Derivation of Scaled Surface Reflectances from AVIRIS Data

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Analysis of high resolution imaging spectrometer data requires a thorough compensation for atmospheric absorption and scattering. A method for retrieving "scaled surface reflectances," assuming horizontal surfaces having Lambertian reflectances, from spectral data collected by the Airborne Visible / Infrared Imaging Spectrometer (AVIRIS) (Vane, 1987) is presented here. In this method, the integrated water vapor amount on a pixel by pixel basis is derived from the 0.94-µm and 1.14-µm water vapor absorption features. The transmission spectrum of water vapor (H_2O) , carbon dioxide (CO_2) , ozone (O_3) , nitrous oxide (N_2O) , carbon monoxide (CO), methane (CH₄), and oxygen (O_2) in the 0.4– 2.5 μ m region is simulated based on the derived water vapor value, the solar and the observational geometry, and through use of narrow band spectral models. The scattering effect due to atmospheric molecules and aerosols is modeled with the 5S computer code (Tanré et al., 1986). The AVIRIS radiances are divided by solar irradiances above the atmosphere to obtain the apparent reflectances. The scaled surface reflectances are derived from the apparent reflectances using the simulated atmospheric gaseous transmittances and the simulated molecular and aerosol scattering data. The scaled surface reflectances differ from the real surface

reflectances by a multiplicative factor. In order to convert the scaled surface reflectances into real surface reflectances, the slopes and aspects of the surfaces must be known. For simplicity, the scaled surface reflectance is simply referred to as the "surface reflectance" in this article. The method described here is most applicable for deriving surface reflectances from AVIRIS data acquired on clear days with visibilities 20 km or greater. More rigorous atmospheric radiative tranfer modeling is required in order to derive surface reflectances from AVIRIS data measured on hazy days.

INTRODUCTION

Imaging spectrometers acquire images in many contiguous spectral channels such that for each picture element (pixel) a complete reflectance or emittance spectrum can be derived from the wavelength region covered (Goetz et al., 1985). In the coming decade, NASA expects to carry the High Resolution Imaging Spectrometer (HIRIS) (Goetz and Davis, 1991) aboard a platform of the Earth Observation System (Eos) for remote sensing of the land and coastal waters (Goetz et al., 1985). The precursor to HIRIS is the Airborne Visible / Infrared Imaging Spectrometer (AVIRIS) (Vane et al., 1993), which is now operational. AVIRIS covers the spectral region from 0.4 μ m to 2.5 μ m in 10-nm channels and has a ground instantaneous field of view of 20×20 m from an

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Figure 1. An example of an AVIRIS spectrum.

altitude of 20 km. Figure 1 shows an example of an AVIRIS spectrum. The solar radiation on the Sun-surface-sensor ray path is subject to absorption and scattering by the atmosphere and the surface. The major atmospheric water vapor bands centered at approximately 0.94 μ m, 1.14 μ m, 1.38 μ m, and 1.88 μ m, the oxygen band at 0.76 μ m, and the carbon dioxide bands near 2.01 μ m and 2.08 μ m are clearly seen. Approximately half of the 0.4-2.5 μ m region is affected by atmospheric gas absorptions. In order to infer the surface reflectances from AVIRIS data, accurate correction of atmospheric absorption and scattering effects is necessary.

BACKGROUND

Gaseous Absorption

There are approximately thirty gases in the Earth's atmosphere. Most of the gases do not produce observable absorption features in the 0.4–2.5 μ m region under typical atmospheric conditions and at the 10 nm AVIRIS spectral resolution. Only seven gases, namely, water vapor (H₂O), carbon dioxide (CO₂), ozone (O₃), nitrous oxide (N₂O), carbon monoxide (CO), methane (CH₄), and oxygen (O₂), produce observable features. Figures 2 and 3 show calculated transmission spectra of the seven gases at 10 nm resolution for an observer above the atmosphere looking straight down and

for a solar zenith angle of 45° using the LOW-TRAN7 Tropical Model (Kneizys et al., 1988). Water vapor has several bands with peak absorptions ranging from a few percent to 100%. Carbon dioxide has relatively strong bands near 2 μ m. Ozone has a band (Chappius band) near 0.6 μ m with a peak absorption of approximately 10%. Nitrous oxide and carbon monoxide have weak bands between 2 μ m and 2.5 μ m with peak absorptions of 1-2%. Methane has a band near 2.35 μ m with a peak absorption of approximately 20%. Oxygen has several bands between 0.6 μ m and 1.3 μ m. The spectral regions in which there is little atmospheric gaseous absorption are called atmospheric "windows." Several windows exist in the 0.4-2.5 μ m region. The narrow spectral regions around 0.85 μ m, 1.05 μ m, and 1.25 μ m are prime examples. Because peak absorptions depend on the spectral resolution, the peak absorptions described above will be different for spectra at resolutions other than 10 nm.

There are differences in the vertical distributions of different gases in the atmosphere (Waters, 1984). Water vapor concentrations usually decrease rapidly with altitude, and the spatial and temporal variation of water vapor concentrations can be dramatic. Carbon dioxide, nitrous oxide, methane, and oxygen are uniformly mixed gases in the troposphere. Approximately 90% of atmospheric ozone is located in the stratosphere with a peak concentration near 25 km. The total



Figure 2. Atmospheric water vapor transmittance spectrum (top plot) and carbon dioxide transmittance spectrum (bottom plot). The spectra, at a resolution of approximately 10 nm, were calculated for an observer above the atmosphere looking straight down and for a solar zenith angle of 45° using the tropical model of LOWTRAN7 (Kneizys et al., 1988).

amount of ozone from ground to space changes with latitude and season. The variations of carbon monoxide concentrations in rural areas on a daily and seasonal basis are not as dramatic as those of water vapor.

Molecular and Aerosol Scattering

Atmospheric molecules and aerosols scatter solar radiation. The molecular scattering (also called

Rayleigh scattering) effect decreases rapidly $(\sim \lambda^{-4})$ with increasing wavelength. Above 1 μ m, the effect is negligible. The aerosol scattering effect also decreases with increasing wavelength, but not as rapidly as that of Rayleigh scattering. Near 1 μ m, for typical atmospheric conditions, the aerosol scattering contributes to approximately 10% of total radiance measured by a downward looking satellite over land areas. The molecular and aerosol scattering is most im-



Figure 3. Transmittance spectra of atmospheric ozone, carbon monoxide, nitrous oxide, methane, and oxygen. The spectral resolution, the geometry, and the model atmosphere used in the calculations are the same as those used in calculating the spectra in Figure 2.

portant in the shorter visible wavelength region. Atmospheric gaseous absorption is most important in the 1.0–2.5 μ m region.

Radiative Transfer

The theory of radiative transfer has been described, for example, by Chandrasekhar (1960). Different techniques, such as the discrete ordinate method and the variational method, have been developed for solving atmospheric radiative transfer problems (Lenoble, 1985). An approximate, yet reasonably accurate radiative transfer code, called Simulation of the Satellite Signal in the Solar Spectrum (5S), has been developed by Tanré et al. (1986). In this code, the apparent reflectance $\rho^*(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)$ is used in the formation of the radiative transfer problem. The definition of apparent reflectance is

$$\rho^*(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda) = \frac{\pi L(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)}{\mu_s E_s(\lambda)}, \quad (1)$$

where θ_s is the solar zenith angle, φ_s is the solar

azimuth angle, θ_v is the sensor zenith angle, φ_v is the sensor azimuth angle, λ is wavelength, L is the radiance measured at the satellite, E_s is the solar flux at the top of the atmosphere, and $\mu_s = \cos$ θ_s . According to Tanré et al. (1986), for a horizontal surface of uniform Lambertian reflectance, $\rho^*(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)$ can be expressed as

$$\rho^{*}(\theta_{s}, \varphi_{s}, \theta_{v}, \varphi_{v}, \lambda) = T_{g}(\theta_{s}, \theta_{v}, \lambda)$$
$$\times \left[\rho_{a}(\theta_{s}, \varphi_{s}, \theta_{v}, \varphi_{v}, \lambda) + \frac{T(\theta_{s}, \lambda)T(\theta_{v}, \lambda)\rho(\lambda)}{1 - \rho(\lambda)S(\lambda)}\right], \quad (2)$$

where T_g is the total gaseous transmittance in the Sun-surface-sensor path, ρ_a is the atmospheric reflectance, which is related to the path radiance resulted from atmospheric scattering, $T(\theta_s)$ is the downward scattering transmittance, $T(\theta_v)$ is the upward scattering transmittance, S is the spherical albedo of the atmosphere, and ρ is the surface reflectance. T_g is expressed as

$$T_{g}(\theta_{s}, \theta_{v}, \lambda) = \prod_{i=1}^{n} T_{g_{i}}(\theta_{s}, \theta_{v}, \lambda), \qquad (3)$$

where T_{g_i} is the transmittance of the *i*th gas in the Sun-surface-sensor path and *n* is the number of gases. T_g is calculated by assuming that there is no atmospheric scattering. The transmittances in Eq. (3) refer to the average transmittances over narrow spectral intervals (a few nanometers).

The scattering terms, ρ_s , $T(\theta_s)$, $T(\theta_v)$, and S, are calculated by assuming that there are no atmospheric gaseous absorptions. In the real atmosphere, the scattering and absorption processes occur simultaneously. Equation (2) treats these as two independent processes. The coupling effects between the two processes are neglected. The coupling effects are small in regions where the atmospheric gaseous absorptions are weak and in regions where the scattering effects are small. Equation (3) is strictly correct only in regions where there are no overlapping absorptions by different gases. It remains a good approximation for the 0.4–2.5 μ m region because little overlapping absorptions occur in this region.

The 5S code was originally designed to simulate radiances measured from satellite platforms using geometric and atmospheric models and using surface reflectances as boundary conditions. However, the code can be modified for retrieving surface reflectances from measured radiances (Teillet, 1989). Solving Eq. (2) for ρ yields

$$\rho(\lambda) = \left(\frac{\rho^*(\theta_s, \varphi_s, \theta_v, \lambda)}{T_g(\theta_s, \theta_v, \lambda)} - \rho_a(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)\right)$$
$$\times \left[T(\theta_s, \lambda)T(\theta_v, \lambda) + S(\lambda)\left(\frac{\rho^*(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)}{T_g(\theta_s, \theta_v, \lambda)} - \rho_a(\theta_s, \varphi_s, \theta_v, \varphi_v, \lambda)\right)\right]^{-1}.$$
(4)

Given a satellite measured radiance, the surface reflectance can be derived according to Eqs. (1) and (4) and using, for example, the method described below.

METHOD

Because of the variability of water vapor concentration with time and altitude (Teillet, 1989), it is not possible to remove completely the water vapor features for retrieving surface reflectances from imaging spectrometer data using standard atmospheric models, such as those in LOW-TRAN7 (Kneizys et al., 1988). In our method, water vapor values are derived from the 0.94- μ m and 1.14- μ m water vapor features in AVIRIS data on a pixel by pixel basis. These water vapor values are then used for proper removal of water vapor features in the entire 0.4–2.5 μ m region. A similar approach for deriving surface reflectances from AVIRIS data was described by Green (1991).

The derivation of water vapor values from AVIRIS data is mainly based on two facts. One is that the surface reflectance curves for common soils and rocks vary nearly linearly with wavelength in the two water vapor band absorption regions (Gao and Goetz, 1990). The other is that under typical atmospheric conditions, the transmittances of the 0.94- μ m and 1.14- μ m water vapor bands are sensitive to the changes in the amount of water vapor (Gao and Goetz, 1990).

A three-channel ratioing technique is used in our derivation of the water vapor value from an AVIRIS spectrum. This technique is also commonly used at the Jet Propulsion Laboratory for derivation of water vapor values from AVIRIS data (Bruegge et al., 1990). Figure 4 shows an example of an apparent reflectance spectrum in which the relevant positions and widths of spectral regions used in our channel ratioing are illustrated. Specifically, apparent reflectances of 5 AVIRIS channels near 0.945 μ m are averaged to



Figure 4. An apparent reflectance spectrum with relevant positions and widths of spectral regions used in the three-channel ratioing being illustrated.

give a mean apparent reflectance of the 0.94- μ m water vapor band. Apparent reflectances of three channels near 0.865 μ m are averaged to give a mean apparent reflectance at the 0.865 μ m "window" region. Apparent reflectances of three channels near 1.025 μ m are averaged to obtain a mean apparent reflectance at the 1.025 μ m "window" region. The mean apparent reflectance at the water vapor center is divided by one half of the sum of the mean apparent reflectances at the two window regions. The ratio effectively removes the linear surface reflectance effect and gives a mean observed transmittance for the 0.94- μ m water vapor band. By comparing the mean observed transmittance with theoretically calculated mean transmittances using atmospheric and spectral models, the amount of water vapor in the Sun-surface-sensor path is obtained. Similar three-channel ratioing procedures are used to derive another water vapor amount in the Sunsurface-sensor path from the 1.14- μ m water vapor band. The average of water vapor values from the $0.94-\mu m$ and $1.14-\mu m$ bands is considered as the best estimate of the water vapor value corresponding to the pixel. In the actual implementation of the three-channel ratio technique, the center positions and widths of the window and water vapor absorption channels are all allowed to vary, for reasons described in the section Error and Sensitivity Analysis.

Our method for the derivation of surface reflectances from AVIRIS data consists of six steps:

- 1. The solar zenith angle is derived based on the AVIRIS flight time and on the geographic location (latitude and longitude) of the scene.
- 2. The total atmospheric transmittance spectra, $T_{\rm g}$ [see Eq. (3)], are calculated and a look-up table is generated. One ozone transmittance spectrum is calculated based on the solar and the observational geometries and using values of ozone absorption cross sections. One transmittance spectrum for each of the five gases, CO₂, N₂O, CO, CH₄, and O₂, is calculated based on an assumed atmospheric model, the solar and the observational geometries, and using the Malkmus (1967) narrow band spectral model. A number of water vapor transmittance spectra are similarly calculated but with the water vapor value in the atmospheric model being scaled by different factors. The scaling factors are selected so that the integrated amounts of water vapor from ground to space, or the column water vapor amount, vary from 0 to 10 cm. This range of column water vapor amounts covers the typical atmospheric conditions in which column water vapor amounts range from 0.6 cm to 4.3 cm. From the transmittance spectra of the seven gases, a number of T_g spectra are obtained based on Eq. (3). The three-channel ratios for the 0.94- μ m and the 1.14- μ m water vapor bands are calculated using the T_g spectra. The water vapor amounts, the three-channel ratios, and the T_g spectra are stored in a look-up table for later use.
- 3. The atmospheric reflectance ρ_a , spherical albedo S, the downward scattering transmittance $T(\theta_s)$, and the upward scattering transmittance $T(\theta_s)$ (see an earlier subsection on Radiative Transfer) are calculated using the 5S code. The Rayleigh scattering and aerosol scattering are included in the 5S calculations, while the atmospheric gaseous absorptions are excluded. The aerosol scattering effects are simulated using a user-selected aerosol model and a user-supplied visibility, or an aerosol optical depth at 0.55 μ m.
- 4. An AVIRIS radiance spectrum is divided by the solar irradiance curve above the atmosphere (Kneizys et al., 1988) to obtain the apparent reflectance spectrum.

- 5. The three-channel ratios for the 0.94- μ m and the 1.14- μ m water vapor bands are calculated from the apparent reflectance spectrum. Based on the observed three-channel ratios and using a look-up table procedure, a best estimation of water vapor value corresponding to the AVIRIS spectrum is obtained. Based on the estimated water vapor value and using the look-up table procedure again, the best estimation of T_g spectrum corresponding to the AVIRIS spectrum is obtained.
- 6. Finally, the surface reflectance spectrum is derived based on Eq. (4).

When using our program for retrieving surface reflectances from an AVIRIS image cube (two spatial dimensions and one spectral dimension). the first three steps only need to be performed once at the beginning of the program execution, and the last three steps are performed for each pixel spectrum. The look-up table procedure greatly speeds up the retrieval process. It takes approximately 25 min, including the time spent on the input and output operations (I/O), on a DEC 5000 workstation to process a complete AVIRIS image cube having 615×512 pixels and 224 spectral channels. The output consists of a surface reflectance image cube having the same size as the input cube and a separate column water vapor image, a byproduct of the retrieval process.

DESCRIPTION OF INPUT

Table 1 gives an example of the input file that is required in order to use our program to derive surface reflectances from AVIRIS data. The file consists of four parts. The first part consists of information necessary for the determination of the Sun-surface ray path geometry. This part includes the date and time of the AVIRIS measurement, and the mean latitude and longitude of the AVIRIS scene. The second part consists of AVIRIS spectral parameters, including the name of AVIRIS wavelength table, the mean spectral resolution (typically 10 nm), the positions and widths of water vapor absorption channels and the window channels used in calculating the three-channel ratios defined in the previous section. The third part consists of atmospheric infor-

Input	Comment			
07 23 1990 20 58 32	Date (mm dd yyyy) and time (hh mm ss)			
37 30 08	Latitude (deg min s)			
N	Hemisphere (N or S)			
117 13 17	Longitude (deg min s)			
W	Hemisphere (E or W)			
/tmp/aviris.wav	Wavelength file			
10.	Resolution of input spectra (nm)			
1	Indicator of whether the band ratio parameters are			
	provided $(0 = no, 1 = yes)$			
0.8630 1.0550 3 3 0.9398 7	Band ratio parameters for first atmospheric window			
1.0550 1.2470 3 3 1.1414 7	Band ratio parameters for second atmospheric window			
2	Atmospheric model number			
1111111	Gas selectors (0 = don't include, 1 = include)			
0.34	Total amount of ozone (cm)			
1 100	Aerosol type and visibility (km)			
1.5	Average elevation (km)			
/tmp/aviris.cub	Input AVIRIS cube			
0	Indicator of whether the cube dimensions are provided $(0 = no, 1 = yes)$			
/tmp/avirisatm.cub	Output file for atmospherically reduced cube			
10.	Resolution of output spectra (nm)			
/tmp/aviris.vap	Output file for water vapor image			

Table 1. An Example Input File

mation, which includes a) the selection of an atmospheric temperature, pressure, and water vapor vertical distribution model, which can be a standard atmospheric model or a user defined model, b) seven indicators that select which of the gases be included in the calculations, c) the vertical column amount of ozone from ground to space, d) the visibility which is used in atmospheric scattering calculations using the 5S code, and e) the mean surface elevation of the AVIRIS scene. The column ozone amount is typically about 0.34 atm-cm. It varies with geographic locations and season. The mean surface elevation is used in redefining the lower boundary of a selected standard atmospheric model. The fourth part consists of I/O parameters, including the name of input AVIRIS data file, the name of output reflectance data file, the resolution of output reflectance spectra, and the name of the output water vapor image. The output spectra can have the same resolution as the input spectra or be smoothed to lower resolution spectra using a gaussian filter. In some cases, particularly when the signal-to-noise ratios of AVIRIS data are low, the smoothing improves our ability in finding weak surface absorption features based on visual inspection.

SAMPLE RESULTS

Our program has been used for deriving surface reflectances from several sets of AVIRIS data acquired over different types of surfaces. Figure 5a shows an AVIRIS spectrum acquired over a vegetated area in the Konza Prairie in Kansas on 31 August 1990. Figure 5b shows our retrieved reflectance spectrum. Because of the total absorption in the strong $1.38-\mu m$ and $1.88-\mu m$ water vapor bands, it is not possible to recover the surface reflectances near the centers of the two bands. Therefore, no reflectances are shown in Figure 5b in these regions. The green reflectance peak near 0.55 μ m, the chlorophyll absorption feature centered near 0.67 μ m, and the weak liquid water bands centered near 0.98 μ m and 1.2 μ m are all evident. The features in this spectrum are very similar to reflectance spectra of vegetation measured in laboratories.

Figure 6a shows an AVIRIS spectrum over an area covered by the mineral kaolinite. The data were measured on 23 July 1990 over Cuprite, Nevada. Figure 6b shows surface reflectances derived from the model. Most of the atmospheric absorption features seen in Figure 6a are removed in Figure 6b. The characteristic kaolinite doublet



Figure 5. a) An AVIRIS spectrum acquired over an vegetated area in the Konza Prairie in Kansas on 31 August 1990 and b) the corresponding retrieved reflectance spectrum. The weak liquid water absorption bands near 0.98 μ m and 1.20 μ m are seen in b).

feature, resulting from the A1-OH transitions, near 2.17 μ m is clearly seen in Figure 6b.

An example of comparison between our retrieved reflectances from AVIRIS data and the field-measured reflectances is shown in Figure 7. The AVIRIS data used in our retrievals were acquired over the Northern Grapevine Mountains, California in September 1989. The solid curve in Figure 7 is the retrieved reflectance spectrum over an area covered by the mineral sericite. The dotted curve is the measured spectrum in the field using a portable spectrometer. The general shapes of the two spectra in the 0.8-2.4 μ m region are similar. However, there are discrepancies beyond 0.8 μ m that can be attributed to the fact that the field measurement is made of a 10 cm area while an AVIRIS pixel covers 20 m \times 20 m. Both spectra show absorption features centered near 2.2 μ m and 2.36 μ m. The retrieved spectrum is not as smooth as the fieldmeasured spectrum. The feature near 0.76 μ m in the retrieved spectrum is due to the incomplete



Figure 6. a) An AVIRIS spectrum acquired over an area covered by the mineral kaolinite in Cuprite, Nevada on 23 July 1990 and b) the corresponding retrieved reflectance spectrum. The characteristic kaolinite doublet feature near 2.17 μ m is clearly seen in b).

removal of atmospheric oxygen absorptions, and those near 2.06 μ m are due to the residual atmospheric carbon dioxide absorptions.

ERROR AND SENSITIVITY ANALYSIS

The scattering and absorption by molecules and aerosols occur simultaneously in the atmosphere. The approximate radiative transfer (RT) modeling technique used in the 5S code (Tanré et al., 1986) treats the atmospheric scattering process and the gaseous absorption process as two independent processes [see Eq. (2)]. The coupling effects between the atmospheric scattering and the gaseous absorption are not modeled. The same RT modeling technique is used in our program. In general, the coupling effects are small in atmospheric window regions where the gaseous absorptions are negligible. The coupling effects are also small in regions where the gaseous absorptions are im-



Figure 7. A retrieved reflectance spectrum (solid line) from AVIRIS data acquired over an area covered by the mineral sericite in the Northern Grapevine Mountains, California in September 1989, and a measured reflectance spectrum (dotted line) in the field using a portable spectrometer.

portant but the scattering is unimportant. Under clear atmospheric conditions with visibilities 20 km or greater, the atmospheric scattering effect is most important below approximately 0.8 μ m, and the gaseous absorption effect is most important above approximately 0.8 μ m (Tanré et al., 1986). The coupling effects in the 0.4–2.5 μ m spectral region are small. Our method is a valid approach for deriving surface reflectances from AVIRIS data acquired on clear days.

However, under hazy conditions with visibilities on the order of a few kilometers, the scattering effect is important in the entire 0.4–2.5 μ m spectral region, and the coupling effects described above are important in atmospheric gaseous absorption regions. Under these conditions, the approximate RT modeling technique (Tanré et al., 1986) is no longer valid for RT modeling in gaseous absorption regions, and rigorous RT modeling techniques are necessary. Therefore, our approximate method is not applicable for deriving surface reflectances from AVIRIS data measured on hazy days. At present, the lack of available rigorous radiative transfer models, which properly handle both the atmospheric scattering and the gaseous absorption and which produce continuous spectra, prevents us from quantifying errors in surface reflectance derivations using the approximate RT modeling technique.

The atmospheric transmittances calculated with the Malkmus narrow band spectral model typically have an accuracy on the order of 10%. The transmittances depend on the widths of band model parameters. The parameters used in our program have a constant width of 2.5 nm. In order to gain confidence in our spectral calculations, the 0.94- μ m and 1.14- μ m water vapor band transmittance spectra calculated with our program were compared with spectra calculated with a line-by-line program (Mankin, 1979) and smoothed to a lower resolution for different observational geometry and with the same atmospheric models. Excellent agreement between spectra calculated with both programs is obtained. An example of such comparison was presented by Gao and Goetz (1990). Similar comparisons for other water vapor bands and for absorption bands of other gases in the 0.4–2.5 μ m region have not yet been made. If differences arise between spectra calculated with the two methods, empirical adjustments to the Malkmus band model parameters, in particular for the mean intensities over narrow spectral intervals, can be made.

The accuracy of water vapor derivations from the 0.94- μ m and 1.14- μ m water vapor bands in AVIRIS data depends not only on the spectral model used, but also on the assumed atmospheric temperature, pressure, and water vapor volume mixing ratio profiles. The errors in estimated water vapor amounts due to assumption of atmospheric models are 5% or less (Gao and Goetz, 1990). The error in derived water vapor amounts due to an error of 0.5 km in assumed surface elevation is approximately 5% (Gao and Goetz, 1990).

AVIRIS data are often acquired with no simultaneous measurements of atmospheric parameters. During our retrievals of surface reflectances from AVIRIS data, water vapor values are frequently derived from the 0.94- μ m and 1.14- μ m bands with an assumed atmospheric model and an estimated surface elevation. The water vapor transmittances in the entire 0.4-2.5 μ m spectral region are calculated using the derived water vapor values, the same atmospheric model, and the same surface elevation. The water vapor transmittances are then used in the process of removing atmospheric water vapor features from the AVIRIS data. Because of the internal consistency, errors in the assumed atmospheric model and surface elevation do not introduce errors in the retrieved surface reflectances, although they introduce errors in the derived water vapor amounts.

In our derivation of water vapor values from AVIRIS data using the three-channel ratioing technique, the surface reflectances are assumed to vary linearly with wavelength in the 0.94- μ m and the 1.14- μ m water vapor band absorption regions. This assumption means that the threechannel ratios described in the Method section and illustrated in Figure 4 remove the surface reflectance effects and give water vapor transmittances of the two absorption channels. The water vapor values are then derived from the transmittances. In reality, surface vegetation has weak liquid water absorption features centered at approximately 0.98 μ m and 1.19 μ m, and snow and ice have absorption bands centered at approximately 1.04 μ m and 1.25 μ m. The three-channel ratios over areas covered by vegetation, snow, and ice contain both the atmospheric water vapor absorption effects and the surface liquid and ice absorption effects. Systematic errors are introduced in derived water vapor values from these three-channel ratios by assuming the linear surface reflectances. However, by selecting properly the center positions and widths of the window and absorption channels, the systematic errors in derived water vapor values using the three-channel ratioing technique can be reduced.

Table 2 gives two sets of positions and widths of the window and water vapor absorption channels, which are suitable for areas covered by vegetation and snow (or ice), respectively. For completeness, Table 2 also gives one set of positions and widths for the window and water vapor absorption channels, which is suitable for areas covered by soils and minerals. The set of channels for vegetation are selected to minimize the liquid water absorption effects for each of the channels. Although snow has absorption bands centered at 1.04 μ m and 1.25 μ m, the reflectance between 0.86 μ m and 1.04 μ m is close to a linear function of wavelength. The same is true for the snow reflectance between 1.06 μ m and 1.25 μ m. These are taken into account in the selection of the set of channels for snow. Our sensitivity studies using reflectance spectra of vegetation and using the

Table 2. Sets of Center Positions and Widths (Number of AVIRIS Channels) of Window and Water Vapor Absorption Channels Useful for Deriving Column Water Vapor Values from AVIRIS Spectra Measured over Areas Covered by Vegetation, Snow (or Ice), Rocks, Soils, and Minerals, Using the Three-Channel Ratioing Technique

Channel	Vegetation		Snow		Rock, Soil, and Minerals	
	Center (µm)	Width (nm)	Center (µm)	Width (nm)	Center (µm)	Width (nm)
0.94-µm band						
Window 1	0.865	30	0.865	30	0.865	30
Window 2	1.030	30	1.040	30	1.030	30
Absorption	0.935	50	0.945	70	0.940	70
1.14-µm band						
Window 1	1.050	30	1.065	30	1.050	30
Window 2	1.230	30	1.250	30	1.235	30
Absorption	1.130	50	1.140	70	1.1375	70

three-channel ratioing technique show that the errors in derived water vapor values when ignoring the liquid water absorptions in vegetation are typically 5%, and the errors when ignoring ice absorption features in snow are typically 2-4%.

Errors in the derived water vapor values due to the nonlinearity of surface reflectances do introduce errors in the retrieved surface reflectances. In order to quantify this effect, a water vapor transmittance spectrum in the Sun-surface-sensor path is calculated using the midlatitude summer model in LOWTRAN7 (Kneizys et al., 1988), assuming a solar zenith angle of 45°, and for a nadir-looking sensor above the atmosphere. Another spectrum was calculated similarly except that the column water vapor amount in the model atmosphere was reduced by 5%. Figure 8 shows the ratio of the spectrum having more water vapor against the spectrum having less water vapor. The ratios remain between 0.98 and 1.0 in most of the spectral regions, except for regions near the centers of the 0.94- μ m, 1.14- μ m, 1.38- μ m, and 1.88- μ m water vapor bands and for the 2.45–2.5 μ m region. Therefore, a 5% error in the derived water vapor values introduces an error of less than 2% in the derived surface reflectances in most of the 0.4-2.5 μ m spectral region. A similar sensitivity study was performed by Green (1990).

In order to study the sensitivity of surface

reflectance derivation to the assumed surface elevation, a transmittance spectrum of CO₂, N₂O, CO, CH₄, and O₂, in the Sun-surface-sensor path is calculated using the midlatitude summer model in LOWTRAN7, assuming a solar zenith angle of 45°, and for a nadir-looking sensor above the atmosphere. Another spectrum was calculated similarly except that the surface elevation was increased from 0 km to 0.5 km. Figure 9 shows the ratio of the spectrum with a 0 km surface elevation against the spectrum with a 0.5 km surface elevation. The oxygen band at 0.76 μ m with a peak absorption of 2% and the CO₂ band near 2 μ m with a peak absorption of approximately 7% are seen. In our current program, only one mean surface elevation for an entire AVIRIS scene is used in calculating transmittances of CO_2 , N₂O, CO, CH₄, and O₂. However, the surface elevations within an AVIRIS scene can change significantly, particularly over mountainous terrain. When using our current version of program to derive surface reflectances from AVIRIS data acquired over areas having elevation differences. the residual oxygen feature at 0.76 μ m and residual carbon dioxide features near 2 μ m will be present in the retrieved reflectances.

AVIRIS scans from side to side perpendicular to the flight direction. The maximum scan angle is 15° off-nadir. In our program, the AVIRIS is assumed only to be looking at nadir. This intro-



Figure 8. Ratio of one atmospheric water vapor transmittance spectrum with more water vapor against another water vapor transmittance spectrum with 5% less water vapor. See text for details.

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Figure 9. Ratio of one atmospheric transmittance spectrum of CO_2 , N_2O , CO, CH_4 , and O_2 in a Sun-surface-sensor path with a surface elevation at sea level against another similar spectrum but with a surface elevation at 0.5 km. See text for details.

duces an error of approximately 2% or less in the calculation of the amount of atmospheric gases in the Sun-surface-sensor path at the edges of the image.

In our program, the aircraft is assumed to be located above the atmosphere, while in reality the aircraft altitude is 20 km. This inconsistency introduces negligible errors in the calculation of transmittances of water vapor and carbon monoxide because these gases are mostly located in the lower part of the troposphere. The errors introduced in the calculation of transmittances of uniformly mixed gases are 0.2-0.6%. Because 90% of ozone is located above 20 km, we have only taken into account the amount of ozone in the Sun-surface path in our calculations of ozone transmittances. The errors introduced in the Rayleigh scattering calculations are approximately 5%. The errors in aerosol scattering calculations are negligible because most aerosols are typically located in the lower few kilometers of the atmosphere. The aircraft altitude will be included in future revisions.

The radiation outside of the field of view can be scattered into it by the atmosphere. When the surface areas are flat, but do not have uniform reflectances, the scattering contaminates the pixel being viewed. This effect is called the atmospheric adjacency effect. The effect is important under hazy conditions in short wavelength regions (<1 μ m). The 5S code itself allows the modeling of this effect. However, we have assumed a uniform background reflectance in our retrieval of surface reflectances. Over a mountainous terrain, one part of the terrain may be illuminated by another part of the terrain, which we call the "topographic adjacency effect," that can be more important (Kawata et al., 1991) than the atmospheric adjacency effect is also not modeled in our program.

DISCUSSION

Atmospheric radiative transfer programs, such as LOWTRAN7 and 5S code, produce spectra at a resolution of 20 cm⁻¹ in wavenumber domain. The 20 cm⁻¹ resolution is better than the 10 nm AVIRIS spectral resolution in the wavelength domain near 1 μ m and slightly worse than the 10 nm AVIRIS resolution near 2.5 μ m. Because of this, we have written our own routines to calculate spectra at equal wavelength intervals and then to produce spectra at AVIRIS channel positions and spectral resolution. The 5S code is used only for modeling the atmospheric scattering effects. The depolarization factor of Rayleigh scattering in the 5S code was changed from 0.0139 to 0.0279, according to the suggestion by Teillet (1990). The 5S code was modified so that the surface elevation can be greater than 0. The elevations within an image are not allowed to vary. Because the atmospheric scattering and absorption effects depend explicitly on the surface elevation, the current version of our program is most applicable to images with surface elevation variations less than about 1 km.

Although methane has a band near 2.35 μ m, with a peak absorption of approximately 20% (see Fig. 3), this band is not being included in many atmospheric radiative transfer models. For example, methane bands were neglected in a recent intercomparison of shortwave codes for climate studies (Fouquart et al., 1991). Methane bands were also not included in the 5S code. We suggest that methane bands be included in shortwave radiative transfer models.

Discrepancies among exoatmospheric solar irradiance curves from different sources exist. For example, above 0.88 μ m, the curve from Neckel and Labs (1984) is very smooth and shows no solar absorption features, while that from LOWTRAN7 shows many absorption features. Below 0.88 μ m, the two curves agree almost exactly. The LOW-TRAN7 solar irradiance curve smoothed to a 10 nm spectral resolution is used in our program.

The liquid water absorption effects are currently not being modeled when deriving water vapor values using the three-channel ratio technique, as described above. Although the nonlinear least squares curve fitting technique (Gao and Goetz, 1990) allows both the atmospheric water vapor and vegetation liquid water absorption effects to be taken into account, this technique is not suitable for the routine derivation of water vapor and liquid water amounts from AVIRIS data and correction of water vapor effects in AVIRIS data because of the excessive computing resources required to operate on every pixel. One possible operational method is to fit logarithms of apparent reflectances by including both the water vapor and liquid water absorption coefficients in the fitting and using the linear fitting technique described by McKenzie and Johnston (1982), which was used in deriving column amount of atmospheric NO₂ from ground-based high spectral resolution solar absoption measurements.

When using our method for surface reflec-

tance retrievals, the band positions between observed and calculated spectra must be matched to 0.5 nm or better. If the band positions between the observed and the calculated spectra are not matched well, residual features will appear in atmospheric band absorption regions in the derived surface reflectance spectra. The sensitivity to AVIRIS spectral calibration was described by Green et al. (1990).

During our derivation of surface reflectances, or in reality the scaled surface reflectances, the surfaces are assumed to be horizontal and to have Lambertian reflectances. The scaled surface reflectance is proportional to the real surface reflectance. In order to convert the scaled surface reflectances into the real surface reflectances, the slopes and the aspects of the surfaces must be known. At present, digital elevation models having sufficient quality to make such a conversion are not readily available.

SUMMARY

An operational method, based on approximate radiative transfer calculations and a look-up table procedure, for deriving surface reflectances from AVIRIS data measured on clear days with visibilities 20 km or greater, has been described. One advantage of the method is that atmospheric water vapor absorption features are removed on a pixel by pixel basis, based on the derived water vapor values from AVIRIS data themselves. The current version of the program is applicable to AVIRIS scenes with small elevation variations (< 1km). The development of the method represents a step forward in developing complex atmospheric radiative transfer code for removing atmospheric effects from the AVIRIS, and, in the distant future, the HIRIS data.

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