIRIS PRECISION

In addition to AVIRIS radiometric accuracy, knowledge of the inflight radiometric precision is often required for both science research and application objectives. A measure of AVIRIS inflight precision is provided by the dark signal data measured before and after acquisition of each spectral image data set. The standard deviation of these dark signal data provide an estimate of the instrument noise. Figure 15 shows a plot of the AVIRIS noise calculated for the inflight calibration experiment data set acquired on June 5, 2000. The AVIRIS channel at 655 nm was excessively noisy in 2000 and is not included in this analysis. Across the spectrum from 400 to 1900 nm, the AVIRIS noise is quite uniform at about 0.7 digitized number (DN). Beyond 1900 the noise rises steadily to 1.4 in DN at 2500 nm. This increase in noise due to the uncertainty in the radiance signal emitted by the AVIRIS spectrometer onto the detectors. At these wavelengths the spectrometer is as significant source of dark signal radiance. AVIRIS radiometric precision may be reported as the noise-equivalent-delta-radiance (NEdL). NEdL is calculated by multiplying the noise in DN by the radiometric calibration coefficients. Figure 16 shows the NEdL for the inflight calibration experiment on June 5, 2000, as well as inflight values from a 1999 data set. This is the dark signal precision of AVIRIS in units of radiance and may be thought of as the precision-related error bars for each spectrum for a dark target. Lower values of NEdL correspond to better precision and better AVIRIS performance. The improvement of AVIRIS from 1999 to 2000 in NEdL is related to a new detector array in the first spectrometer and general efforts towards signal-chain noise suppression across the AVIRIS spectral range. As target brightness increases, the NEdL increases due to the statistical uncertainty in the radiance signal incident at the AVIRIS instrument. The inflight NEdL for 2000 given here provides a basis for comparison of AVIRIS performance from year to year as well as an estimate of the radiance uncertainty in each AVIRIS spectrum due to noise.

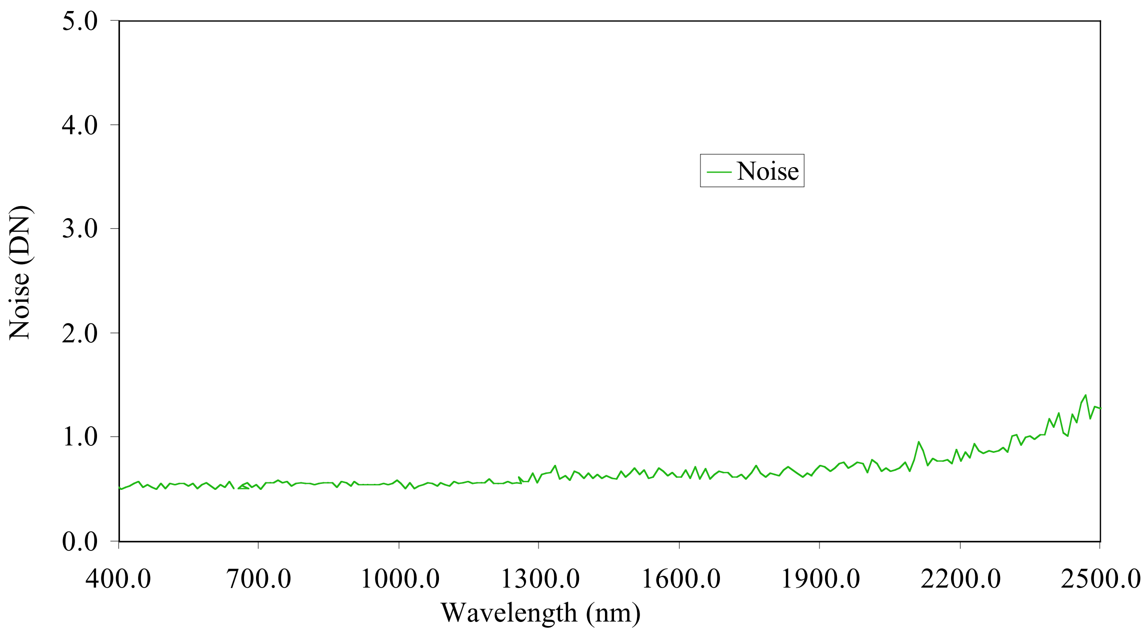

Figure 15. AVIRIS noise calculated from the dark signal for the inflight calibration experiment.

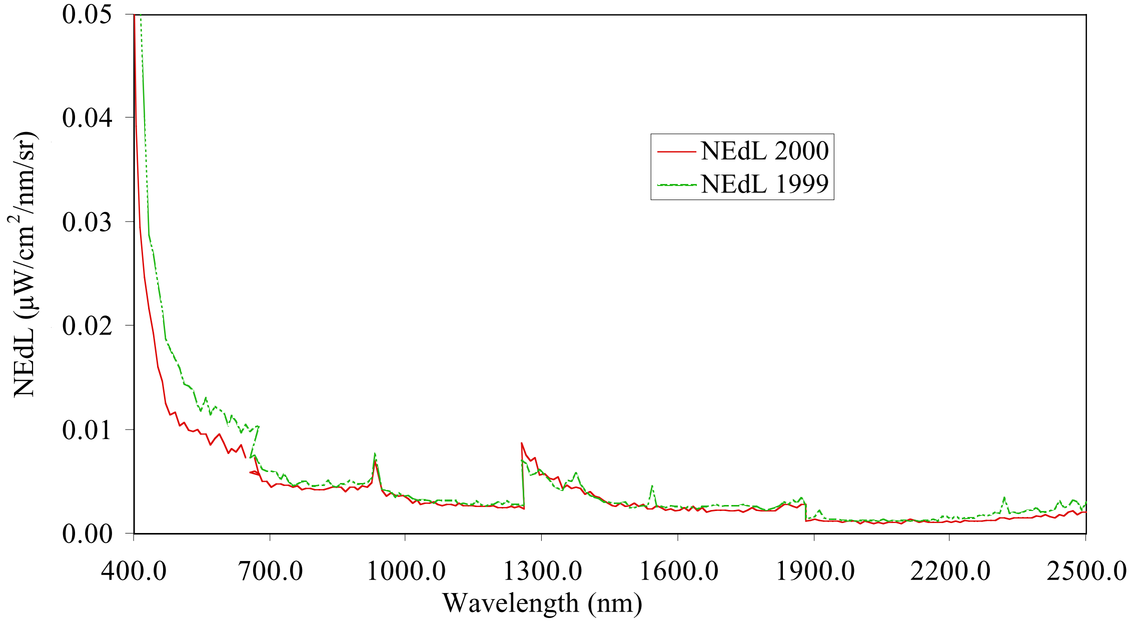

Figure 16. Noise equivalent delta radiance for the inflight calibration experiment on June 5, 2000. The corresponding values are given for 1999.

CONCLUSION

An AVIRIS inflight calibration experiment was orchestrated on June 5, 2000, at Rogers Dry Lake, California. For this experiment, a visually homogeneous calibration target was designate on the dry lakebed bed surface. Surface reflectance measurements were acquired by thoroughly sampling a 40- by 120-m area of the calibration target. The data were analyzed to produce an average reflectance spectrum for the calibration target with compensation for surface BRDF and for the reflectance standard spectral characteristics. Adjacent to the calibration target a solar radiometer was used to measure atmospheric attenuation in 10 spectral channels from 370 to 1030 nm. These measurements were analyzed to derive the atmospheric optical depth as well as the total column water vapor abundance at the time of the AVIRIS overflight of the calibration target. A ratio of the 600-nm and 4450-nm AVIRIS images was formed to locate the calibration target between the blue demarcation tarps in the AVIRIS data set. The average AVIRIS spectrum of the calibration target was extracted and calibrated to radiance using the laboratory-derived radiometric calibration coefficient and spectral calibration data. The measured in situ surface and atmospheric measurements were used to constrain the MODTRAN radiative transfer code and predict the radiance incident at the AVIRIS instrument. The AVIRIS-measured and MODTRAN-predicted radiance spectra were compared and found to have a 96.2 percent absolute average agreement exclusive of the strong atmospheric absorption regions. The regions of residual disagreement in the spectral comparison are related to a number of factors. These include uncertainties in the AVIRIS calibration standards, changes in AVIRIS performance, uncertainties in the underlying MODTRAN parameters and calculation, as well as uncertainties in the surface and atmospheric measurements and analyses. Research is ongoing to identify, assess, and improve the residual uncertainty in these factors that effect the inflight calibration experiment results. In addition to radiometric accuracy, the inflight radiometric precision was calculated and reported as the dark signal NEdL of AVIRIS in 2000. Comparison with the 1999 NEdL showed marked improvement in the range from 400 to 700 nm, as well as modest improvement across the spectrum. The measurements, analyses, and results reported here provide the core validation of AVIRIS inflight performance for the 2000 flight season. Assessment and validation of AVIRIS performance in the flight environment is essential because data sets acquired for scientific research and application objectives are only acquired in the flight environment.

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