Retrieval of Reflectance from Calibrated Radiance Imagery Measured by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) for Lithological Mapping of the Clark Mountains, California

Robert O. Green

Jet Propulsion Laboratory
California Institute of Technology,
Pasadena, California 91109

ABSTRACT

Spectral radiance images measured by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) are reduced to reflectance through compensation for atmospheric scattering, water-vapor absorption, absorption of the well-mixed gases, solar irradiance, and the solar zenith angle. The LOWTRAN-7 radiative-transfer code form the basis for this retrieval. LOWTRAN 7 is constrained with water-vapor determinations from the AVIRIS radiance data through an algorithm operating on the 940-nm atmospheric water band for every spatial element. In situ measurements of atmospheric optical depths are used to constrain the LOWTRAN-7 aerosol models. Accuracy of the retrieved reflectance spectra is evaluated with respect to surface spectra measured at the time of the overflight. The mineral bastnaesite is identified in the analysis of the retrieved reflectance imagery. These reflectance data provide a means to map the subtle mineral gradients in the Precambrian block of the Clark Mountain range in southeastern California.

1.0 INTRODUCTION

AVIRIS measures the incident total spectral radiance with 224 channels from 400 to 2450 nm in the electromagnetic spectrum. The spectral sampling interval is nominally 10 nm, which corresponds to the spectral response function for full-width-at-half-maximum (FWHM) throughput. Image data are acquired with a width of 10.5 km and a length ranging from 10 to 100 km with nominally 20- by 20-m spatial resolution for all spectral channels. These data are provided in units of radiance, and the spectral position and response function of each channel is given.

The Clark Mountain Precambrian block is selected for the spectrally distinct surface mineralogy, the potential for rock-unit separation in previously undifferentiated metamorphosed Precambrian terrain, and the occurrence of a preexisting AVIRIS data set. The study site is located in southeastern California adjacent to the Nevada border and south of Las Vegas, Nevada. The region covered by the AVIRIS data and the location of the asphalt parking lot and gravel pit targets are given in Figure 1.

Reduction of AVIRIS-measured radiance to surface spectral reflectance offers the potential to quantitatively map the distribution of surface constituents based on physically determined spectral absorption features.

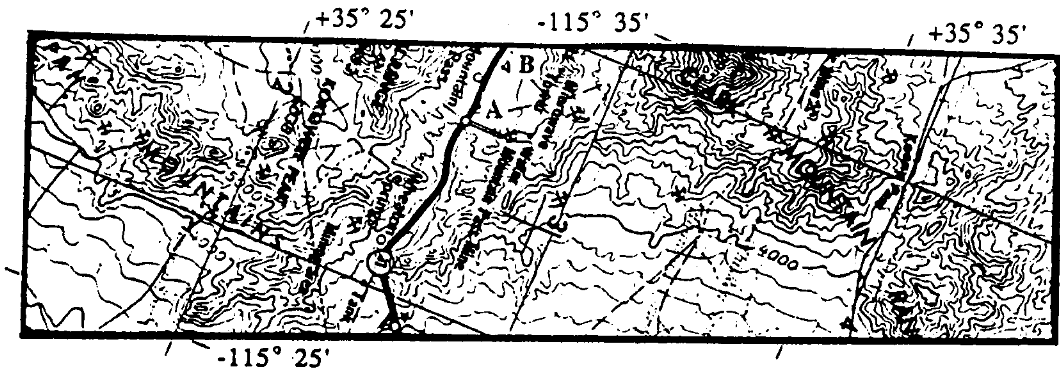

Figure 1. Location of the study area in the Clark Mountains of California. Target A is an asphalt parking lot. Target B is a gravel pit.

2.0 AVIRIS DATA

AVIRIS data were acquired over the Clark Mountain Precambrian block on the 28th of April 1989 at 12:05 p.m. These data were acquired in conjunction with an in-flight calibration experiment for verification of AVIRIS in-flight spectral characteristics. The mineral bastnaesite, which contains rare earth elements, has 12 strong absorption features over the AVIRIS spectral range. These features are used to validate the in-flight spectral calibration. The spatial coverage of the AVIRIS data set is 10.5 by 40 km trending northwest on the eastern flank of the Clark Mountains. These data are provided in units of total radiance with complete spectral calibration parameters for each channel (Chrien et al. 1990). Figure 2 gives the calibrated AVIRIS radiance for a gravel pit and asphalt parking lot targets located within the data set.

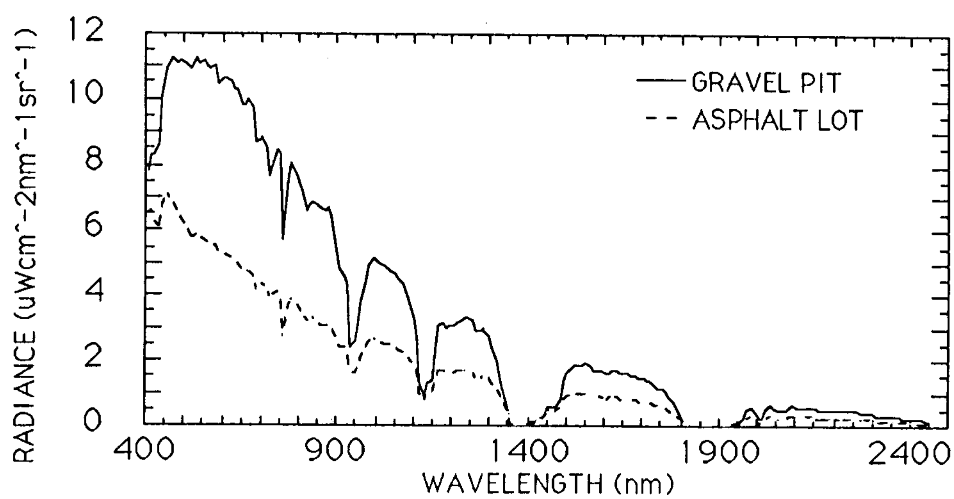

Figure 2. AVIRIS radiance spectrum for the asphalt parking lot (target A) and the gravel pit (target B).

3.0 FIELD MEASUREMENTS

In support of this experiment, measurements of the atmospheric optical depth and surface reflectance were acquired. On the day of the AVIRIS overflight, solar illumination measurements were acquired with a radiometer from sunrise to local solar noon. The instrument used has 10 discrete spectral channels with 10-nm response function FWHM in the region from 370 to 1030 nm. These data were reduced to atmospheric optical depth with the Langley plot method (Bruegge 1985). Figure 3 gives the reduced optical depths and the corresponding LOWTRAN-7 (Kneizys et al. 1989) optical depths that are used over the entire AVIRIS spectral range. These measured and modeled optical depths show good agreement in the region of overlap where aerosol scattering dominates. The LOWTRAN-7 visibility corresponding to these optical depths was 260 km.

Reflectance spectra for two surface targets were acquired in conjunction with this data set. These spectra were measured with a field spectrometer (Goetz 1987), which has a spectral channel sampling interval and response function FWHM that are less than half that of AVIRIS. Sets of 16 surface reflectance measurements, distributed evenly over the asphalt and gravel targets, were averaged and are given in Figure 4. These spectra are convolved to the AVIRIS spectral characteristic at the time of data acquisition.

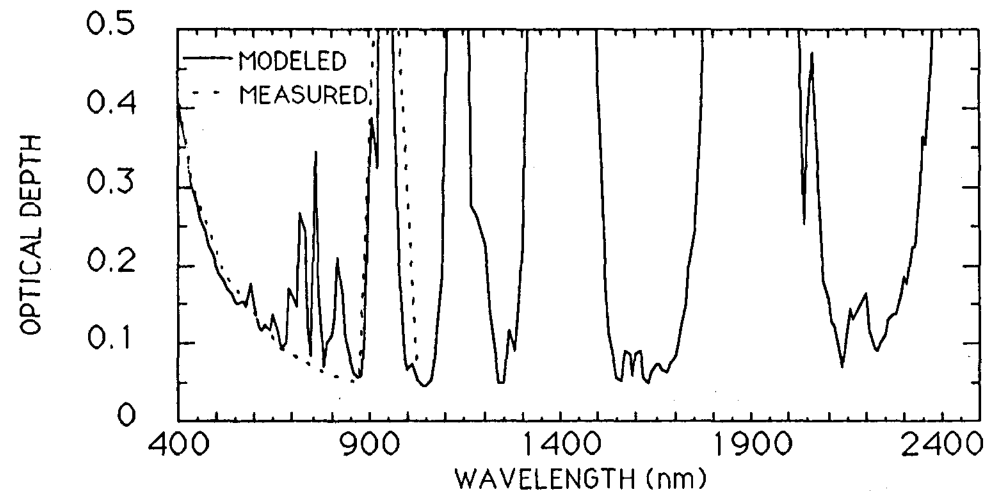

Figure 3. Atmospheric optical depths measured concurrently with the acquisition of AVIRIS data. Also given are the corresponding LOWTRAN-7 optical depths used to constrain the atmospheric model over the range of 400 to 2450 nm.

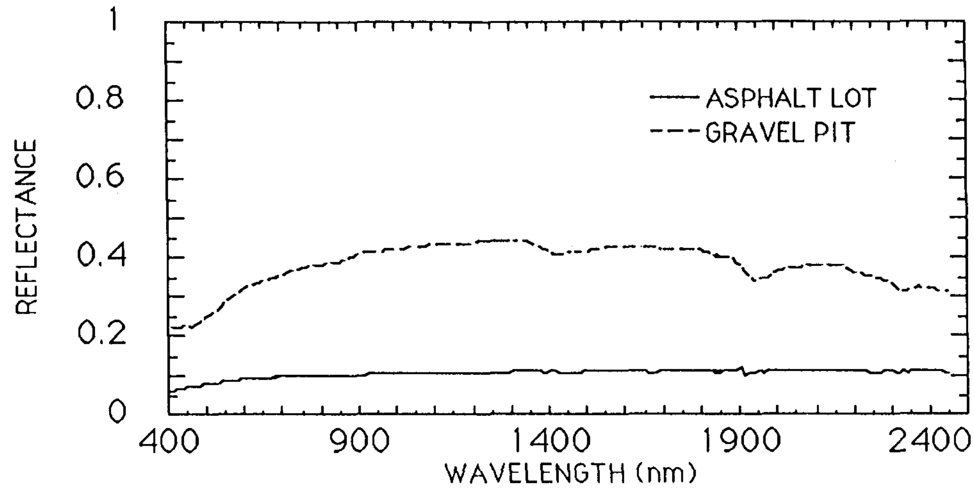

Figure 4. Measured surface reflectance for asphalt parking lot and gravel pit target.

4.0 REDUCTION OF AVIRIS DATA TO REFLECTANCE

An algorithm to retrieve reflectance directly from imaging spectrometer-measured radiance using a radiative-transfer code was originally developed for data acquired from the Airborne Imaging Spectrometer (AIS) (Conel et al. 1987). This reflectance-retrieval algorithm compensates for atmospheric scattering and absorption as well as solar illumination geometry; however, the surface incident and emergent angles and the bidirectional reflectance function remain uncompensated. Currently, aerosol and well-mixed gas variations with topography are approximated by the mean elevation. In the future, with the use of a topographic elevation data set, these parameters may be more accurately accounted for.

This algorithm treats AVIRIS-measured, total spectral radiance as the linear combination of radiance that has been reflected from the surface and radiance that is derived solely from atmospheric path scattering, as in Equation 1. Radiance scattered along the atmospheric path to AVIRIS without reflecting from the surface is given as L_p. L_r is the component of the AVIRIS radiance reflected by the surface. The total radiance measured by AVIRIS is given as L_t. The reflected radiance (L_r) is given in Equation 2 as the solar irradiance E_s multiplied by the cosine of the solar zenith angle over pi steradians and multiplied by the downward atmospheric transmittance (T_d), surface reflectance (ρ), and upward atmospheric transmittance (T_u).

$$L_t = L_r + L_p \tag{1}$$

$$L_r = (E_s \cos\theta/\pi) T_d \rho T_u \tag{2}$$

$$L_r = L_t - L_p \tag{3}$$

$$L_r/L_{r25} = (E_s \cos\theta/\pi) T_d \rho T_u \;/\; (E_s \cos q/\pi) T_d \rho_{25} T_u \tag{4}$$

$$\rho = (L_r/L_{r25}) \rho_{25} \tag{5}$$

Path radiance may be calculated with LOWTRAN 7 for the conditions of data acquisition leading to Equation 3, where the product L_r is isolated. With LOWTRAN 7, the reflected radiance (L_{r25}) for a 25-percent reflectance surface (ρ_{25}) may be modeled as in the denominator of Equation 4. AVIRIS reflectance may then be solved for as in Equation 5. This approach to deriving reflectance through modeling a known reflectance requires only minimal modification of an existing radiative-transfer code, such as LOWTRAN 7, and is easily adapted to other codes.

This radiative, transfer-based algorithm is sensitive to the absolute radiometric calibration of the AVIRIS data. Errors in calibration propagate directly to errors in retrieved reflectance. Calculations involving AVIRIS-measured radiance spectra and LOWTRAN-7-modeled spectra require the modeled data to be convolved to the exact in-flight spectral characteristics of AVIRIS. These calculations are highly sensitive to the spectral channel sampling interval and response-function calibration.

To constrain LOWTRAN 7 for calculation of the path and reflected radiance, atmospheric parameters were determined. AVIRIS-measured radiance is dominantly affected by atmospheric water vapor, as shown with a series of LOWTRAN-7 models for differing water in Figure 5. As the amount of water vapor varies from 0.0 to 23.56 precipitable mm, absorption features increase in depth across most of the spectral range from 400 to 2450 nm. In addition, a continuum absorption from water vapor affects the entire range. Over terrestrial surfaces, wide ranges of water vapor amounts are encountered. In regions with topographic relief, precipitable water vapor is modulated by changes in atmospheric path length through the vertical water-vapor distribution. Lateral and vertical heterogeneities of water vapor in the terrestrial atmosphere are also caused by local sources and sinks of water.

To show the importance of accurately constraining atmospheric water vapor, a sensitivity analysis for radiative, transfer-based reflectance retrievals, with respect to error in the knowledge of water vapor, is given in Figure 6. The error in retrieved reflectance is shown for an under-estimate of the actual water vapor present by 1, 10, and 30 percent. At a 10-percent error in knowledge of water vapor, significant reflectance errors occur in the spectral regions of strong absorption, particularly the 940-, 1130-, 1400-, 1900-, and 2500-nm bands.

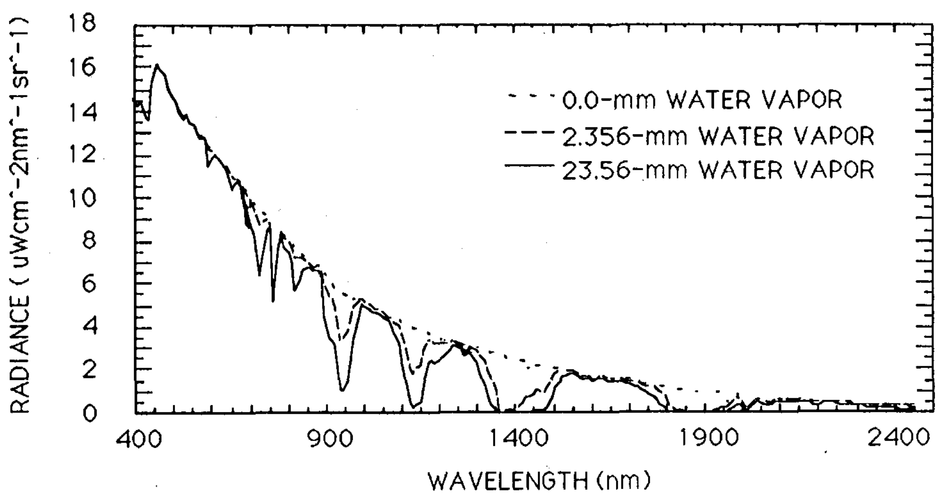

Figure 5. Modeled AVIRIS radiance for a constant 25-percent reflectance surface for differing amounts of atmospheric water vapor.

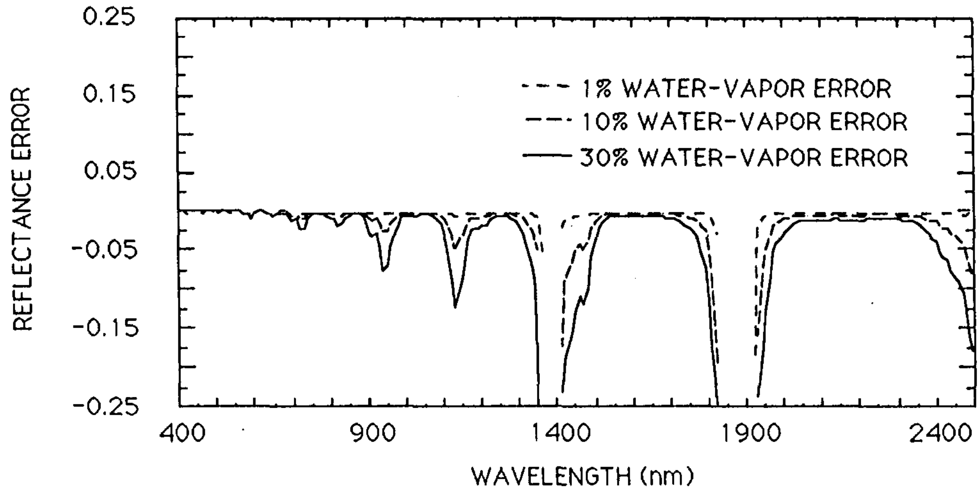

Figure 6. Sensitivity of reflectance recovery to total column atmospheric water vapor. Inaccuracies in knowledge of atmospheric water vapor result in errors in retrieved reflectance in regions of water absorption.

Sensitivity of the absorption depth in the 940- and 1130-nm atmospheric water band to the amount of water offers an approach to recovery of water vapor directly from the radiance data. A ratio-based algorithm was originally developed for recovery of total column water vapor from AVIRIS data (Conel et al. 1988, and Conel et al. 1989). The sensitivity of this technique to background surface reflectance prompted the development of the continuum-interpolated band ratio (CIBR) (Green et al. 1989 and Bruegge et al. 1990). For the 940-nm water band, the CIBR is calculated as the interpolated continuum from AVIRIS channels on either side of the water band ratioed to the channel in the band center. The CIBR is then calibrated to the vertical column equivalent of water vapor, using LOWTRAN 7 for the conditions of observation.

To constrain the radiative, transfer-based reflectance retrieval of the Clark Mountain data set, the CIBR algorithm is used to recover estimates of the total water vapor for each spatial element. Over this data set, water-vapor retrieval ranged from 7 to 18 precipitable mm. This wide range confirms the need to estimate the water vapor for each spatial element. With these water estimates, a 25-percent reflectance LOWTRAN-7 path and reflected-radiance spectrum library is developed for each tenth of a millimeter variation in water vapor in the data set. Measured optical depths, mean topographic elevation, and solar-illumination geometry at the time of data acquisition are used to further constrain LOWTRAN 7. Reflectance is solved from the AVIRIS-calibrated radiance data for each spatial element, with the correct water-vapor-constrained library spectrum. Figure 7 gives the AVIRIS radiance spectrum for the gravel target, with the LOWTRAN 7 library spectra for path and reflected radiance. Figure 8 is the retrieved reflectance for the asphalt and gravel targets. Good agreement is seen between the field measurement given in Figure 4 and these AVIRIS-retrieved reflectance spectra.

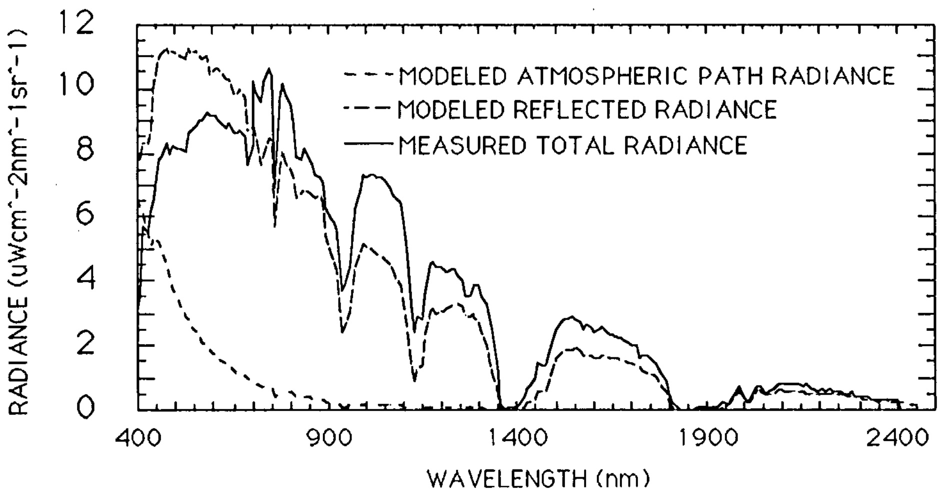

Figure 7. AVIRIS-calibrated radiance spectrum for the asphalt parking lot. The modeled LOWTRAN-7 path and reflected radiance for the observations are given for a 25-percent reflectance surface under solar illumination, atmospheric aerosols, and calculated water vapor.

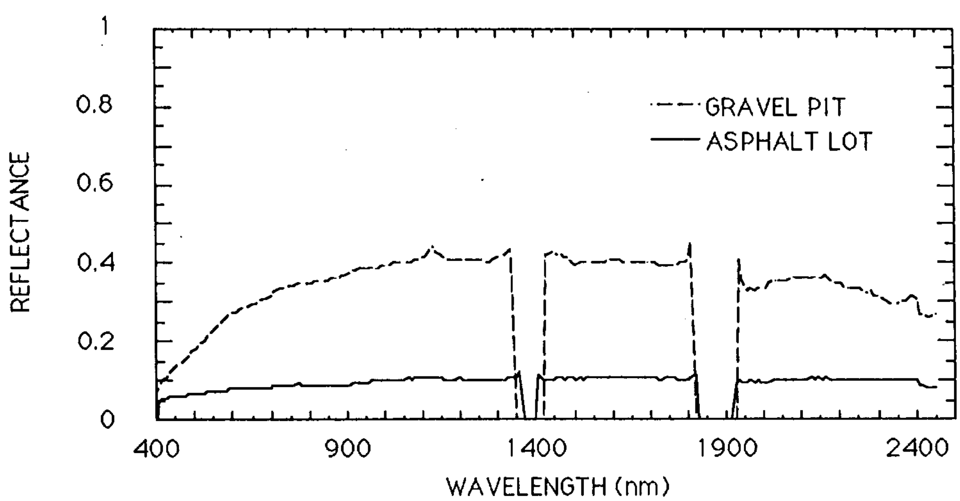

Figure 8. Radiative transfer-based retrieval of reflectance for the asphalt and gravel targets.

In the future, to more accurately constrain the radiative-transfer code, the aerosol estimate will be derived directly from the AVIRIS data through an iterative algorithm based on the differential effect of scattering on the 940- and 1130-nm water bands in AVIRIS data (Green et al. 1989). A CIBR assessment of the depth of the atmospheric oxygen band at 760 nm will be used to estimate the pressure altitude to constrain LOWTRAN-7 aerosol and well-mixed gas absorption parameters for variation in surface topography and pressure.

5.0 COMPOSITIONAL MAPPING

With the AVIRIS data in units of reflectance, physically based compositional identification may be determined for the surface. An example of a retrieved reflectance spectrum for the mineral bastnaesite and a laboratory spectrum of the same mineral are given in Figure 9. The unique combination of spectral absorptions allows unambiguous identification of this mineral. An unmixing algorithm (Adams et al. 1986) offers an approach to quantitatively explaining the entire AVIRIS reflectance data in terms of a suite of mineral endmembers. This and other approaches to spatial mapping the distribution of minerals in this data set will be investigated and confirmed in the field.

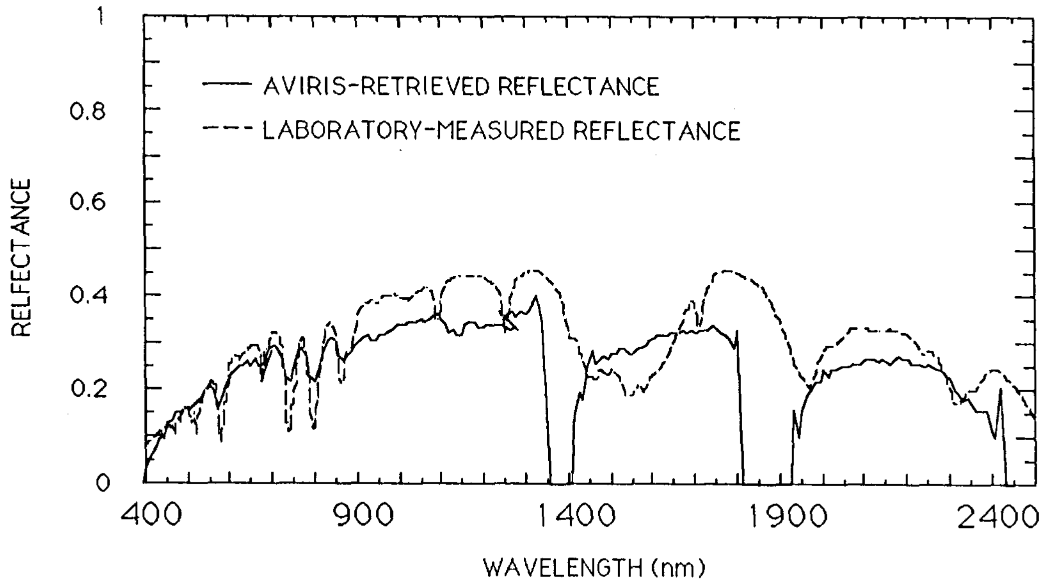

Figure 9. Retrieved reflectance for exposed bastnaesite associated with the Mountain Pass mine and laboratory-measured spectrum.

6.0 CONCLUSION

Reflectance spectra have been retrieved from AVIRIS radiance data using a radiative-transfer-code-based algorithm. In this instance, LOWTRAN 7 was used. To constrain the code, atmospheric water-vapor estimates were derived directly from the AVIRIS radiance data for every spatial element of the imagery. Aerosols, measured at the time of the overflight and the solar-illumination geometry were used to further constrain the code. Algorithms retrieving aerosols and pressure altitude from AVIRIS radiance data at known accuracy and precision are being developed to improve this radiative-transfer-based reflectance recovery in the future. The retrieved reflectances agree with measurement of targets in the field. Accuracy of this retrieval is a function of both the radiative-transfer code and constraints as well as the accuracy of AVIRIS spectral and radiometric calibration. Calculated AVIRIS surface reflectance data offer a quantitative approach to regional geological analysis through determinations of surface mineralogy and lithology at known accuracies and precisions.

7.0 ACKNOWLEDGMENTS

Thanks are due Carol Bruegge who acquired and reduced the atmospherical optical depth data. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

8.0 REFERENCES

Adams, J.B., M.O. Smith, and P.E. Johnson, Spectral mixture modeling: a new analysis of rock and soil types at the Viking Lander 1 site, J. Geophys. Res. 91, 1986.

Bruegge, C.J., In-flight absolute radiometric calibration of the Landsat Thematic Mapper (Published under Kastner), Ph.D. Dissertation, University of Arizona, 1985.

Bruegge, C.J., J.E. Conel, J.S. Margolis, R.O. Green, G. Toon, V. Carrere, R.G. Holm, and G. Hoover, In-situ atmospheric water-vapor retrieval in support of AVIRIS validation, SPIE Vol. 1298, Imaging Spectroscopy of the Terrestrial Environment, in press, 1990.

Chrien, T.G., R.O. Green, and M. Eastwood, Laboratory spectral and radiometric calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), SPIE Vol. 1298, Imaging Spectroscopy of the Terrestrial Environment, in press, 1990.

Conel, J.E., R.O. Green, G. Vane, C.J. Bruegge, R.E. Alley, and B.J. Curtiss, AIS-2 Radiometry and a comparison of methods for the recovery of ground reflectance, in Proceeding of the Third Airborne Imaging Spectrometer Data Analysis Workshop (G. Vane, ed.), JPL Publication 87-30, Jet Propulsion Laboratory, Pasadena, CA, 1987.

Conel, J.E., R.O. Green, V. Carrere, J.S. Margolis, R.E. Alley, G. Vane, C.J. Bruegee, and B.L. Gary, Atmospheric water mapping with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Mountain Pass, CA., in Proceedings of the AVIRIS Performance Evaluation Workshop (G. Vane, ed.). JPL Pub. 88-38, 21-26, 1988.

Conel, J.E., R.O. Green, V. Carrere, J.S. Margolis, R.E. Alley, G. Vane, C.J. Bruegee, and R.E. Alley, Spectroscopic measurement of atmospheric water vapor and determination of evaporation from land and water surfaces using the AVIRIS, IGARSS'89 12th Canadian Symposium on Remote Sensing, 4, 2658-2663, 1989.

Goetz, A.F.H., The Portable Instantaneous Display and Analysis Spectrometer (PIDAS), Proceedings of the Third Airborne Imaging Spectrometer Data Analysis Workshop (G.Vane, ed.), JPL Publication 87-30, Jet Propulsion Laboratory, Pasadena, CA, 1987.

Green, R.O., V. Carrere, and J.E. Conel, Measurement of atmospheric water vapor using the Airborne Visible/Infrared Imaging Spectrometer, ASPRS, Image Processing '89, 1989.

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, AFGL, Hanscom AFB, MA, 1989.