Calibration of AVIRIS Digitized Data

Robert O. Green, Steven A. Larson, and H. Ian Novack
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an Earth-observing imaging spectrometer that acquires data for scientific investigations of the surface and atmosphere. These data are distributed to investigators calibrated with respect to their spectral, radiometric, and geometric characteristics. The process of calibrating these data through application of the calibration data files and calibration algorithms is described in this paper.

1. Introduction

AVIRIS measures the total upwelling radiance from 400 to 2450 nm in the electromagnetic spectrum through 224 spectral channels. The spectral sampling interval and response function for each channel is nominally 10 nm. Spatial images of 11 by ≤100 km are acquired with approximately 20- by 20-m spatial resolution.

The calibration of AVIRIS requires four distinct processes which were originally described in part in 1987 (Vane et al., 1987). First, calibration measurements are acquired in the laboratory of the spectral, radiometric, and geometric characteristics of the sensor (Chrien et al., 1990). Second, these measurements are reduced to a set of calibration data files, which are compatible with AVIRIS data characteristics. Third, the laboratory calibration is validated through an in-flight calibration experiment. Fourth, science data are routinely calibrated with the calibration data files and distributed to requesting investigators. This paper describes and presents an example of this fourth process.

Data recorded on July 23, 1990 over the in-flight calibration site at Rogers Dry Lake, California, are used to demonstrate the process of the calibration of AVIRIS digitized data. An AVIRIS image of the calibration site is given in Figure 1 [see slide 9].

2. Radiometric Calibration

For every spatial resolution element, AVIRIS records the upwelling radiance as digitized numbers (DNs) ranging from 0 to 1024 for each of the 224 spectral channels. A digitized spectrum from the calibration site at Rogers Dry Lake is given in Figure 2. The shape of this spectrum is predominantly a consequence of the upwelling radiance, the instrument radiometric response, and the additive instrument dark current. Dark-current spectra are measured by AVIRIS at the end of each image scan-line. Individual dark-current spectra contain the full minimum to maximum noise properties of AVIRIS; therefore, the mean of 100 lines of dark-current spectra is formed to provide a low-noise spectrum. A spectrum of the mean dark current for the calibration site is given in Figure 3. This mean dark current for each channel and line, $DC_{c,l}$, is subtracted from the measured signal for each channel, line, and sample, $DN_{c,l,s}$, to generate a spectrum with values proportional to the upwelling radiance,

$DN'_{c,l,s}$, as shown in Equation 1. The Rogers Dry Lake calibration site spectrum from which the dark current has been subtracted is given in Figure 4.

$$DN'_{c,l,s} = DN_{c,l,s} - \overline{DC_{c,l}} \quad (1)$$

To transform this spectrum to units of radiance, the radiometric calibration coefficients determined during the laboratory calibration are multiplied through the data. Figure 5 shows these coefficients for the data acquired during the AVIRIS operational period beginning July 23, 1990. These coefficients are in units of radiance per DN. A radiometric calibration coefficient is required for each of the 224 AVIRIS spectral channels. As given in Equation 2, the nadir upwelling radiance, $L_{c,l,s}$, is calculated through multiplication of the dark-current subtracted DN, $DN'_{c,l,s}$ by the radiometric calibration coefficients, RCC_c. The radiometrically corrected spectrum for the calibration site is given in Figure 6.

$$L_{c,l,s} = RCC_c \cdot DN'_{c,l,s} \quad (2)$$

For AVIRIS spectra measured off-nadir, a small cross-track vignetting correction is required. These factors compensate for the greater optical path through the hatch and foreoptics windows at the edge of the ±15-deg field of view. Vignetting correction factors are generated as part of the laboratory calibration prior to each operational period. A correction factor exists for each of the 614 cross-track elements and each spectral channel. Equation 3 describes the vignetting correction, where the radiance for each channel, image line, and cross-track sample, $L_{c,l,s}$, is multiplied by the vignetting correction factor, $VCF_{c,s}$, to generate the vignetting corrected radiance, $L'_{c,l,s}$. The vignetting correction factors valid for the calibration experiment data for spectral channel 130 are shown in Figure 7.

$$L'_{c,l,s} = VCF_{c,s} \cdot L_{c,l,s} \quad (3)$$

In addition to radiometric calibration, an estimate of radiometric precision is provided as the noise-equivalent-delta-radiance (NEdL) with all distributed AVIRIS data. This estimate is derived from the dark current measured at the end of each image line. These dark-current data provide the sensor response to a homogeneous dark target and the variations in these data are used to estimate the instrument noise. In Figure 8, the root-mean-squared-deviation (RMSD) for the dark current measured in the laboratory is compared to the RMSD for the signal measured over the integrating sphere, a homogeneous bright target. In Figure 9, the in-flight RMSD of the dark current and the RMSD of a 2 by 10 element area over the Rogers Dry Lake calibration site are given. For both the laboratory and in-flight conditions, the end-of-line dark-current measurements are shown to accurately assess AVIRIS noise properties. For every AVIRIS data scene, the in-flight NEdL is determined as the dark-current derived noise multiplied by the radiometric calibration coefficients. The NEdL spectrum for the Rogers Dry Lake data is shown in Figure 10. This NEdL reports the precision of the calibrated radiance spectra for every spatial element in the AVIRIS data set.

3. Spectral Calibration

The spectral position and spectral response function for each of the 224 AVIRIS channels are determined in the laboratory prior to each period of data acquisition. A plot of the wavelength position versus the channel number for data acquisition beginning on July 23, 1990 is given in Figure 11. The channel spectral response functions as the full width at half maximum (FWHM) of corresponding Gaussian functions are given in Figure 12. The four distinct regions in each of these figures correspond to the four spectrometers used by AVIRIS to cover the range from 400 to 2450 nm. The spectral calibration objective is to determine these spectral characteristics to better than ±2 nm. Spectral calibration data are essential for physically based analysis of the AVIRIS data and for comparison of AVIRIS spectra acquired in one period to those acquired in another as well as for comparison of AVIRIS data with spectra measured by other instruments. Spectral calibration data files are distributed with all AVIRIS data.

4. Geometric Calibration

AVIRIS is a scanning imaging spectrometer which acquires cross-track spatial elements through movement of a scan mirror and along-track elements through the forward motion of the aircraft platform. The number of cross-track elements in a scan is fixed at 614 and along-track elements vary from 500 to 5000 depending on the length of the flight line. In the laboratory prior to each operational period, the spatial sampling and spatial response functions of AVIRIS are measured. For the period beginning March 7, 1991, the sampling was determined as 17 m by 17 m at nadir with the aircraft moving at 734 km/h. The spatial response FWHM was determined as 20-m along track by 21-m cross track.

A geometric correction is applied to AVIRIS data to compensate for the readout-delay of the spectrometer detector arrays. The delay in time from reading the first detector to reading the sixty-fourth detector in the spectrometer arrays is slightly less than 17 m of cross-track displacement on the surface. A linear interpolation is used to resample the cross-track elements for each channel. Equation 4 gives the resulting radiance, $L''_{s,d}$, for the linear interpolation between the radiance in each cross-track sample, $L'_{s,d}$, and the adjacent sample, $L'_{s+1,d}$, as a function of detector array element. There are 32 detector elements in spectrometer A and 64 elements in spectrometers B, C, and D. This resampling brings the channels in the four spectrometer arrays into nominal spatial coregistration.

$$L''_{s,d} = [(d-1)/66] \cdot L'_{s+1,d} + [(67-d)/66] \cdot L'_{s,d} \qquad (4)$$

5. Additional Calibration Information

Data from the aircraft navigation system, engineering parameters from the AVIRIS sensor, and the signal from an AVIRIS reference light source are acquired in conjunction with all data. Table 1 gives the navigation parameters recorded with each scan-line of data. Engineering parameters are listed in Table 2. The reference source is viewed by AVIRIS through four filter positions before and after each flight line. These filter positions provide a high-intensity, low-intensity, spectrally distinct and dark signal. In each filter position, 614 spectra are acquired with the 224 AVIRIS channels. These navigation, engineering, and reference data are included with all distributed AVIRIS data.

6. Calibration Validation

The in-flight spectral and radiometric calibration of AVIRIS is validated through implementation of calibration science experiments (Green et al., 1988; Conel et al., 1988; and Green et al., 1990). These experiments predict the upwelling radiance expected at AVIRIS through in situ field measurements of the surface and atmosphere which are used to constrain a radiative transfer code. For the calibration experiments in 1990, the LOWTRAN 7 (Kneizys et al., 1989) radiative transfer code was used. In future, MODTRAN (Berk et al., 1989) is planned to be used. The AVIRIS laboratory calibrated radiance over the calibration site is evaluated with respect to the calibration experiment predicted radiance. This comparison provides a rigorous validation because the AVIRIS measured and the radiative transfer predicted radiance are derived from two completely independent pathways. The AVIRIS radiance is calibrated based upon a National Institute of Standard and Technology (NIST) irradiance lamp and the predicted radiance is based upon an exoatmospheric solar irradiance spectrum. Results from the in-flight calibration experiment completed on July 23, 1990 are given in Figure 12. Excluding the regions of strong atmospheric water absorption the absolute radiometric agreement between the measured and predicted spectrum is better than 8%. A continuing AVIRIS objective is to further improve and validate the absolute radiometric calibration.

7. Conclusion

An essential process in the calibration of AVIRIS is the routine calibration of the digitized data with respect to their radiometric, spectral, and geometric characteristics. Radiometric calibration results in a transformation of the measured signal to units of total upwelling radiance. Spectral calibration of the data is achieved by providing the laboratory-determined channel positions and response functions for the 224 AVIRIS channels. Geometric calibration is fulfilled through detector readout delay corrections and distribution of the laboratory-determined spatial sampling and response function. Navigation, engineering, and reference light source data are provided to allow further characterization of the AVIRIS data. Because the operational environment (ambient conditions at 20-km altitude) differs substantially from the laboratory calibration environment, the in-flight characteristics are validated periodically through in-flight calibration experiments. All data used for the calibration of AVIRIS data are included with the distributed data to facilitate quantitative analysis by the science investigator. This calibration process is required for quantitative analysis of AVIRIS data as well as for comparison of AVIRIS data acquired from different regions, from different times and with data measured by different instruments.

Acknowledgment

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

- Berk, A., L. S. Bernstein, and D. C. Roberson, *MODTRAN: A Moderate Resolution Model for LOWTRAN 7,* U.S. Air Force Geophysical Laboratory, Hanscom Air Force Base, Massachusetts, 1989.

- Chrien, T. G., R. O. Green, and M. Eastwood, "Laboratory Spectral and Radiometric Calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *Imaging Spectroscopy of the Terrestrial Environment,* SPIE Vol. 1298, 1990.

- Conel, J. E., R. O. Green, R. E. Alley, C. J. Bruegge, V. Carrere, J. S. Margolis, G. Vane, T. G. Chrien, P. N. Slater, S. F. Biggar, P. M. Teillet, R. D. Jackson, and M. S. Moran, "In-Flight Radiometric Calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *Recent Advances in Sensors, Radiometry and Data Processing for Remote Sensing,* SPIE Vol. 924, 1988.

- Green, R. O., G. Vane, and J. E. Conel, "Determination of Aspects of the In-Flight Spectral, Radiometric, Spatial and Signal-to-Noise Performance of the Airborne Visible/Infrared Imaging Spectrometer Over Mountain Pass, Ca.,"*Proceedings of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Performance Evaluation Workshop,* JPL Publication 88-38, 162-184, 1988.

- Green, R. O., J. E. Conel, J. S. Margolis, V. Carrere, C. J. Bruegge, M. Rast, and G. Hoover, "In-Flight Validation and Calibration of the Spectral and Radiometric Characteristics of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *Imaging Spectroscopy of the Terrestrial Environment,* SPIE Vol. 1298, 1990.

- Kneizys, F. X., E. P. Shettle, G. P. Anderson, L. W. Abrew, J. H. Chetwynd, J. E. A. Shelby, and W. O. Gallery, *Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 7,* U.S. Air Force Geophysical Laboratory, Hanscom Air Force Base, Massachusetts, 1989.

- Vane, G., T. G. Chrien, E. A. Miller, and J. H. Reimer, "Spectral and Radiometric Calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Flight and Ground Data Processing System," *Imaging Spectroscopy II: 20-21 August 1987, San Diego, California,* SPIE Vol. 834, 1987.

Tables and Figures

Table 1. AVIRIS aircraft navigation data

Record No.	Parameter	Record No.	Parameter
1	Flight number	11	North-South velocity
2	Flight line	12	East-West velocity
3	Year	13	True heading
4	Month	14	Ground speed
5	Day	15	Vertical velocity
6	Hour	16	Altitude
7	Minute	17	True air speed
8	Second	18	Pitch
9	Latitude	19	Roll
10	Longitude		

Table 2. AVIRIS sensor data

Record No.	Parameter	Record No.	Parameter
1	A detector array temperature	14	Analog voltage (+20)
2	B detector array temperature	15	Analog voltage (-20)
3	C detector array temperature	16	Digital voltage (+5)
4	D detector array temperature	17	Aircraft power (+28)
5	A spectrometer temperature	19	Analog voltage (+8)
6	B spectrometer temperature	20	Reference lamp current
7	C spectrometer temperature	21	Hardware status codes
8	D spectrometer temperature	22	Focus position
9	Foreoptics temperature	23-33	Scan mirror encoder marks
10	Scan drive temperature	34-44	Sensor roll gyro
11	Analog electronics temp.	45-53	Sensor pitch gyro
12	Digital electronics temperature	97-112	Firmware status
13	Power supplies temperature		

Figure 1. AVIRIS image over Rogers Dry Lake, California, acquired on July 23, 1990. The in-flight calibration site is shown as site A in the image [see slide 9].

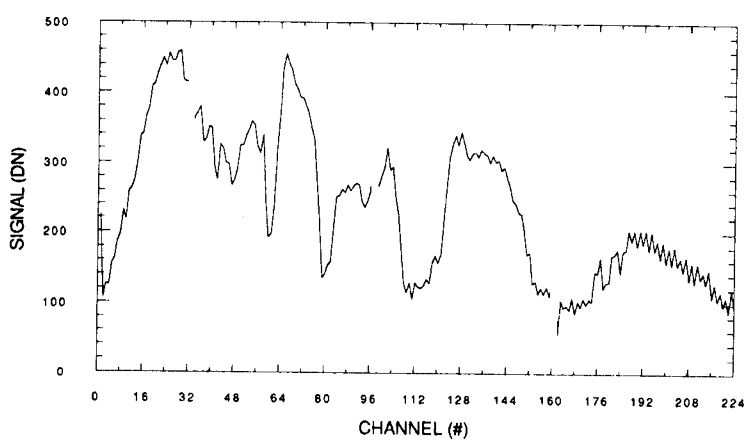

Figure 2. Spectrum of the signal measured by AVIRIS over the Rogers Dry Lake, California, calibration site on July 23, 1990.

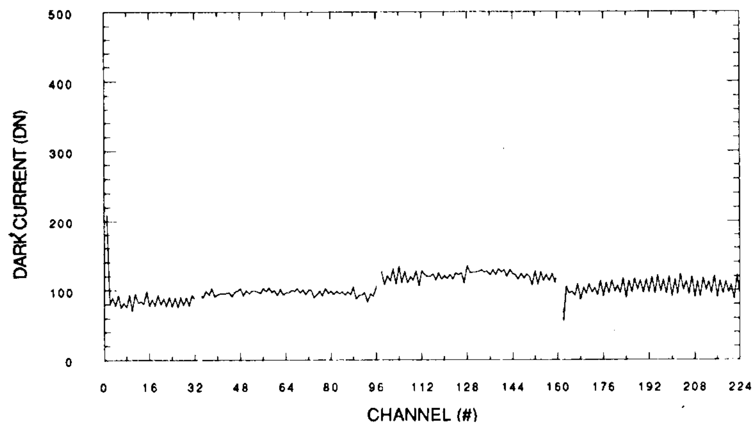

Figure 3. Mean dark-current spectrum for the calibration site. Dark-current data are measured at the end of each cross-track line of data acquired.

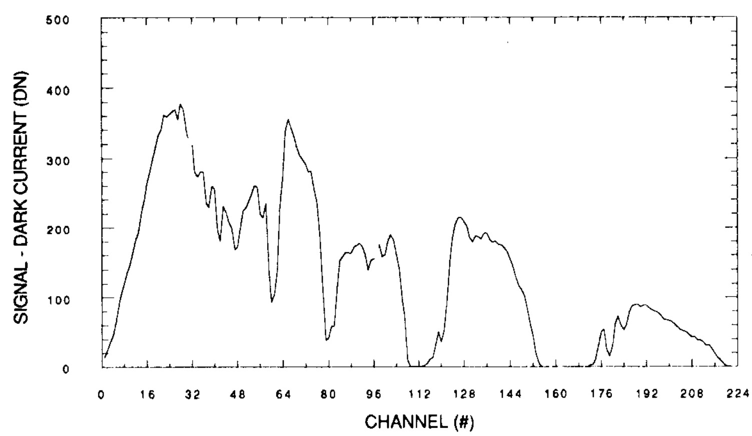

Figure 4. An AVIRIS spectrum with dark current subtracted of the Rogers Dry Lake, California, calibration site.

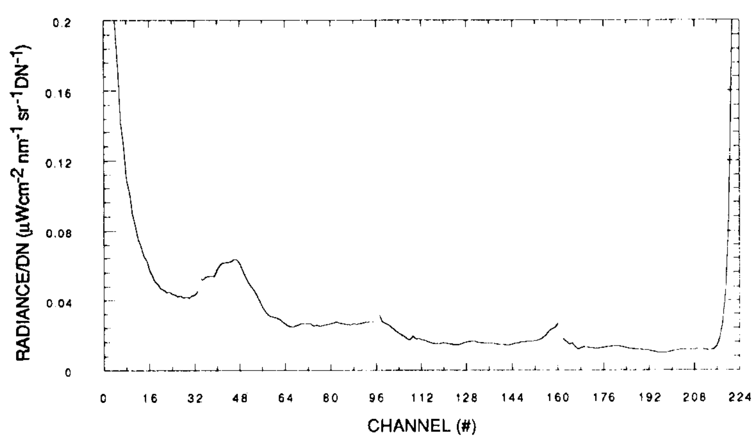

Figure 5. The radiometric calibration coefficients determined in the laboratory.

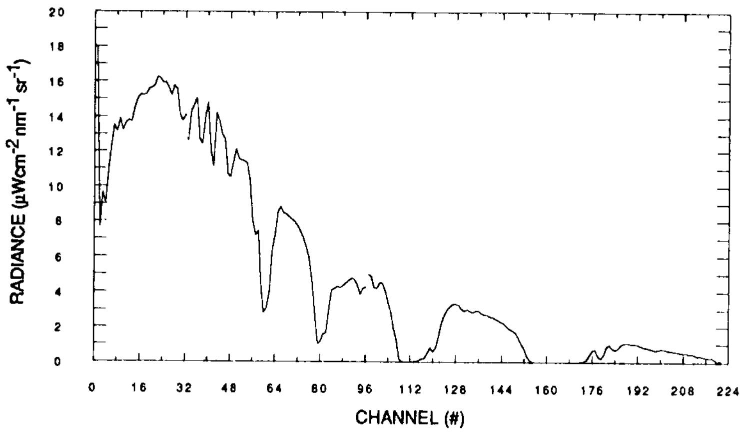

Figure 6. Radiometrically calibrated AVIRIS spectrum.

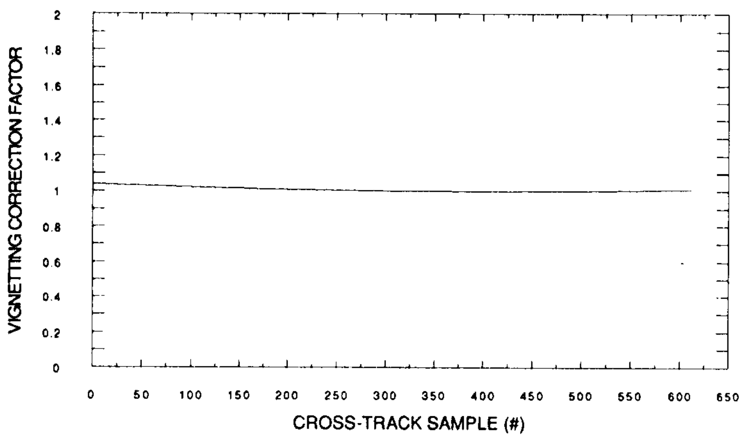

Figure 7. Cross-track vignetting correction factors for channel 130. Vignetting correction factors are determined in the laboratory for each spectral channel.

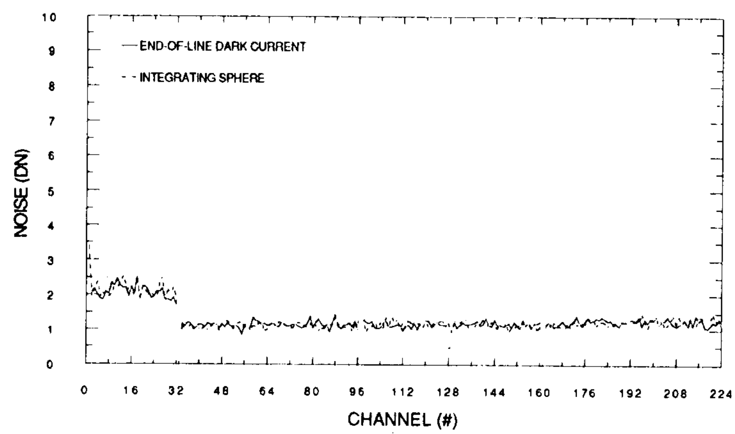

Figure 8. AVIRIS noise spectrum determined both from the laboratory integrating sphere signal and the end-of-line dark current.

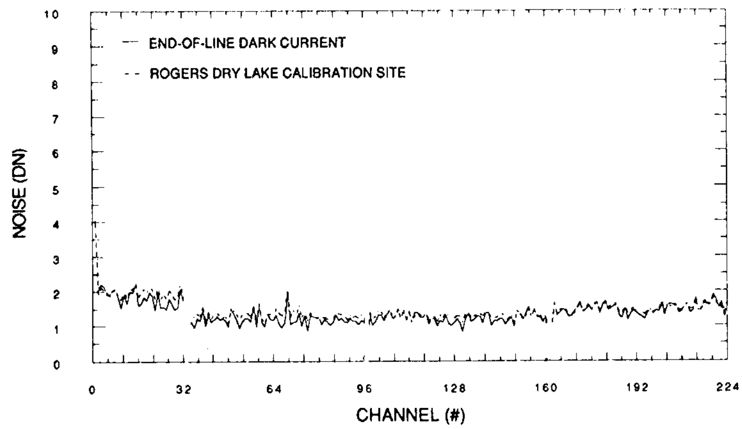

Figure 9. In-flight noise determined from the homogeneous Rogers Dry Lake, California, calibration surface and end-of-line dark current.

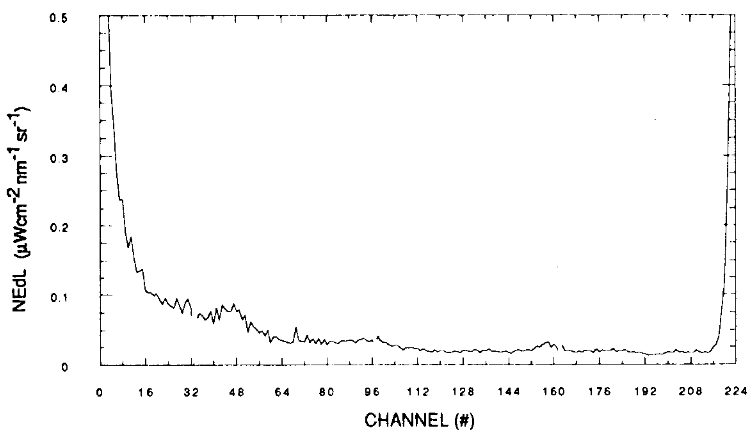

Figure 10. Radiometric precision is determined as the DN noise calibrated to units of radiance. This noise-equivalent-delta-radiance (NEdL) represents the precision at 1 root-mean-squared-deviation (RMSD) for AVIRIS radiance spectra.

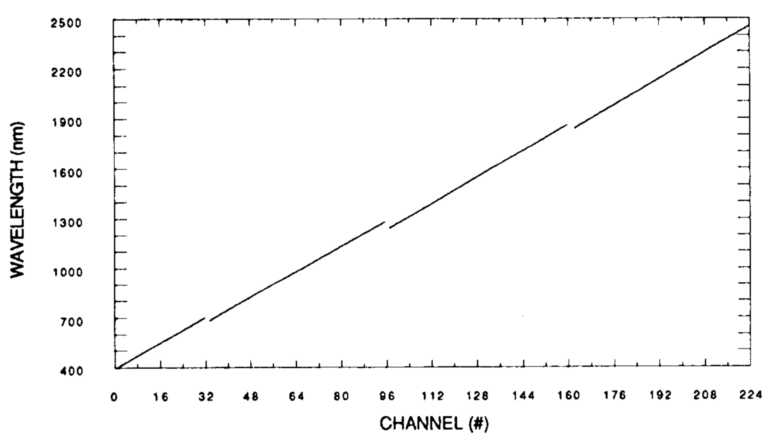

Figure 11. The spectral channel position of the 224 AVIRIS channels as measured in the laboratory.

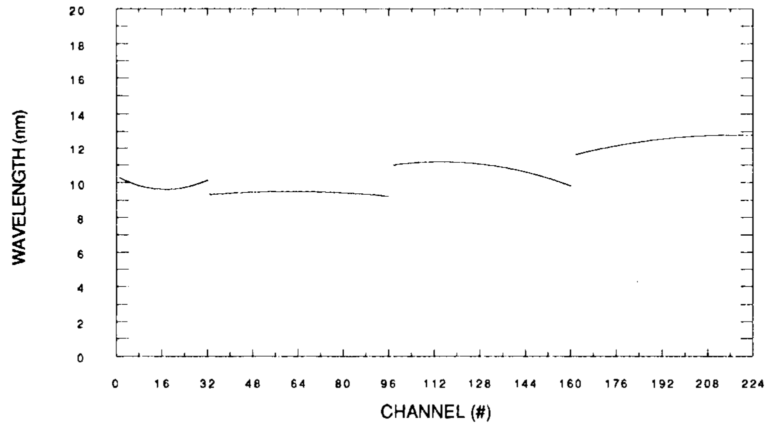

Figure 12. The spectral response function of the 224 AVIRIS channels. Spectral response is reported as the full width and half maximum of the corresponding Gaussian function.

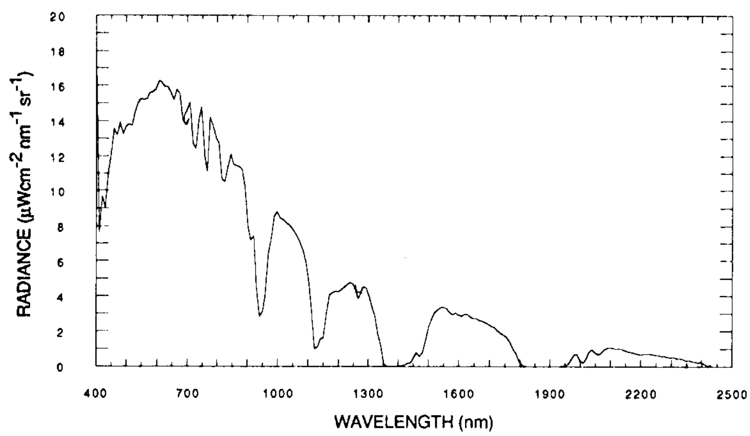

Figure 13. Spectrally and radiometrically calibrated AVIRIS spectrum of the calibration site at Rogers Dry Lake, California.

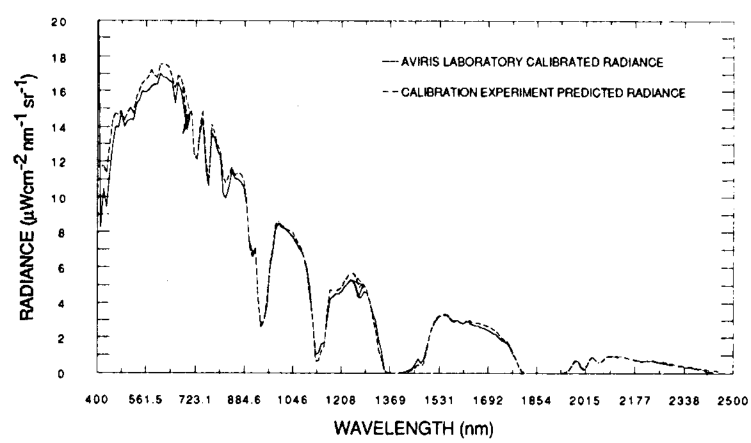

Figure 14. Comparison of the AVIRIS-measured spectrum from the calibration site and a radiative transfer-code predicted spectrum.