## DETECTION OF CIRRUS CLOUDS AT 1.13 μM IN AVIRIS SCENES OVER LAND

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### 1. INTRODUCTION

Cirrus clouds play an important role in the radiative energy balance of the atmosphere. They also are a major source of interfering radiation when viewing the Earth's surface from satellites and high-altitude aircraft. Both the radiative properties themselves and the underlying physical parameters defining them, such as optical thickness, coverage, altitude, and particle size/shape distribution, are of great interest to climatologists and can potentially be retrieved from spectrally resolved images. Recent advances in spectral imagers such as AVIRIS present new opportunities for cirrus cloud sensing as well as new requirements for compensating surface images for their presence. Such corrections are possible because cirrus clouds are thin, although by the same token this makes them difficult to detect.

In a series of papers, Gao and coworkers (1998, 1995, 1990) proposed and demonstrated with AVIRIS images the technique of using a spectral channel near 1.37 μm to detect cirrus clouds in down-looking views from high altitudes. This wavelength typically provides enough water vapor absorption to completely suppress both the surface reflectance and low-altitude clouds while at the same time adequately transmitting high-altitude cloud-scattered radiation. A drawback is that because the transmittance of the cloud-scattered radiance is not 100% (it depends on the water vapor column density above the cloud and on the sensor viewing and solar angles), the 1.37 μm signal by itself provides insufficient information for deriving the cloud properties, including the optical depth, that are needed for modeling its radiance contributions at other wavelengths and hence for properly compensating the surface reflectance spectrum.

In this paper we describe a new pairwise regression (PR) method for spectral imagery data that allows the retrieval of a cirrus cloud radiance signal from two sets of wavelength channels in the vicinity of a partially absorbing water vapor band, such as the 1.13 μm band, over spatially structured terrain. The method, which uses spatial filtering and linear regression to cancel the surface background, has been applied to several rural and urban AVIRIS scenes. Because the 1.13 μm cloud signal is only weakly absorbed, it directly yields an approximate cloud reflectance. The ratio of the 1.13 μm and 1.37 μm cloud signals indicates the water vapor column above the cloud, hence an effective cloud altitude, which in turn can be used to determine the cloud optical thickness. Extension of the method to longer wavelength bands, where the cloud spectrum is sensitive to the particle size distribution, should also be possible. The PR cloud method is summarized and some preliminary results are presented here. Possible approaches for using the retrieved cirrus cloud information to compensate spectral images are outlined.

### 2. DERIVATION OF THE 1.13 μm CLOUD SIGNAL

The general equation for the radiance $R_i$ at a sensor pixel in spectral channel $i$ is

$$R_i = R_i^{atm} + \frac{\mu F_i}{\pi} \left[ \frac{\rho_i T_i}{1 - \rho_{ai} s_i} + \frac{(\rho_{ai} - \rho_i) T_i}{1 - \rho_{ai} s_i} r_i \right] \quad (1)$$

where $R_i^{atm}$ is the atmospheric backscatter term, $\mu$ is the cosine of the solar zenith angle, $F_i$ is the solar irradiance, $T_i$ is the sun-ground-sensor total transmittance, $r_i$ is the diffuse-to-total transmittance ratio for the ground-sensor path, $\rho_i$ is the surface reflectance within the pixel, $s_i$ is the atmospheric spherical albedo, and $\rho_{ai}$ is the surface reflectance averaged over a broad region (of order 1 km) around the pixel. Equation (1) holds rigorously for monochromatic radiation and Lambertian surfaces, but it is also satisfactory for bandpass radiation and "effective" non-Lambertian reflectance. To examine the $\rho_i$-dependence of the radiance, we express Equation (1) as

$$R_i = A_i + B_i\rho_i \tag{2}$$

The first term combines the atmospheric backscatter and "adjacency" contributions, while the second term represents the direct surface contribution. Since $A_i$ and $B_i$ depend only on the atmosphere and the spatially averaged surface reflectance, their variation across the image is gradual. Also, since Equation (2) is linear in $\rho_i$ the index $i$ can be generalized to designate a combination of channels rather than just a single one.

With appropriate spectral channel combinations it is possible to extract combinations of the Equation (2) parameters, including cloud scattered radiance, directly from data without prior assumptions about the surface or atmosphere. To illustrate this we choose an "absorption" set of channels from within the 1.13 μm water band and the another "reference" set from either side of the band. Assuming (as is commonly done in water vapor retrievals) that the effective surface reflectances for the absorption and reference sets are the same, we may write

$$R_a = A_a + B_a\rho \tag{3}$$

$$R_r = A_r + B_r\rho \tag{4}$$

Elimination of $\rho$ leads to

$$(R_rW - R_a)/(W - 1) = (A_rW - A_a)/(W - 1) \equiv D \tag{5}$$

where $W = B_a/B_r$ and $D$ is defined as the PR image. The purpose of the $W$–1 denominator will be clarified shortly.

Equation (5) has several notable characteristics. The left-hand side specifies $D$ as a $W$-weighted difference of the absorption and reference images; $W$ may vary gradually across the scene. Since the $\rho$ dependence has been eliminated, no surface features appear in this image. This cancellation of features is a sufficient condition for determining $W$ from the data, as shown below. $D$ is meaningful only when $W$ differs from unity ($B_a$ and $B_r$ differ), a condition that is satisfied by having chosen both absorbing and non-absorbing channel sets. In the approximation that the only parameters in Equation (1) that differ significantly between the absorption and reference sets are the total transmittance $T$ and the atmospheric reflectance $R^{atm}$, the PR image is

$$D = (R_r^{atm}W - R_a^{atm})/(W - 1) \tag{6}$$

It may be seen that the atmospheric scattering contributions to $D$ are weighted differently according to the altitude of origin. Contributions to $R_a^{atm}$ and $R_r^{atm}$ from close to the ground are in a ratio close to $W$ and largely cancel. At the other extreme, where the scattering is from above the water vapor column, $R_r^{atm}$ and $R_a^{atm}$ are essentially equal. In this limit, which approximates the behavior of high-altitude cirrus clouds, a canceling $W$–1 factor appears in the numerator and $D = R_r^{atm} = R_a^{atm}$ -- i.e., the PR image radiance equals the cloud scattered radiance. For lower altitude clouds, the contribution to $D$ is reduced.

Since only the correct value of $W$ leads to cancellation of the surface features in the PR image, $W$ can be found by variance minimization. To allow for a gradual variation of $W$ across the scene, separate minimizations are performed over different regions of the image. The procedure is as follows. Local regions over which $W$ is considered to be constant are defined around each pixel. For each region the averages of images $R_r$ and $R_a$ are taken and the results are subtracted from the original images, resulting in high-pass spatially-filtered images $F_r$ and $F_a$ having local mean values of zero. Writing the variance as the sum over the local pixels of the squared filtered image difference and minimizing with respect to $W$ leads to

$$W = \sum (F_aF_r - F_a^2) / \sum (F_r^2 - F_aF_r) \tag{7}$$

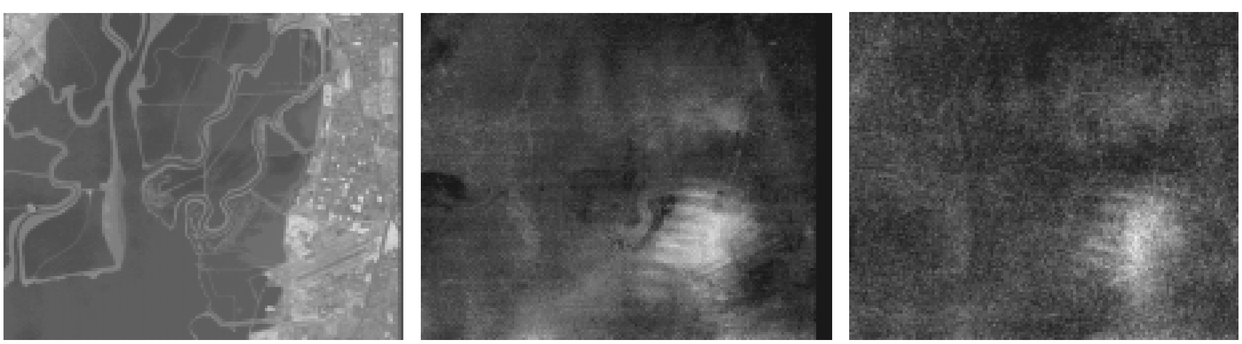
Cirrus clouds are easily recognized in a gray scale display of $D$. Their presence can be confirmed with a pixel-to-pixel correlation plot against the 1.37 μm image. The slope of the plot is the cloud signal ratio, which correlates directly with the water vapor column above the cloud and therefore indirectly with the altitude. Because of this altitude dependence, clouds of different altitudes within the scene can be distinguished. The intercept, which is small, depends on scattering properties of the clear sky (i.e., the aerosol profile).

The PR cloud algorithm is mathematically very closely related to a standard pairwise regression technique for retrieving the upwelling radiance term (corresponding to $A$ in Equation (2)) in one of two wavelength bands (Schott, 1997, Chavez, 1988). In this method it is assumed that the reflectances in the two bands are in some fixed ratio. This leads to an equation analogous to Equation (5) in which the reflectance ratio would be subsumed into one of the $B$ values. The equation is solved using standard linear regression. The essential difference between this method and our PR cloud algorithm has to do with the choice of wavelengths. For retrieving the total upwelling radiance, which includes aerosol, Rayleigh, and cloud scattering components, one requires wavelength bands for which the upwelling radiances are in a very different ratio than the surface reflected radiances. Such bands need to be far apart in wavelength and may not necessarily have consistent reflectance ratios. In contrast, for retrieving the high-altitude cloud radiance component by itself we choose nearby groups of wavelength channels in the vicinity of a water absorption feature. The close proximity of these channels and the combining of reference channels on both sides of the absorption feature insure a very high degree of reflectance correlation between the absorption and reference bands for all types of terrain.

## 3. DATA ANALYSIS EXAMPLE

Figures 1a-c show the results from AVIRIS data taken on 4/7/94 over Moffett Field, CA. Neither the 1.13 μm absorption image (Figure 1a) nor the reference image, which looks nearly identical, show any evidence of cirrus clouds because of interference from the surface features. However, the 1.13 μm PR image (Figure 1b) clearly shows a thin cirrus cloud at the lower right. The presence of the cloud is confirmed by the 1.37 μm image (Figure 1c).

A correlation plot of the 1.13 μm and 1.37 μm signals yields a signal ratio of 5±2. This ratio correlates directly with the water vapor column above the cloud and therefore indirectly with the altitude. This is shown quantitatively in Figure 2 which is based on MODTRAN4 simulations (Berk *et al.,* 1996). The simulations were performed for the solar and sensor geometries of the Moffett Field scene with the US Standard model atmosphere, a 23 km visibility rural aerosol, and the Standard Cirrus Model (64 μm mode radius ice particles). A range of cloud thicknesses (0.2 to 0.7 km) and extinction coefficients (0.4 to 1.4 per km) were used; the results are not very sensitive to these values and averages were taken for Figure 2. The signal ratio is seen to be highly sensitive to the cloud base altitude below around 6 km, where most of the water vapor resides, while above 10 km there is little water vapor absorption and the signal ratio is close to the ratio of the solar function values. The Moffett Field cloud signal ratio corresponds to an effective altitude of around 5 km. The actual altitude will differ if the true water vapor profile differs significantly from that assumed in the model atmosphere.



Figures 1a-c. Demonstration of the PR cloud retrieval method with an AVIRIS image of Moffett Field, CA (No. PG02104). (a) (Left) Image at 1.13 μm; (b) (Center) PR difference image at 1.13 μm showing a cirrus cloud over the air field; (c) (Right) Image at 1.37 μm.

Figure 3 shows the relationship between the MODTRAN4-simulated 1.13 μm cirrus cloud radiance and the cloud absorbance. The radiance offset is due to the aerosol scattering component; the remaining radiance is from the cloud and is altitude-dependent. The relationship becomes nonlinear at high absorbance due to multiple scattering. Combining the altitude estimated from Figure 2 with the average 1.13 μm cloud signal, the average absorbance for the Moffett Field cloud is estimated from Figure 3 to be around 0.4 (optical depth = 0.5).

Figure 3 implies that with only a rough cloud altitude estimate a reasonably accurate absorbance can be derived from the 1.13 μm signal alone. For example, for all altitudes above 5 km the variation in retrieved absorbances for a given signal is only around 50%. In contrast, for the 1.37 μm signal the retrieved absorbances vary over a factor of 4 due to the higher sensitivity of this wavelength to water vapor.

Figures 4 and 5 show some results from a similar analysis of AVIRIS data taken under hazy conditions over a rural area of North Carolina on 7/22/93. Here the atmosphere was very moist, so the 1.13 μm signal contains relatively little surface background to begin with.. The 1.37 μm image looks virtually identical to Figure 4 and is not shown. The correlation plot in Figure 5 is tight; the signal ratio is 2.0-2.1, consistent with cloud altitudes of around 8 km or greater and water absorption of 10% or less at 1.13 μm.

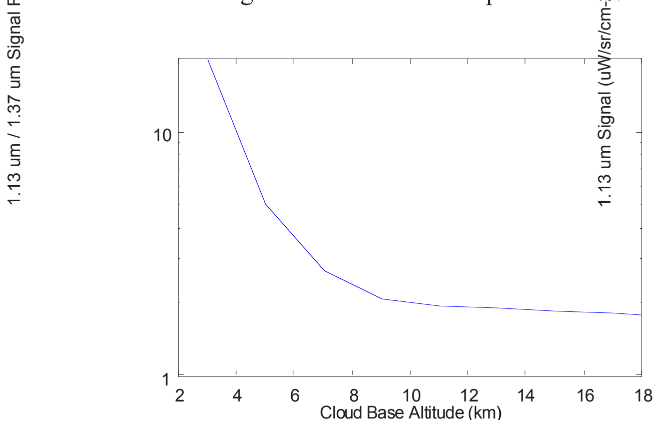



Figure 2. Simulated altitude dependence of the 1.13 μm to 1.37 μm cloud signal ratio.

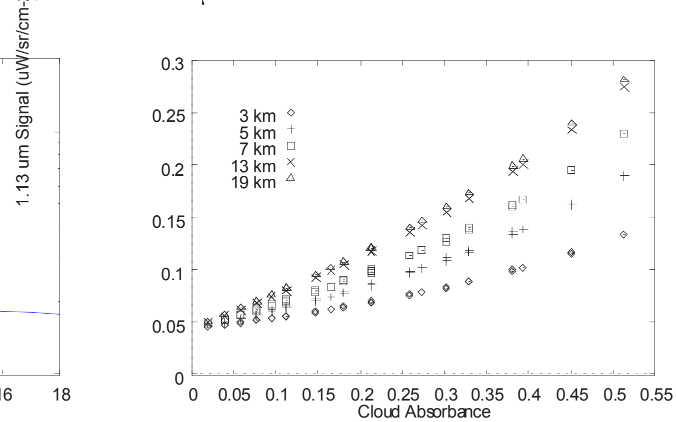



Figure 3. Simulated radiance vs. absorbance relationship for the 1.13 μm cloud signal.

## 4. SURFACE REFLECTANCE CORRECTION

Gao *et al.* (1998) describe a semi-empirical approach for removing cirrus clouds from AVIRIS images. Neglecting the cloud absorption effects, the approach is to subtract a cloud reflectance image from the apparent reflectance of the surface plus atmosphere at each wavelength. The cloud reflectance may be scaled from the 1.37 μm image, the scaling factor accounting for atmospheric absorption (mainly water vapor above the clouds). Gao *et al.* show that appropriate scaling factors for short wavelengths can be derived directly from the image when cloud-covered "dark" pixels (such as vegetation or deep water) are available. When such dark pixels are not available, we propose approximating the cloud reflectance using the 1.13 μm PR signal (in units of effective reflectance). This approach should work for virtually all land surfaces and does not require explicit modeling of atmospheric absorption for wavelengths where the absorption is not significantly greater than at 1.13 μm.

A more sophisticated approach, which would involve MODTRAN simulations of the 1.13 μm and 1.37 μm cloud signals, will be needed for highly accurate image correction. A complication pointed out by Gao *et al.,* 1998 is the "non-local nature" of cloud transmittance--i.e., effects due to cloud shadows, which depend on the sun angle and cloud altitude. As MODTRAN's radiative transfer scheme assumes infinite clouds, a direct simulation essentially places the shadow directly below the cloud. For better accuracy a simulation approach for unshadowed terrain under clouds needs to be developed. Another complication is the cloud "adjacency effect"--i.e., the scattering of upwelling radiance into the sensor This can be handled using a method similar to an adjacency correction that has been implemented for aerosol and Rayleigh scattering (Adler Golden *et al.,* this issue).

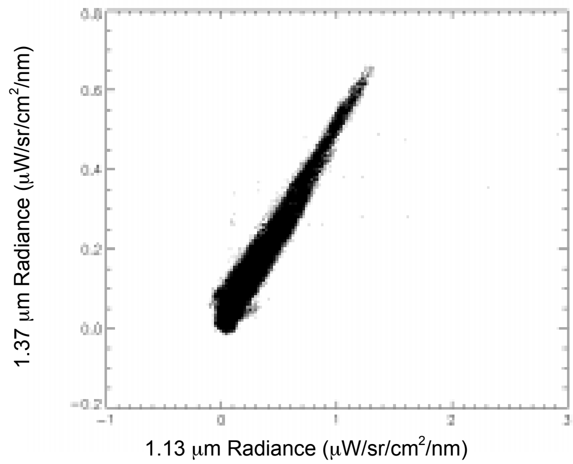



Figure 4. 1.13 μm PR cloud image from 7/22/93 North Carolina data.

Figure 5. Correlation between the 1.13 μm and 1.37 μm cloud signals for the North Carolina data.

## 5. CONCLUSIONS

We describe a new pairwise regression (PR) method for spectral imagery that retrieves cirrus cloud signals in the vicinity of a partially transmitting band, such as the 1.13 μm band, over any type of spatially structured terrain. The method, which uses spatial filtering and linear regression to cancel the surface background, has been demonstrated using both rural and urban AVIRIS scenes. With a single cloud or cloud layer in the scene, the 1.13 μm and 1.37 μm cloud signals are closely correlated; the slope of the correlation plot indicates the column water vapor above the cloud and thus the approximate cloud altitude. This information allows cirrus cloud radiances to be accurately simulated throughout the 0.4-2.5 μm region of AVIRIS and, with the development of a suitable algorithm, should allow the clouds to be effectively removed from the data. The 1.13 μm signal also contains a small scattering contribution from the clear sky, which could potentially provide some information on the aerosol profile.

## 6. ACKNOWLEDGEMENT

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