# VALIDATION OF ATMOSPHERIC CORRECTION OF AIRBORNE VISIBLE/INFRARED IMAGING SPECTROMETER (AVIRIS) RADIANCE DATA BASED ON RADIATIVE TRANSFER MODELING

V. Carrère and J. E. Conel
Jet Propulsion Laboratory / California Institute of Technology
MS 183-501.4800 Oak Grove Drive,CA91109, USA

## ABSTRACT

An evaluation of atmospheric correction of AVIRIS data using radiative transfer codes LOWTRAN 7 and MODTRAN is presented. The algorithm employed is based on a simplified model of radiance $L$, at each wavelength at the sensor that can be written approximately $L_{AV} \approx L_p + T_p \rho$, where subscript AV refers to AVIRIS, $L_p$ is the path radiance and $T_p$ is the diffuse + direct transmitted radiance of the atmosphere at AVIRIS. The Lambertian surface reflectance $\rho$ is the quantity to be estimated. Two steps are involved in the recovery: (1) $L_p$ and $T_p$ are estimated from LOWTRAN 7 or MODTRAN runs, using the following parameters: latitude, longitude, target and observer elevations, day and time of acquisition, flight azimuth and viewing angle, an atmospheric model for gaseous components and water vapor, aerosols, and a user defined surface reflectance; (2) using the $L_p$ and $T_p$ terms derived from the previous step, and assuming uniform atmospheric conditions apply, the reflectance $\rho$ is obtained for each pixel of an AVIRIS image. An example of reflectance retrievals from AVIRIS radiance data at Cuprite, Nevada, is presented. No concurrent ground measurements were available. To help constrain the model in this case, (1) approximate. ground spectral reflectances were. estimated from the radiances at wavelengths of high atmospheric transparency and low path radiance, (2) water vapor total column abundance was retrieved from AVIRIS radiance data using simple algorithms based on band radiance ratios, (3) total modeled radiance and path radiance were calculated with the radiative transfer codes assuming rural aerosols and a visibility of 250 km, and (4) ground spectral reflectance was retrieved. Laboratory hemispherical reflectance measurements of samples collected in the field were then used only to assess accuracy of the recoveries. MODTRAN retrieved reflectance was found to be closer to the laboratory spectrum. Major sources of discrepancy are shown to arise from atmospheric gaseous absorption and solar irradiance file used in the radiative transfer code as well as uncertainties in instrument calibration coefficients, particularly in the visible part of the spectrum and around 1200 nm. Generalization to an entire AVIRIS scene implies knowledge on a pixel-by-pixel basis of ground elevation, viewing geometry, water vapor content and estimated ground reflectance. Systematic departure from model assumptions mainly translate in the retrieved reflectance into residual absorption or spikes corresponding to over- or undercompensation for atmospheric gases.

## 1. INTRODUCTION

We report here preliminary results on our assessment of the accuracy of an algorithm for atmospheric correction of high spectral resolution imaging spectrometer data. This algorithm is based on a simplified model of radiance $L$ at each wavelength at the sensor that can be approximately written:

$$L_{AV} = L_p + T_p \rho \tag{1}$$

Subscript AV refers to AVIRIS, $L_p$ is the path radiance and "$T_p$", the diffuse + direct transmitted radiance of the atmosphere at AVIRIS. $L_p$ and $T_p$ are estimated using the radiative transfer codes LOWTRAN 7 (Kneizys et al., 1988 ) and MODTRAN (Berk et al., 1989).

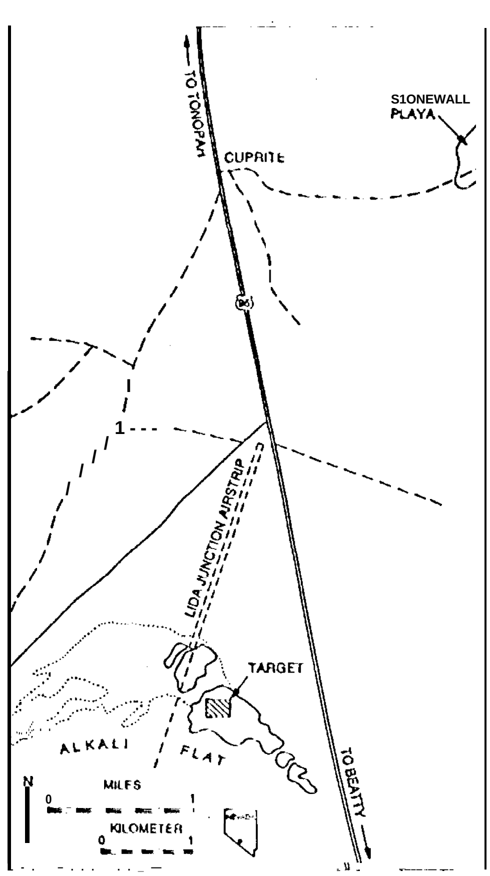


Figure 1. Location of the test area

The algorithm was tested on an AVIRIS data set acquired on July 23, 1990, over Cuprite, Nevada, provided by G. Swayze and R. Clark (USGS, Denver). Our analysis focussed on a 200x 200 m area of playa (dry lake bed) located SW of Highway 95, next to the Lida Junction Airstrip (Fig. 1). We selected that area because playa are generally flat, homogeneous surfaces at the sensor spatial resolution and present simple spectral responses.

Our objective is to understand the nature and magnitude of potential sources of errors in the recovery of ground surface reflectance from imaging spectrometer data such as those acquired by AVIRIS. AVIRIS is a test-bed for future spacecraft sensors such as the High Resolution Imaging Spectrometer (HIRIS) and the Moderate Resolution Imaging Spectrometer (MODIS) planned for the Earth Observing System. AVIRIS measures the total upwelling radiance from 400 to 2450 nm in the electromagnetic spectrum through 224 contiguous spectral channels. The spectral sampling interval and response function for each channel is nominally 10 nm. The approximate spatial resolution is 20 m and the swath width 11 km.

Reliable, accurate recovery of surface reflectance is required for quantitative analysis of AVIRIS data, detection of spectral and temporal changes or comparison with data measured by other instruments.

The case presented here illustrates the general situation faced by most investigators, i. e., no concurrent ground measurements (atmospheric characteristics and surface spectral reflectance) are available to constrain the model. First, we describe the methodology followed to retrieve ground reflectance from AVIRIS radiance data. Results are then analyzed and a preliminary error analysis of the nature and magnitude of sources of discrepancy is presented through comparison of the retrieved reflectances with a laboratory hemispherical reflectance spectrum of samples previously collected in the field. Concluding remarks describe future plans and first assessment of what is involved to generalize the methodology to an entire AVIRIS scene.

## 2. METHODOLOGY

As mentioned above, this algorithm is based on a simplified relationship between radiance at the sensor and ground spectral reflectance (Equation 1). This equation is underdetermined. Radiative transfer modeling allows, by predicting the total radiance $L_m$ at the sensor for the conditions of observation, to solve for $L_p$ and $T_p$, providing the following parameters: latitude, longitude, target and observer elevations, day and time of acquisition, flight azimuth and viewing angle, an atmospheric model for gaseous components and water vapor, aerosols, and a user defined surface reflectance. $\rho_m$. From Equation (1):

$$L_p = L_m \quad \text{for } \rho = 0, \tag{2}$$

and

$$T_p = L_m - L_p / \rho_m \tag{3}$$

$L_m$, $L_p$ and $T_p$ are calculated by the model with a better spectral resolution that AVIRIS and have to be convolved to AVIRIS bandpasses using 10 nm FWHM gaussian filters.

Recovering ground spectral reflectance from AVIRIS radiance data involves the following steps:

(1) An approximate ground reflectance is estimated from the AVIRIS radiance at wavelengths of high atmospheric transparency (high transmittance) and low path radiance (Fig. 2), using Equation (4):

$$\rho_{app.} = L_{AV} * \pi / E_o T^2 \cos \theta_s \tag{4}$$

whet-c $E_o$ is the solar irradiance, T the atmospheric transmittance and $\theta_s$ the solar zenith angle.

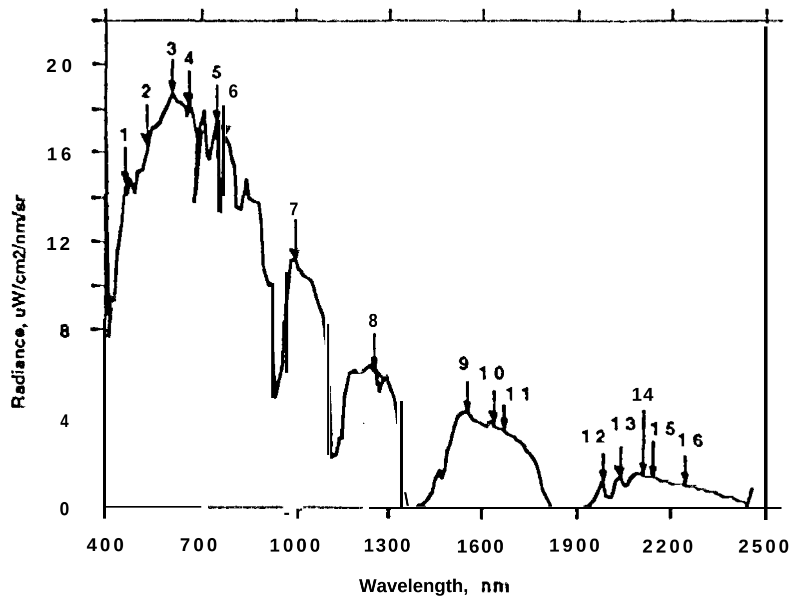


Figure 2. Wavelengths at which apparent reflectance was estimated from the AVIRIS radiance

(2) Water vapor total column abundance is retrieved from AVIRIS radiance data using a simple algorithm based on 3 band radiance ratio, the Continuum Interpolated Band Ratio or CIBR (Green et al., 1990). Previous sensitivity anal ysis of this technique to systematic and random errors (Carrère and Cone], 1992) has shown the accuracy of the recovery to be better than 1% on a clear day when some estimate of the ground reflectance is available.

(3) Total radiance at the sensor $L_m$ is modeled using the estimated reflectance and water vapor abundance as input to the radiative transfer code.

(4) Resulting total radiance is compared to AVIRIS radiance' to assess accuracy of input model parameters, particularly visibility and water amount.

(5) When a "reasonable" agreement is reached, path radiance $L_p$ is calculated using Equation (2).

(6) Diffuse +- direct transmitted radiance of the atmosphere $T_p$ is calculated using Equation (3).

(7) Finally, ground reflectance is retrieve.d from AVIRIS radiance, using Equation (5):

$$\rho_{AV} = L_{AV} - L_p / T_p \tag{5}$$

$\rho_{AV}$ is then compared to the laboratory hemispherical reflectance for validation and error analysis.

## 3. RESULTS

The following sections present a preliminary analysis of the retrieved reflectances using LOWTRAN 7 and MODTRAN and of the problems encountered along the path. A first attempt is made to explain in detail the sources of discrepancy between the two models, and the resulting reflectances and the laboratory hemispherical reflectance used as a reference.

### 3.1 ESTIMATION OF MODEL, INPUT PARAMETERS

#### 3.1.1 Apparent reflectance

"l'he apparent reflectance retrieved from AVIRIS radiance data using Equation (4) at the wavelengths highlighted in Fig. 2 is shown in Fig. 3. It is obvious that the values retrieved in the visible region are non realistic and confirm a problem already mentioned byCarter (1992).

A multiplicative calibration adjustment factor, CAL($\lambda$), has to be applied in this region of' the spectrum ($400 < \lambda < 700$ nm) to adjust the total radiance measured by AVIRIS to the modeled radiance using the laboratory spectral reflectance to constrain the model spectrally:

$$CAL(\lambda) = L_m / L_{AV} \tag{6}$$

The partially resealed reflectance was used to constrain themodel for the next steps. Reflectance values between estimated points are linearly interpolated by the model to calculate the radiance at each wavelength.

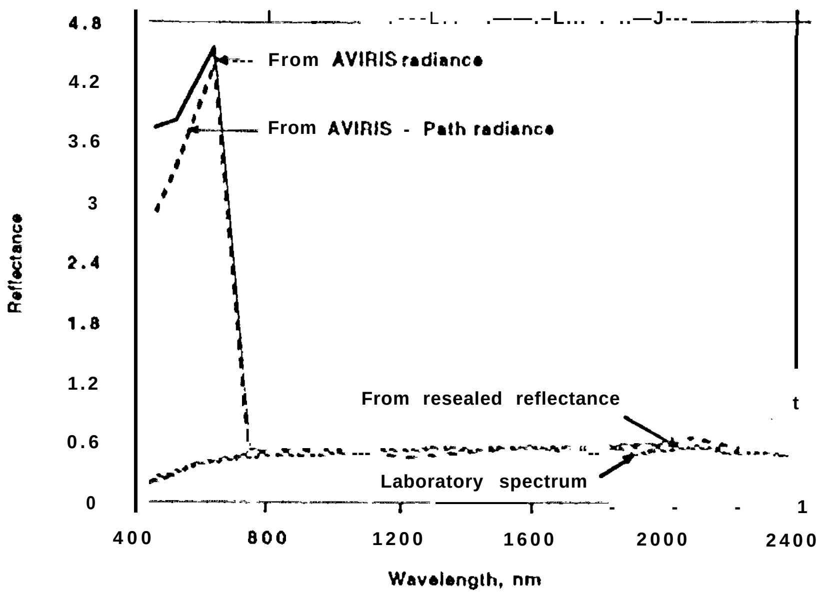


Figure 3. Comparison between laboratory hemispherical reflectance and apparent reflectance estimated from AVIRIS radiance, AVIRIS radiance - path radiance and "resealed" apparent reflectance after calibration adjustment in the visible.

### 3.1.2 Water vapor

Estimation of the total column abundance of atmospheric water vapor from AVIRIS radiance data using the CIBR algorithm requires to constrain the radiative transfer model to establish the calibration law relating radiance ratio to precipitable centimeters of water. Since no ground measurements were available and considering the day of acquisition and the location of the target, the visibility (or meteorological range) was set to 250 km, reflecting clear day conditions. In general, it is impossible to estimate extinction due to scattering at 550 nm, used by the model to compute meteorological range, from AVIRIS data themselves except when values of surface spectral reflectance are available or the scene contains a dark target such as a body of water over which an estimate of path radiance can be obtained and visibility retrieved by inversion of the radiative transfer code.

Onc of the three standard aerosol types provided by the model, the rural aerosol type, was selected as characteristic of the area. Rural aerosols arc assumed to be comprised of 70% water soluble material (ammonium and calcium sulfate and organics) and 30% dust aerosol (Shuttle and Penn, 1979).

Location of the target in the scene implied a viewing angle of 11.8" for a crosstrack azimuth of N270 (the flight azimuth was N 180). Target elevation was 1411 m according to the topographic map.

The water amount retrieved over the target by the CIBR algorithm was of 0.8 g/cm$^2$ for LOWTRAN 7 and 1.2 g/cm$^2$ for MODTRAN, corresponding respectively to 81 % and 83% of the total standard column included in the models. An uncertainty of about 1% should be expected on these values based on our previous error analysis (see Carrère and Conel, 1992., for details).

## 3.2 GENERAL REMARKS ON RETRIEVED REFLECTANCES

As shown in Fig. 4, the resulting reflectances arc not as "smooth" as the laboratory spectrum. Furthermore, except for the visible region between 400 and 700 nm where the adjustment factor was applied, and the region between the 1400 and 1900 nm water bands, the average retrieved reflectance dots not match the laboratory spectrum. "l"he offset observed is not consistent across the spectrum: retrieved reflectance is too high between 700 and 1200 nm, too low between 1200 and 1400 nm and too high again in the shortwave infrared (SWIR). Onc can also notice big "spikes" outside the main saturated water bands.

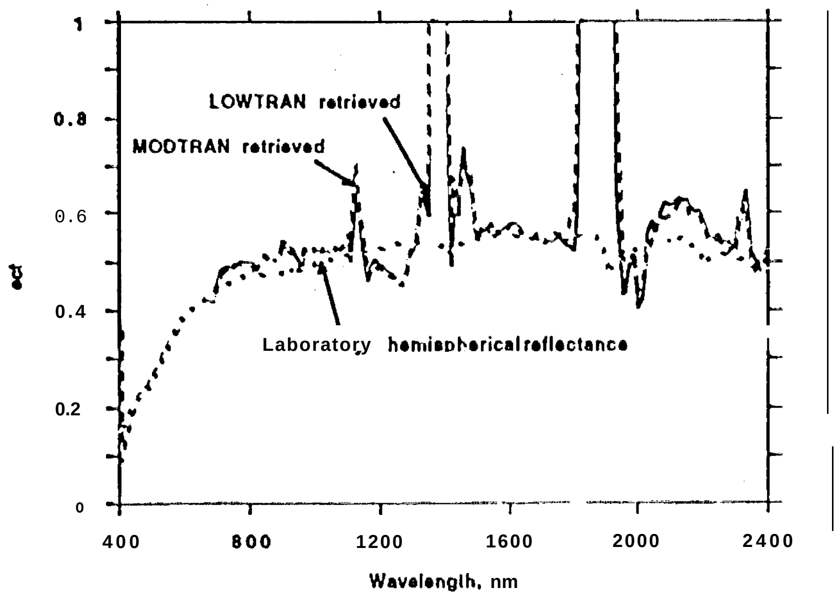


Figure 4. Comparison between reflectances retrieved using LOWTRAN 7 and MOD-l-RAN and average laboratory hemispherical reflectance of samples collected in the field.

## 3.3 COMPARISON BETWEEN LOWTRAN AND MODTRAN RETRIEVALS

Reflectance retrieved using LOWTRAN 7 and MODTRAN present some differences. As shown in Fig. 5, most of these differences can be explained by improvements made to MODTRAN (Berk et al., 1989).

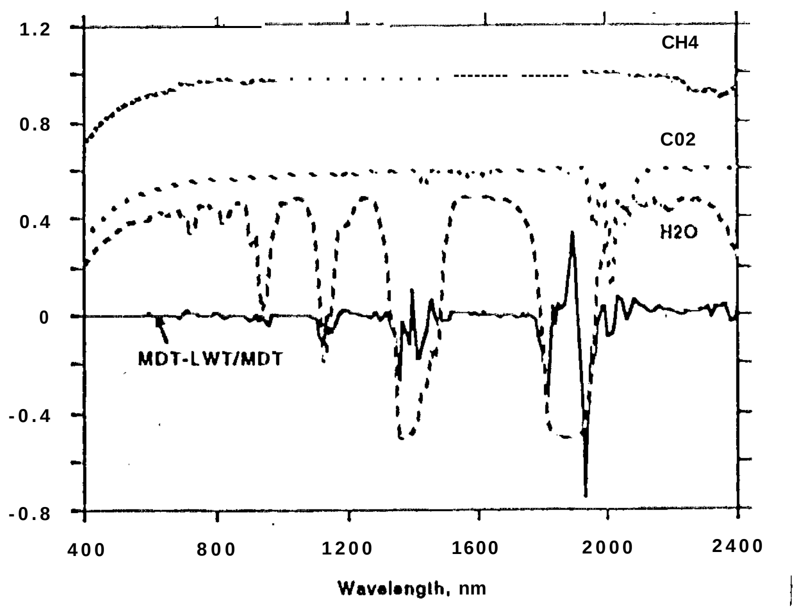


Figure 5. Normalized difference between LOWTRAN 7 and MODTRAN modeled radiances and comparison with transmittance for $CO_2$, $CH_4$ and $H_20$. The transmittance curves arc displaced vertically for clarity.

In addition to having different spectral resolutions (2 $cm^{-1}$ for MODTRAN versus 20 $cm^{-1}$ for LOWTRAN 7), the two models differ in their approaches to calculate molecular transmittance. For several different spectral intervals, L OWTRAN 7 uses a one parameter band model (absorption coefficient) plus molecular density scaling functions. The MODTRAN band model uses three temperature dependent parameters, an absorption coefficient, a line density parameter and an average line width. The absorption coefficient measures the total strength of lines in an interval. The line density is a line-strength weighted average for the number of lines in the interval and the line width parameter is a line-strength weighted average line-width. MODTRAN uses a bin width of one wavelength and line data from the HITRAN database, the AFGL line atlas, to calculate the band model par-meters.

LOWTRAN 7 and MODTRAN implementations of the multiple scattering routines arc also different. LOWTRAN trees the k-distribution method to approximate multiple scattering contribution to each 5 $cm^{-1}$ interval as the sum of three monochromatic calculations. Since the intervals in MODTRAN are only 1 $cm^{-1}$ wide, the partitioning into sub-intervals has been eliminated and the single average absorption coefficient is used for each bin (Berk et al., 1989).

Consequently to those modifications, the standard amount reported for each atmospheric gases is different. More specifically, the amount of $CO_2$ has been adjusted to fit more recent estimates and reflect the increase in $CO_2$ content of the atmosphere. The difference in calculation of molecular transmittance is also noticeable, particularly in the wings of the major absorptions.

## 3.2 ERROR ANALYSIS

We initiated a detailed error analysis to understand the source and signification of every single observed discrepancy.

Generally, sources of discrepancy can arise from:

(1) systematic errors in model input parameters (reflectance, visibility, type of aerosol), affecting the modeled total radiance, path radiance and transmitted atmospheric radiance;

(2) inaccuracy in the model which does not represent reality;

(3) the behavior of the instrument inflight being different from when it was characterized in the laboratory.

### 3.4.1 Systematic errors in model input parameters

To investigate if the discrepancies could originate in systematic errors in parameters used to constrain the model, a comparison was made between the observed AVIRIS radiance and a modeled radiance constrained using the laboratory reflectance. If all the other parameters are correct (mainly visibility, aerosols, and water absorption), the modeled radiance should represent exactly the radiance of the target at the sensor and be identical to the observed radiance.

As shown on Fig. 6, some important differences appear. AVIRIS radiance is systematically higher than the predicted radiance in the visible near infrared. It is drastically lower than the modeled radiance between the 1130 and 1400 nm water bands (which has already been reported for other data sets). The match seems better for longer wavelengths.

The fact that AVIRIS radiance is systematically higher in the visible could be explained by the real visibility being higher that the one used to constrain the model. However, a visibility of 250 km already corresponds to a very clear day and no improvement was obtained by increasing it. It was thus postulated that the difference arises from gaseous absorption (water in particular) which were less important than in the model. The model was thus run again with a visibility of 250 km but with no major gases absorption and no aerosols. As shown on Fig. 6, the discrepancies observed previously remain, confirming that the source of error is not due to inaccurate representation of atmospheric characteristics.

c-03

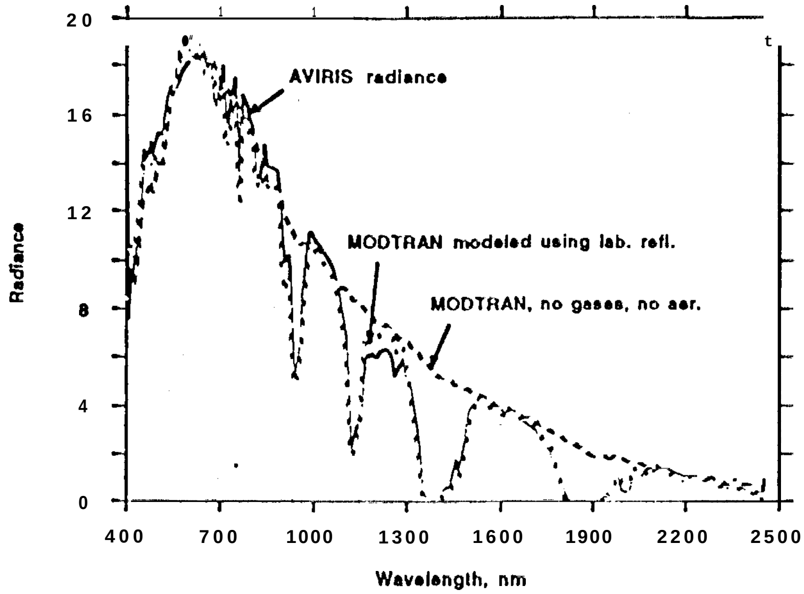


Figure 6. Comparison between: AVIRIS radiance, MODTRAN modeled radiance using the laboratory hemispherical reflectance andMODTRAN modeled radiance derived when removing gas absorption and aerosols.

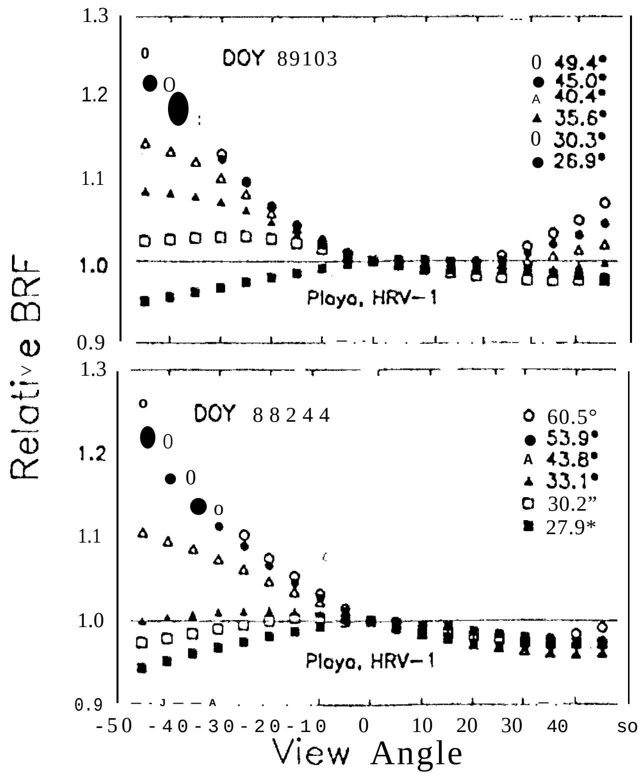


Figure 7. Relative bidirectional reflectance factors measured over the playa at Rogers (Dry) Lake, Mohave, California on DOY 88244 and 89103, as a function of view angle at a number of solar zenith angles (After Jackson et al., 1990).

The next possible explanation could be the fact that the laboratory hemispherical reflectance does not represent the reflectance observed by the instrument on the day of data acquisition. Since the samples were collected at a different time, it is possible that the surface of the playa was drier at the time of the overflight which would increase its reflectance in the visible. Additionally, Laboratory hemispherical reflectance does not account for directional effects arising from viewing and illumination geometry. It was not possible to verify directly these hypotheses since no concurrent measurements were available. However, an analysis of bidirectional reflectance factors (B RFs) for various surfaces published by Jackson et al. (1990), including measurements made at Rogers Dry Lake, California, under similar conditions, shows that the BRFs for a playa surface for a solar zenith angle of 22.5° and a view angle of -11.8° corresponding to the viewing geometry of our target is very close to 1 (≈ 0.99, Fig. 7). The directional effect is minimal for those conditions of observation and would have the opposite effect, lowering the reflectance by comparison to normal, hemispherical reflectance.

We conclude that systematic errors in model input parameters cannot satisfactorily explain the observed discrepancies.

3.4.2 Inaccuracy in the model

The ability for a radiative transfer model to accurately represent reality relies on our improving knowledge of spectroscopy and physics of the Earth's atmosphere as it is demonstrated by the improvement from L OWTRAN 7 to MODTRAN for example.

In the case presented here, systematic errors arising from the model can originate in (1) the amount of gas absorbers defaulted in the model (for example, the amount of $C0_2$ in the atmosphere has increased and is taken into account in MODTRAN when it was not in LOWTRAN 7), (2) the physical model used to calculate gas absorption, and (3) the solar irradiance file used in the model.

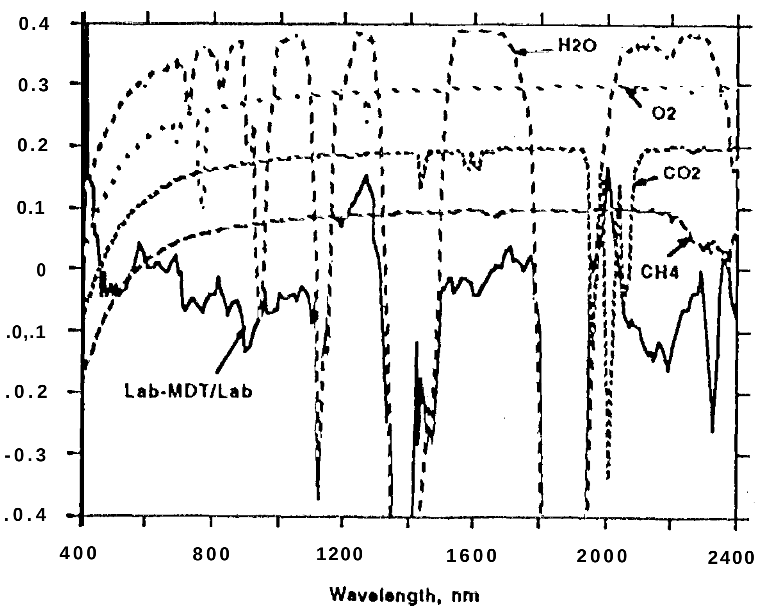


Figure 8. Comparison between discrepancies observed between the laboratory hemispherical reflectance and the MODTRAN retrieved reflectance (expressed as normal ized di fference) and transmittance for main atmospheric gases absorbing in the wavelength range covered by AVIRIS. The transmittance curves are displaced vertically for clarity.

Amount of (therefore depth of the absorption) well mixed gases such as $O_2$, $CO_2$, and $CH_4$, which have absorption features in the wavelength range covered by AVIRIS, should be directly proportional to path length, represented by the two input parameters, observer and target elevations. Some of the''roughness" of the retrieved reflectance can be explained by under- or overcompensation for these gases (Fig. 8), probably due to inaccurate standard total column abundance used by the model. The effect of the model used to calculate absorption and thus determine the shape of the features is particularly sensitive in the wings of the major absorption such as the saturated 1400 and 1900 nm water bands. It is clear that the MODTRAN calculation is closer to reality than LOWTRAN 7's.

Comparison of various sources of solar irradiance files (Arvesen et al., 1969; WCRP, 1986; Tanré et al., 1985; Fig. 9) shows that none of the major discrepancies can be explained by the usc of an inappropriate solar irradiance file in MODTRAN. The magnitude of the difference between the various existing solar irradiance files is much smaller than the discrepancies observed. However, small differences can be correlated with some of the "roughness" on the reflectance, particularly in the infrared, as shown on Fig. 10.

Additional information could be obtained by replacing the solar irradiance file in MODTRAN by onc from another source and repeating the procedure.

3.4.3 Errors related to the instrument

Possible sources of systematic error in retrieved reflectance due to the instrument itself can be increased noise inflight (related to plane vibration, electronic noise, etc.) and/or instrument calibration,

For every spatial resolution element, AVIRIS records the upwelling radiance as digitized numbers (DNs) ranging from O to 1024 for each 224 spectral channels. The shape of each spectrum is predominantly a consequence of the upwelling radiance, the instrument radiometric response, and the additive instrument dark current (Green et al., 1991). A mean of 100 lines of dark current is subtracted from the measured signal for each channel, line and sample to generate a spectrum with values proportional to the upwelling radiance.

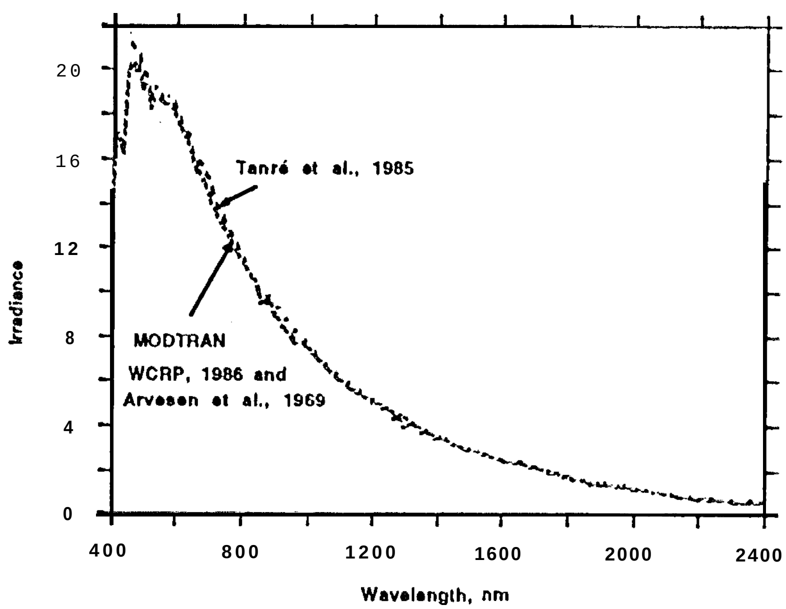


Figure 9. Examples of available spectral solar irradiance files

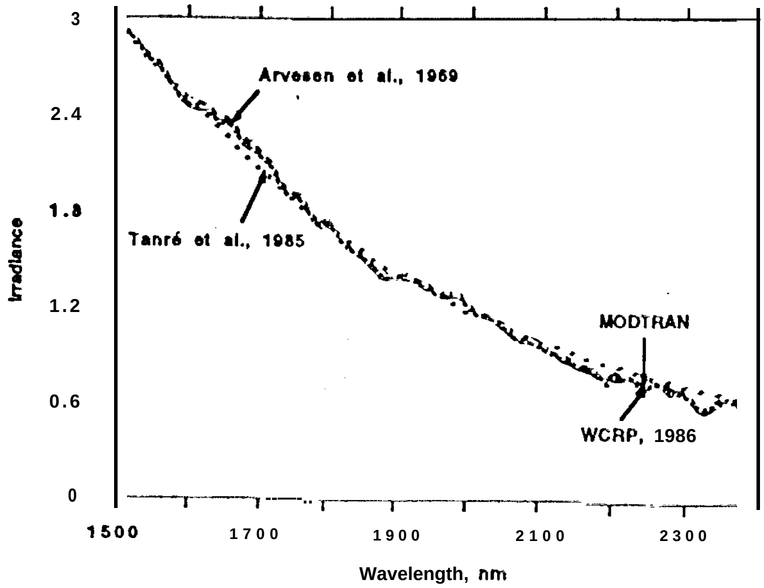


Figure 10. Detail of the available solar spectral irradiance files between 1500 and 2400 nm

To transform this spectrum into units of radiance, the radiometric calibration coefficients determined in the laboratory (using a calibrated integrating sphere, sec Chrien et al., 1990, for details) arc multiplied through the data. Thus, the nadir upwelling radiance $L_{AV}$ is calculated as shown in Equation (7):

$$L_{AV} = (DN - DC) * \text{"coef."} \quad (7).$$

As mentioned above, these coefficients have shown to be inaccurate at the shorter wavelengths (less than 500 nm) where instrument sensitivity is not optimum (Carter, 1992). A similar explanation seems possible for the region between 1100 and 1300 nm. This other major discrepancy has been repetitively observed in other data sets. This might also apply to the SWIR where a discrepancy of similar magnitude is observed.

Instrument noise inflight could also explain some of the smaller features observed. The estimated noise-equivalent-delta-radiance (NEdL) is derived from the dark current, which provides the sensor response to an homogeneous dark target. The root-mean-squared deviation of 100 lines of dark current data provides an accurate estimate of the instrument noise. The NEdL is defined as the dark current derived noise multiplied by the radiometric calibration coefficients (Green et al., 1991 ). However, as shown on Fig. 11, the magnitude of AVIRIS NEdL once resealed to NEdR, is not sufficient to explain most of the spikes observed. AVIRIS instrument noise does not appear to be a limiting factor for the retrieval,

A more detailed analysis has to be pursued to attribute a source to each spikes or depression observed in the retrieved reflectance in order to quantify the magnitude of the uncertainty expected in the retrieved reflectance and eventually improve the algorithm.

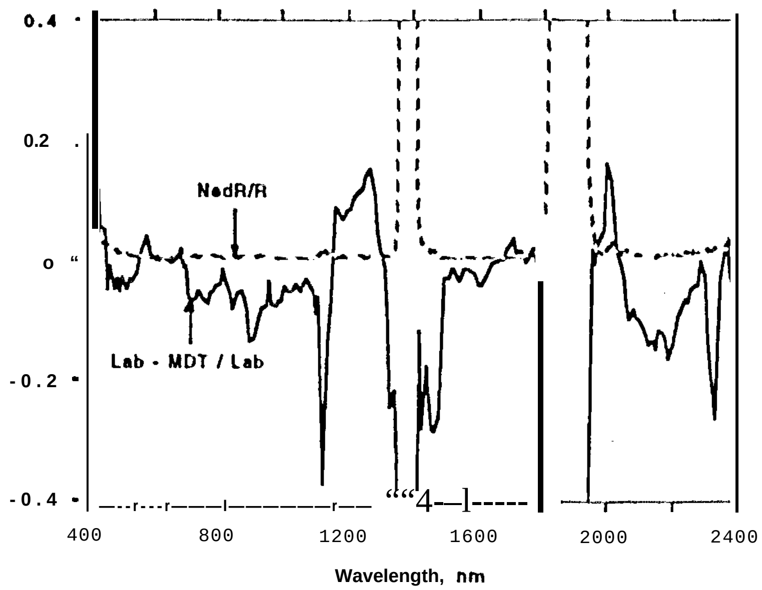


Figure 11. Comparison between discrepancies observed between laboratory hemispherical reflectance and MODTRAN retrieved radiance (re.presented by the normalized difference) and AVIRIS noise-equivalent-delta-reflectance.

## 4. GENERALIZATION TO AN ENTIRE AVIRIS SCENE

The final objective of this analysis is evidently to be able to use such algorithms to retrieve ground spectral reflectance over an entire scene with an acceptable accuracy for various scientific applications. Previous error analysis at the local scale has already demonstrated the sensitivity of the technique to various sources of errors. Correcting an entire scene implies being able to constrain the radiative transfer model on a pixel-by-pixel basis which requires taking into account changes in background reflectance, viewing / illumination geometry, target elevation, etc., and thus variations in amount of atmospheric gases. and aerosols related to change in path length, variation in water vapor distribution due also to change in path length and the fact that water is not a well mixed gas and sources and sinks of water vapor are expected over large areas, and change in scattering across track.

Some simple assessments of the sensitivity of the algorithm (using MODTRAN) to changes in basic parameters such as viewing geometry, target elevation, and background reflectance follow. Variations of these parameters have, as shown above, an impact on both the amount of water vapor retrieved from AVIRIS data using the CIBR algorithm and the model total radiance, path radiance and atmospheric transmitted radiance.

Fig. 12 shows the impact on retrieved reflectance when parameters arc changed from the ones characterizing the radiance at the test area, namely: viewing angle of 11.8° off-nadir, target elevation of 1411 m, and background reflectance estimated from AVIRIS radiance.

Results show that:

(1) If one assumes nadir viewing (which simplify model calculation) instead of 11.8° off-nadir, the amount of water retrieved will be underestimated by 1.1%. impact on reflectance recovery is minimal outside the gas absorption. Well mixed gases such as $O_2$ and $CO_2$ will be undercompensated for (shorter path length), leaving residual absorptions in the spectrum.

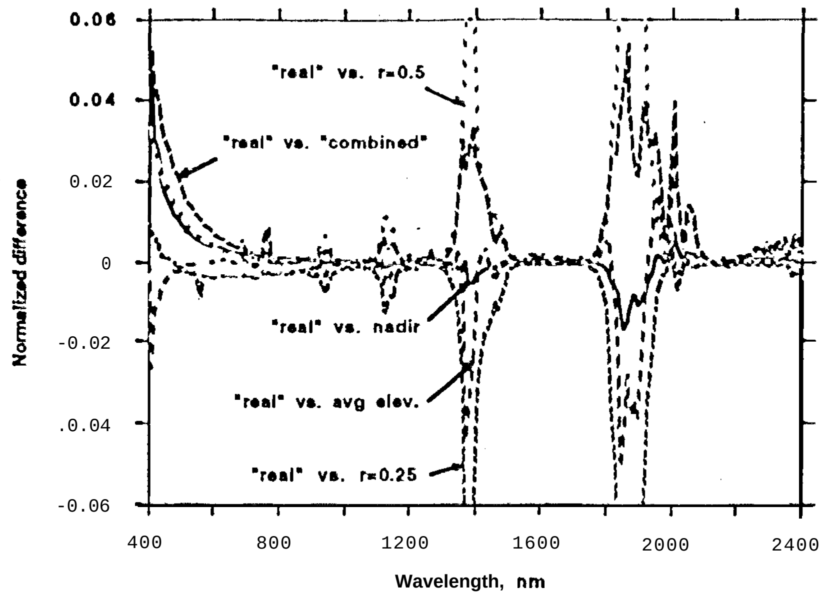


Figure 12. Effect of systematic departure from input model parameters. The curves represent a , normalized difference between the MODTRAN retrieved reflectance using "real" conditions and the MODTRAN retrieved reflectance using modified conditions.

(2) If one assumes the target elevation to be equal to the average scene elevation (mean between the highest and lowest point in the scene, based on topographic information; here 1631 m instead of 1411 m), the amount of water will be underestimated by 1%. The retrieved reflectance shows more undercompensated atmospheric gas absorption (up to 2% outside the two main water bands) as well as important differences in the visible due to change in aerosol attenuation. The error will of course increase with increased difference in elevation.

(3) Finally, if one assumes a constant background reflectance, for example 0.5 which constitutes a reasonable assumption for a bright target such as a playa, instead of using the apparent reflectance derived from the radiance data, the amount of water is underestimated by only 0.6%. The impact on retrieved reflectance is fairly important in the visible as expected since in reality the reflectance decreases rapidly short of 600 rim. The effect on the rest of the spectrum is minor since ().5 reflectance is fairly close to the real value.

However, if onc had assumed a reflectance of 0.25, constant across the spectrum, the amount of water would be overestimated by 1.2% and the general effect on die retrieved reflectance could reach at least 1 % outside the gaseous absorption.

There preliminary results show that the main effect of making general assumptions for model parameters in order to simplify calculation and speed up the process for correcting entire scenes translates into residual absorption in the retrieved reflectance due to over- or undercompensation for gas absorption. The presence of these features could be misleading when interpreting the resulting reflectance data.

## 5. CONCLUDING REMARKS

Development of reliable, easy to usc algorithms for atmospheric correction of high spectral resolution imaging spectrometer data is essential if one wants to usc such data in a quantitative fashion and take advantage of the full potential of imaging spectrometry.

The most physically correct approach is to usc radiative transfer modeling which allows to' predict radiance at the sensor. Accurate modeling in principle requires knowledge of atmospheric . conditions at the time of the overflight, thus acquisition of concurrent ground measurements which arc usually not available to the general user (lack of appropriate equipment, remoteness of study area, etc.). It is essential to develop techniques that can be independent of such measurements and assess their accuracy in order to understand the validity of the results (danger of identifying absorption that are. not real but due to incorrect correction of the data).

Some of the information needed can be extracted from the radiance data such as water vapor and apparent reflectance with some accuracy (1 %). However, most of the parameters characterizing the atmosphere at the time of flight such as visibility and type of aerosols have to be assumed since it is generally impossible to estimate meteorological range and aerosol type from the radiance data thcm.selves except when values of surface spectral reflectance are available or the scene contains a dark target such as a body of water.

This preliminary study shows that errors seem to arise from two principal sources:

(1) The model used: MODTRAN gives more accurate results than LOWTRAN 7 because of better gas absorption model, higher spectral resolution and better scattering model; some of the small discrepancies could possibly be related to the solar irradiance file used in the model.

(2) The instrument calibration: adjustment scaling factors had to be used in the shorter wavelengths and there are good evidences that a similar correction should be applied between 1150 and 1300 nm and even perhaps in the SWIR.

AVIRIS instrument noise does not appear to be a limiting factor for the retrieval.

Finally, generalization to an entire AVIRIS scene implies:

(1) including, as additional input, information on ground elevation (Digital Elevation Model) to accurately model the absorption due to well mixed gases such as $O_2$ and $CO_2$ and retrieve water vapor amounts;

(2) estimation on a Pixel-bymixcl basis of the apparent reflectance in order to improve accuracy of recovery of water vapor abundance and total modeled radiance; accurate modeling of viewing geometry on a pixel-by-pixel basis to take scattering and change in path length into account.

We plan to pursue our analysis into more detail by applying the algorithm to other data sets, particularly one with concurrent ground observation in order to have a better understanding of the sources and magnitudes of errors by limiting uncertainties on parameters used to constrain the model. It would also be interesting to test the algorithm on a data set corresponding to "thicker" atmospheric conditions, i. e., higher load of aerosols and lower visibility to assess impact of aerosols amount and distribution on recoveries.

We also plan to use other radiative transfer codes available such as 5S (Tanré et al., 1985), 6S when available and the Atmosphere Removal Program (ARP) developed at CSES in Boulder, Colorado, (Gao et al., 1992) and compare results.

## ACKNOWLEDGEMENTS

The authors would like to thank Gregg Swayze and Roger Clark from USGS Denver for providing the AVIRIS data set and the laboratory spectrum.
This work has been carried out at the Jet Propulsion Laboratory, California Institute of Technology in relation to the HIRIS Project, under a contract with the National Aeronautics and Space Administration.

<-03

# REFERENCES


Arvesen, J. C., R. N. Griffin and B. D. Pearson, 1969: *Appl. Optics,* 8, 2215.

Berk, A., L. S. Bernstein, and D. C. Robertson, 1989: MODTRAN: a Moderate Resolution Model for LOWTRAN 7. AFGL-TR-89-0122, Air Force Geophysics Laboratory, Hanscom AFB, MA 01731 (April 1989).

Carrère, V. and J. E. Conel, 1992: Comparison of two techniques for recovery of atmospheric water vapor total column abundance from imaging spectrometer data - Sensitivity analysis and application to Airborne Visible/Infrared Spectrometer (AVIRIS) data. *Remote Sensing of Environment, Special Issue on Imaging Spectrometry,* in press.

Carter, K. L., 1992: AVIRIS calibration and application in coastal oceanic environments. In *Summaries of the Third Annual JPL Airborne Geoscience Workshop,* June 1-5, 1992, JPL Publication 92-14, vol. 1, p.56-59.

Chrien, T., R. O. Green, and M, L. Eastwood, 1990: Accuracy of the spectral and radiometric laboratory calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). *Proceedings of the Second Airborne Visible/Infrared Spectrometer (A VIRIS) Workshop,* June 4 and 5, 1990, JPL Publication 90-54, p.]- 14.

Gao, B. C., K. G. Heidebrecht , and A. F. H. Goetz, 1992: Atmosphere Removal Program (ARP) User's Guide. CSES/CIRES Publication, May 1992, 23 p.

Green, R. O., V. Carrère, and J. E. Conel, 1990: Measurement of atmospheric water vapor using the Airborne Visible/Infrared Imaging Spectrometer. *Image Processing '89, American Society for Photogrammetry and Remote Sensing,* Sparks, Nevada, p.31 -44.

Green, R. O., S. A. Larson and H. I. Novack, 1991: Calibration of AVIRIS digitized data. In *Proceedings of the Third Airborne Visible/Infrared Spectrometer (A VIRIS) Workshop, May 20 -21, 1991,* JPL Publication 91-28, p.109-118.

Kneizys, F. X., E. P. Shettle, L. W. Abreu , J. H. Chetwynd, G. P. "Anderson , W. O. Gallery, J. E. A. Shelby, and S. A. Clough, 1988: "Users Guide to Lowtran". AFGL-TR-88-0177, Air Force Geophysics Laboratory, Hanscom AFB,MA01731 (August 1988), ADA 206773.

Shettle E.P. and R. W. Fenn, 1979: Models of the aerosols of the lower atmosphere and the effect of humidity variations on their optical properties. AFGL-TR-79-021 24, Air Force Geophysics Laboratory, HanscomAFB,MA01"/31, ADA 085951.

Tanré D., C. Deroo, P. Duhaut, M. Herman, J. J. Morcrette, J. Perbos, and P. Y. Deschamps, 1985: Effets atmosphériques en télédétection - logiciel de simulation du signal satellitaire clans le spectre solaire, *Proc. 3rd Int. Colloquium on Spectral Signatures of Objects in Remote Sensing,* Les Arcs, France, Dec. 16-20, p.3 15-320.

World Climate Research Programme (WCRP) Publication Series NO. 7, WMO I-I'D-NO. 149, pp. 119-126, October 1986.

## KEY WORDS

Atmospheric correction, radiative transfer, imaging spectrometer, AVIRIS, LOWTRAN 7, MODTRAN, Error analysis, validation, retrieval of surface spectral reflectance.