

Determination of cloud area from AVIRIS data

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ABSTRACT

Fractional cloud area is derived from spectral images collected by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). The derivation is made by ratioing radiances near the 0.94- and the 1.14- μm water vapor band centers against those in the intermediate atmospheric window regions. The derivation makes use of the facts that (1) the reflectances of most ground targets vary approximately linearly with wavelength in the absorption region of the 2 water vapor bands, and (2) atmospheric water vapor concentration decreases rapidly with altitude. The band ratioing technique effectively discriminates among clouds and surface areas having similar reflectance values. It is expected that the use of water vapor channels in the near infrared region in future satellites will improve the ability to determine cloud cover over land.

1. INTRODUCTION

Clouds reflect and absorb solar radiation in the visible and near-infrared (VNIR) region, absorb infrared (IR) radiation originating from the earth's surface, and emit IR radiation to space. Consequently, clouds strongly influence the radiative transfer processes in the atmosphere. In order to improve the understanding of the nature of cloud-radiation feedbacks, global cloud parameters, including cloud cover fraction and cloud optical properties, must be monitored reliably.

Meteorological satellites make possible the global monitoring of clouds on a daily basis. The data typically have fields of view that are 1 to 8 km in diameter on the ground, while the sizes of many clouds can range from approximately 30 m to a few km or even larger. Consequently, a typical satellite image may contain many pixels that are partially filled by clouds. Accurate determination of fractional cloud area from low spatial resolution (1 km or larger) data requires the proper treatment of partially cloud-filled pixels [Shenk and Salomonson, 1972]. Arking and Childs [1985] developed a technique, that used a "maximal clustering" scheme to treat the partial cloud filling problem, for deriving cloud parameters from the Advanced Very High Resolution Radiometer (AVHRR) data. They found that, when a pixel was considered to be partially cloud-filled, there was a wide range in the combination of cloud amount, height, and optical thickness that matched the observed radiances. This demonstrates that the information content of AVHRR data on cloud parameters is limited.

Shenk and Salomonson [1972] predicted theoretically that sufficiently high spatial resolution data would minimize the partial cloud filling problem discussed above and allow the accurate determination of cloud cover with a simple radiance threshold method. However, Wielicki and Welch [1986] studied high spatial resolution (79 m) Landsat Multispectral Scanner (MSS) data and found that the derived fractional cloud cover strongly depended on the assumed threshold because large portions of clouds had reflectances comparable to or smaller than the surface.

In this paper we present results from an improved cloud detection technique using imaging spectrometry data from AVIRIS [Vane, 1987]. Total column atmospheric water vapor amounts are used to separate cloudy and clear areas. This method may be applicable to future imaging spectrometer data from the earth observation system (Eos) mission [Butler et al., 1987].

2. IMAGING SPECTROMETRY

Imaging spectrometers are being developed for remote sensing of the earth from aircraft and from space [Goetz et al., 1989]. The most recent imaging spectrometer under development is AVIRIS [Vane, 1987]. This instrument images the earth's surface in 224 spectral bands approximately 10 nm wide, covering the spectral region from 0.4 to 2.5 μm , from an ER-2 aircraft at an altitude of 20 km, with a swath width of 12 km. The ground instantaneous field of view (GIFOV) is 20x20 m. Complete descriptions of the AVIRIS instrument, including radiometric calibration and data processing, are given by Vane [1987]. Figure 1 shows an example of an AVIRIS spectrum. The main water vapor features centered at approximately 0.94, 1.14, 1.35, and 1.87 μm are clearly observed. A method for quantitative retrievals of column atmospheric water vapor from AVIRIS data with a spectral curve fitting technique has been described by Gao and Goetz [1990]. This technique has high precision (~3%) and can be used to map elevation differences of approximately 100 m based on changes in column water vapor amounts.

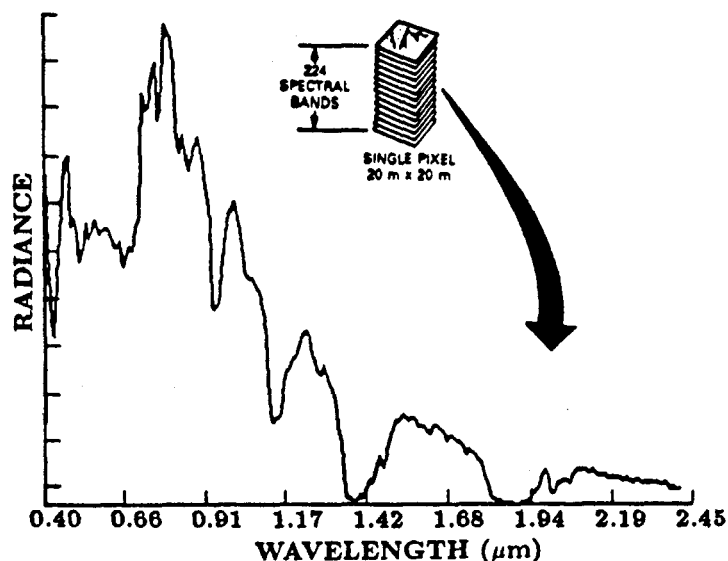


Fig. 1 An AVIRIS spectrum from single pixel (from Vane, 1987).

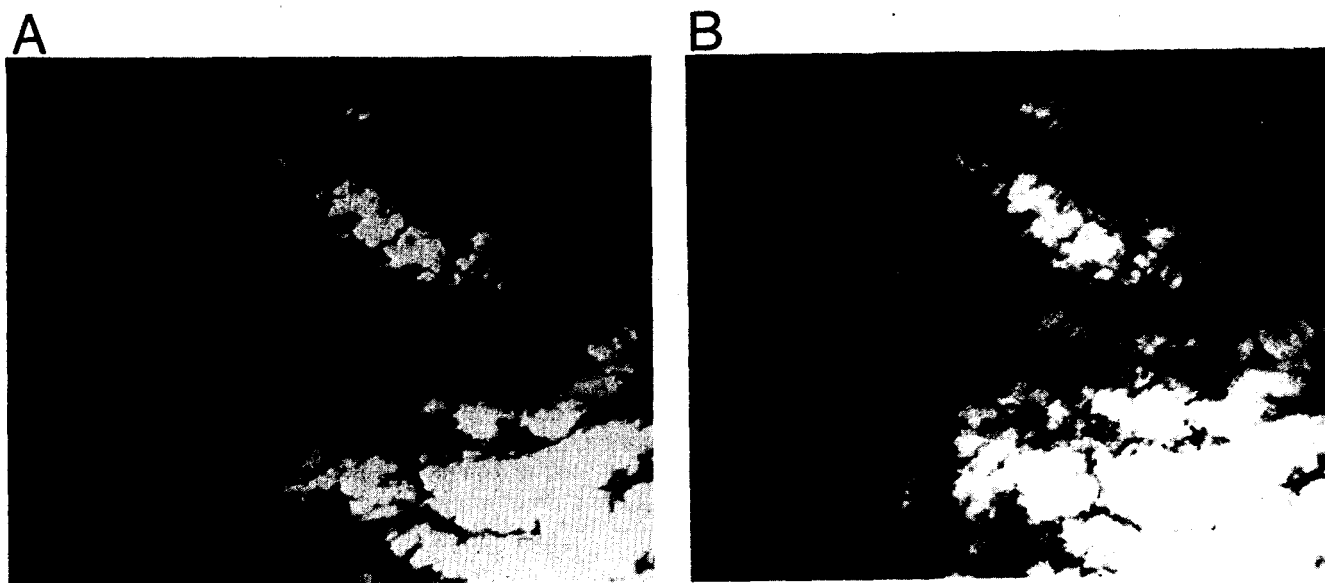


Fig. 2 (a): An AVIRIS image ($0.704 \mu\text{m}$) of Rogers Dry Lake, CA. The data were collected on a partly cloudy day on September 1, 1988. Some dark portions are the low-reflectance cloud areas. (b): An image processed from band ratios.

3. BAND RATIOING

For the sake of simplicity, we describe the band ratioing method for cloud area determination by means of examples.

AVIRIS data taken over Rogers Dry Lake in California on September 1, 1988 and over northern Death Valley in California on May 31, 1989 are used in our cloud cover studies. Figure 2a shows a $0.704 \mu\text{m}$ Rogers Dry Lake image. The image contains 614×512 pixels, corresponding to a ground area of approximately $12 \times 10 \text{ km}$. The variation of surface elevation over the entire scene is less than 50 m. The bright portions of the image are clouds. The dark portions can not all be classified as

cloud shadows, because their shapes are very different from those of bright clouds. A road traverses the image from the upper left to the middle right.

Figure 3 shows a continuous histogram of the radiances at 0.704 μm for the entire scene. The distribution shows no clusters at large or small radiances. It is difficult to select a radiance threshold that separates clouds from clear areas. A large threshold results in misclassification of the low-reflectance clouds as clear surface areas, and a small threshold results in misclassification of high-reflectance surface areas as clouds. If a threshold is placed at the position marked in the figure, then the fractional cloudy area of the scene is 25%. In this situation, the atmospheric water vapor absorption features are useful in cloud area determination.

Figure 4 shows reduced and normalized AVIRIS spectra over a cloudy pixel with the cloud top height approximately 2 km above ground, and a spectrum over a clear pixel. The reduction was performed by dividing the AVIRIS radiances by a solar radiance curve above the atmosphere [Iqbal, 1983] in order to remove the effects of the variation of solar radiance with wavelength. The resulting reduced spectra are referred to as the "apparent reflectance spectra". The normalization was made at 1.01 μm in the atmospheric "window" region. The peak absorptions, relative to the window, of the 0.94 and 1.14 μm water vapor bands over the cloudy pixel are significantly smaller than those over the clear pixel, because the atmospheric water vapor concentrations decrease rapidly with increasing altitudes. The differences in water vapor absorption features above clouds and above clear areas allow the delineation between cloudy pixels and clear pixels.

The AVIRIS radiances are also functions of surface reflectance. After studying a variety of surface target reflectances [Bowker et al., 1985], Gao and Goetz [1990] concluded that reflectances of most common surfaces vary approximately linearly with wavelength in the 0.9- to 1.3- μm region, except for iron-rich soils and minerals, which have broad electronic bands centered near 0.9 μm . The deviations from linearity for most surface targets are typically on the order of 1%. Because of this linearity in common surface reflectances, a band ratio (BR),

$$\text{BR} = (R(0.94 \mu\text{m}) + R(1.14 \mu\text{m})) / (2 \times R(1.04 \mu\text{m})) \quad (1)$$

will essentially eliminate effects associated with differing surface spectral reflectances. In Eq. (1), R represents the apparent reflectance described above. The error, associated with the removal of the linear surface reflectance effect using Eq. (1), is estimated to be 0 - 2% for common surfaces and atmospheric conditions.

4. RESULTS

Figure 2b shows an image processed from the band ratios that were calculated according to Eq. (1). In order to increase the S/N ratios, apparent reflectances of five AVIRIS channels around 0.94 μm were first averaged to give a mean apparent reflectance at 0.94 μm . The same arithmetic operations were carried out for the channels around 1.14 and 1.04 μm before the ratio based on Eq. (1) was made. There are several salient features in Figure 2b. For example, the road is hardly visible. This indicates that the band ratio does remove the surface reflectance effects. Many dark portions in Figure 2a are now shown as clouds. Also, the bright areas in Figure 2b have cloud morphologies.

Figure 5 shows the brightness distribution of the entire ratioed scene. The ratios were multiplied by 1000 for computational purposes. The continuous distribution curve also makes it difficult to select a threshold above which pixels can be classified as cloudy. However, we propose that the cloud area fraction can be derived quantitatively from the distribution curve with procedures described below.

The terrain within the Rogers Dry Lake scene, as shown in Figure 2a, is flat. Therefore, the amounts of water vapor over clear pixels on a partly cloudy day should be within 3% of the same value [Gao and Goetz, 1990]. The band ratios of clear pixels, calculated according to Eq. (1), should also be the same. However, because of the presence of instrument noise, the band ratios for clear pixels will exhibit a gaussian distribution. The clear area fraction is derived by fitting all points in Figure 5 with pixel values less than 260 with a gaussian function by using a non-linear least squares method. The resulting fitted curve is also shown in Figure 5. The normalized area below the gaussian curve is 44 on a scale of 100 with the area uncertainty of approximately 1, based on the uncertainties of the derived gaussian parameters. This means that the clear surface area fraction is 44%. The remaining 56% is attributed to the cloudy area fraction.

The ratio method was applied to a more complex area containing significant elevation differences. Band ratios were calculated with Eq.(1) from AVIRIS data measured over northern Death Valley. The surface elevation differences within the AVIRIS scene were approximately 1 km. The fitting technique described above is not applicable for the derivation of clear area fraction over this scene, because the band ratios are sensitive to elevation differences. Several other techniques were used

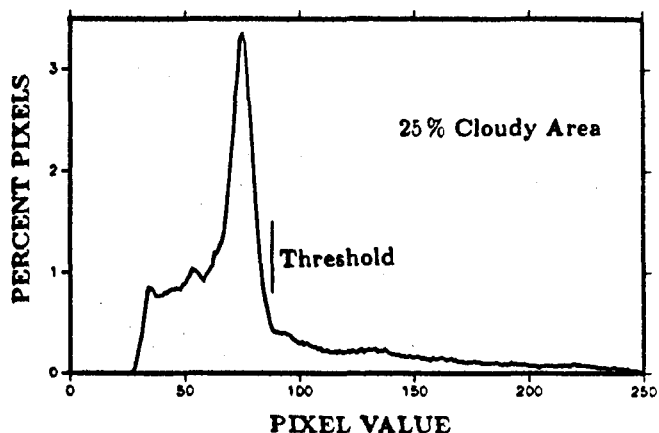


Fig. 3 Distribution of radiances corresponding to the image in Fig. 2a.

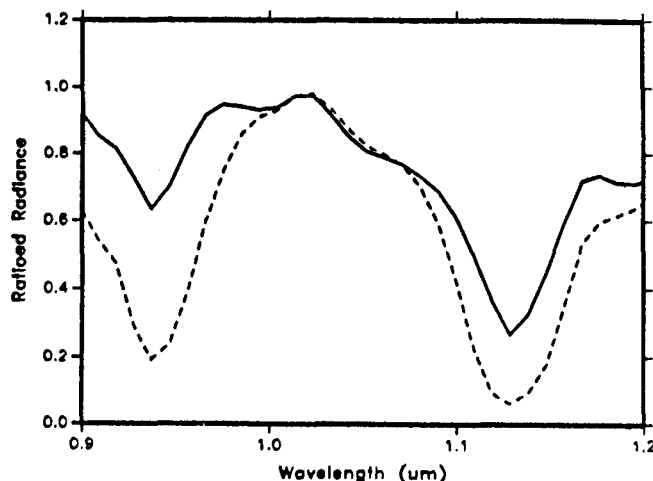
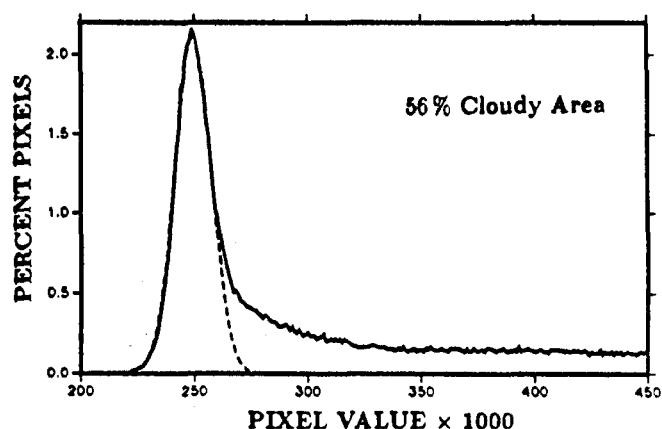


Fig. 4 Examples of AVIRIS spectra over a thick cloud (solid line) with top height of approximately 2 km above the ground, and over a clear pixel (dotted line). The measurements were made in Rogers Dry Lake, CA on September 1, 1988. The spectra were obtained by dividing the observed radiances by a solar radiance curve above the atmosphere (Iqbal, 1983) and then normalizing at 1.03 μm . The water vapor peak absorptions at 0.94 and 1.14 μm over the cloudy pixel are smaller than those over the clear pixel.

Fig. 5 Distribution (solid curve) of band ratios corresponding to the image in Fig. 2b and a gaussian function curve (dotted curve) which approximates the distribution of band ratios from clear pixels.

to estimate the cloud area coverage from the ratioed image. The estimated cloud area coverage from the band ratioed image is 15.4% with an error of less than 2%. For comparison, thresholding techniques were also applied to original AVIRIS images for determining cloud area fractions. Threshold values were selected with the method described by Wielicki and Welch [1986] for land areas. The resulting cloud area fractions for 11 AVIRIS band-images in the 0.7-0.8 μm region, the bandpass of MSS channel 6, were between 4.9 and 7.0% with the average being 6.2% (R. Welch and K. S. Kuo, personal communication, 1990). This demonstrates that significant underestimation of cloud area over land can occur with simple radiance thresholding techniques.

5. DISCUSSION

Our observations indicate that clouds with top altitudes of 500 m have significantly smaller water vapor absorption depths than clear surface pixels. Therefore, the band ratioing method can be used to detect clouds with top altitudes of at least 500 m or greater. The peak absorptions of the 0.94 and 1.14 μm water vapor bands over a cloudy pixel depend not only on the amount of water vapor above the cloud top, but also on the absorption and scattering properties of particles (solid and liquid) and water vapor within the cloud. Theoretical studies by Arking et al. [1987] have demonstrated the importance of water vapor absorption within clouds. It is possible that the very low level clouds (or fog) with cloud top altitudes of approximately 300 m or less may give ratios (see Eq. (1)) comparable to the ratios over clear surface areas, and the band ratioing method may not be able to detect the low level clouds. Because of these concerns, we have not claimed the accuracy with which the cloud area fraction can be determined using our band ratioing method. Theoretical and experimental studies of absorption and scattering properties of very low level clouds are required in order to resolve the accuracy issue.

6. SUMMARY AND CONCLUSIONS

Over high-reflectance land areas the simple radiance threshold method for cloud area determination does not allow the discrimination between low-reflectance clouds and high-reflectance surface areas. Because the atmospheric water vapor concentration decreases rapidly with height, the depths of water vapor absorption bands above clouds are usually smaller than those above clear surface areas. The band ratios, calculated with Eq. (1) by using radiances from narrow spectral channels located at the 0.94 and 1.14 μm water vapor band centers and at the atmospheric window near 1 μm , eliminate the surface reflectance variation effects and allow the separation between clouds and clear surface areas.

In the mid-1990s, NASA expects to carry, among others, two imaging spectrometers, the Moderate Resolution Imaging Spectrometer (MODIS) [Salomonson et al., 1989] and the High Resolution Imaging Spectrometer (HIRIS) [Goetz and Herring, 1989] aboard the Earth Observing System (Eos) Polar Platform. Because HIRIS has spectral channels and a spatial resolution similar to that of AVIRIS, our method is directly applicable to cloud area determination from HIRIS. Also, the results from HIRIS data analysis may be useful in refining algorithms for retrieving cloud parameters from data measured by MODIS, which has a pixel size of approximately 0.5 km and has the capability of global coverage.

7. ACKNOWLEDGMENTS

The authors are grateful to R. O. Green and G. Vane of the Jet Propulsion Laboratory for providing the AVIRIS spectral image data. This work was partially supported by the Jet Propulsion Laboratory, California Institute of Technology under contract 958039.

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