Imaging Spectrometry for Studying Earth, Air, Fire and Water

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Abstract

Imaging spectrometry for studies of the Earth has been undergoing development for the last decade. Both commercial and research imaging spectrometers are now available and the number of applications for these kinds of data is steadily increasing.

The most ambitious imaging spectrometer development is embodied in the High Resolution Imaging Spectrometer (HIRIS), slated to be part of the Earth Observing System (EOS) Payload on the first platform in 1998. HIRIS has the capability of observing any point of the Earth every two days or less with a nadir swath 24 km wide and 30 m pixels in 192 spectral bands ranging from 0.4 to 2.45 µm. HIRIS operates at an intermediate scale between the human and the global, and thus is essential to link the studies of processes at the surface of the Earth to the global monitoring program that is one of the functions of EOS. Some of the fundamental questions in earth system science revolve around the scale dependence of processes along with the interactions of processes that occur at fundamentally different scales.

Some of the results already demonstrated with the Airborne Visible Infrared Spectrometer (AVIRIS) are high precision, total column precipitable water in the atmosphere, better discrimination between clouds and the land surface, biological components in turbulent waters, biochemical components of plant canopies, and direct identification of surface mineralogy.

1. INTRODUCTION

Imaging spectrometry is defined as the simultaneous acquisition of images in hundreds of contiguous spectral bands such that for each picture element (pixel) a complete reflectance or emittance spectrum can be derived for the wavelength region covered (Goetz *et al.* 1985). During the last decade, several airborne imaging spectrometer systems have been developed for the wavelength region 0.4-2.5 µm. It has been shown (Goetz 1989) that a 10 nm bandwidth for an imaging spectrometer is sufficiently narrow to allow the acquisition of all of the information available in the solar signal scattered from the surface. Not all disciplines make use of the complete reflectance spectrum because the absorption features of interest in the spectrum for water, vegetation, atmospheric transmission, and rocks and soils occupy different locations in the spectral region

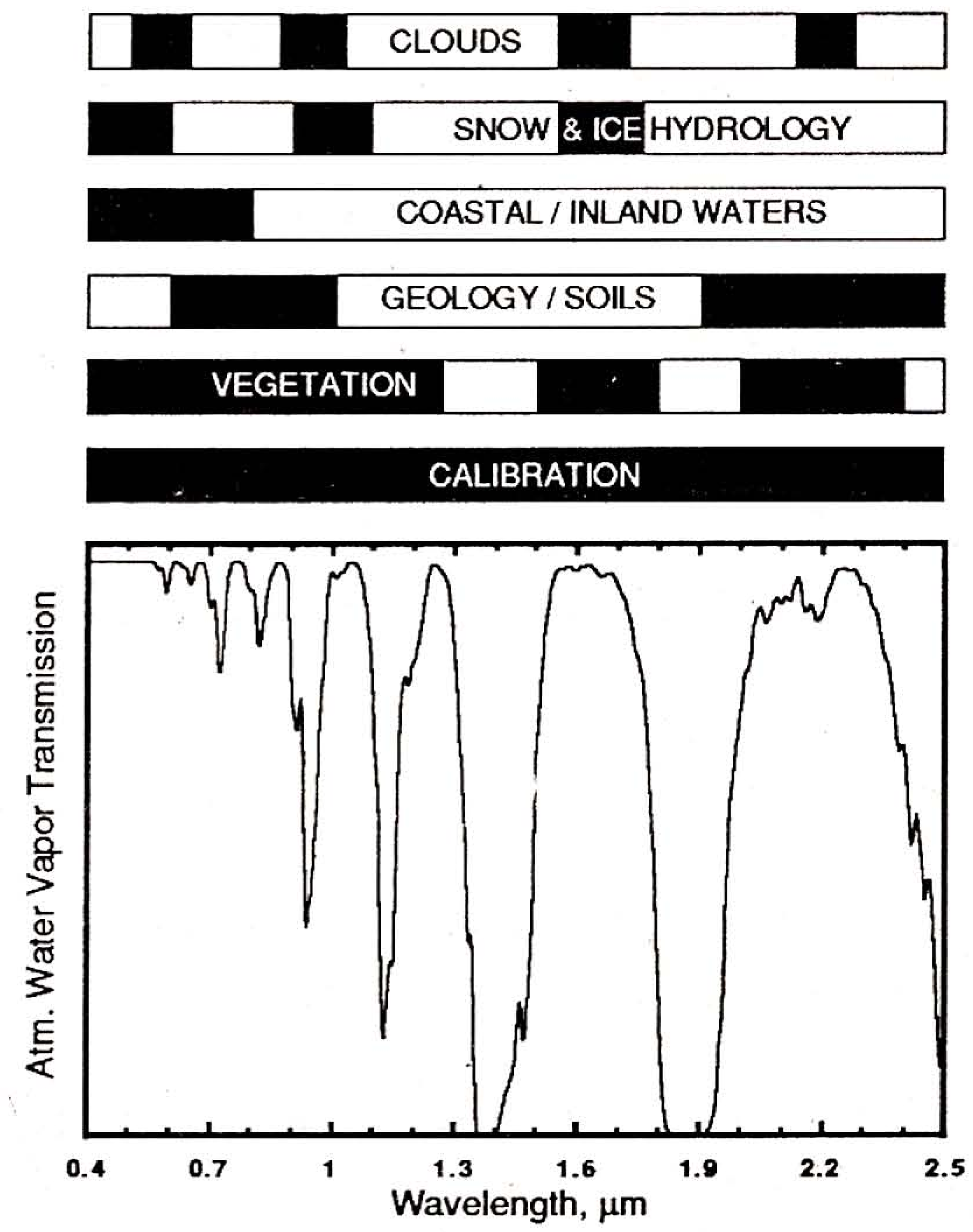

Fig. 1. Spectral coverage requirement for different Earth Science disciplines. The dark bars are the spectral regions for which imaging spectrometry is required. The full wavelength region is required for calibrating an imaging spectrometer.

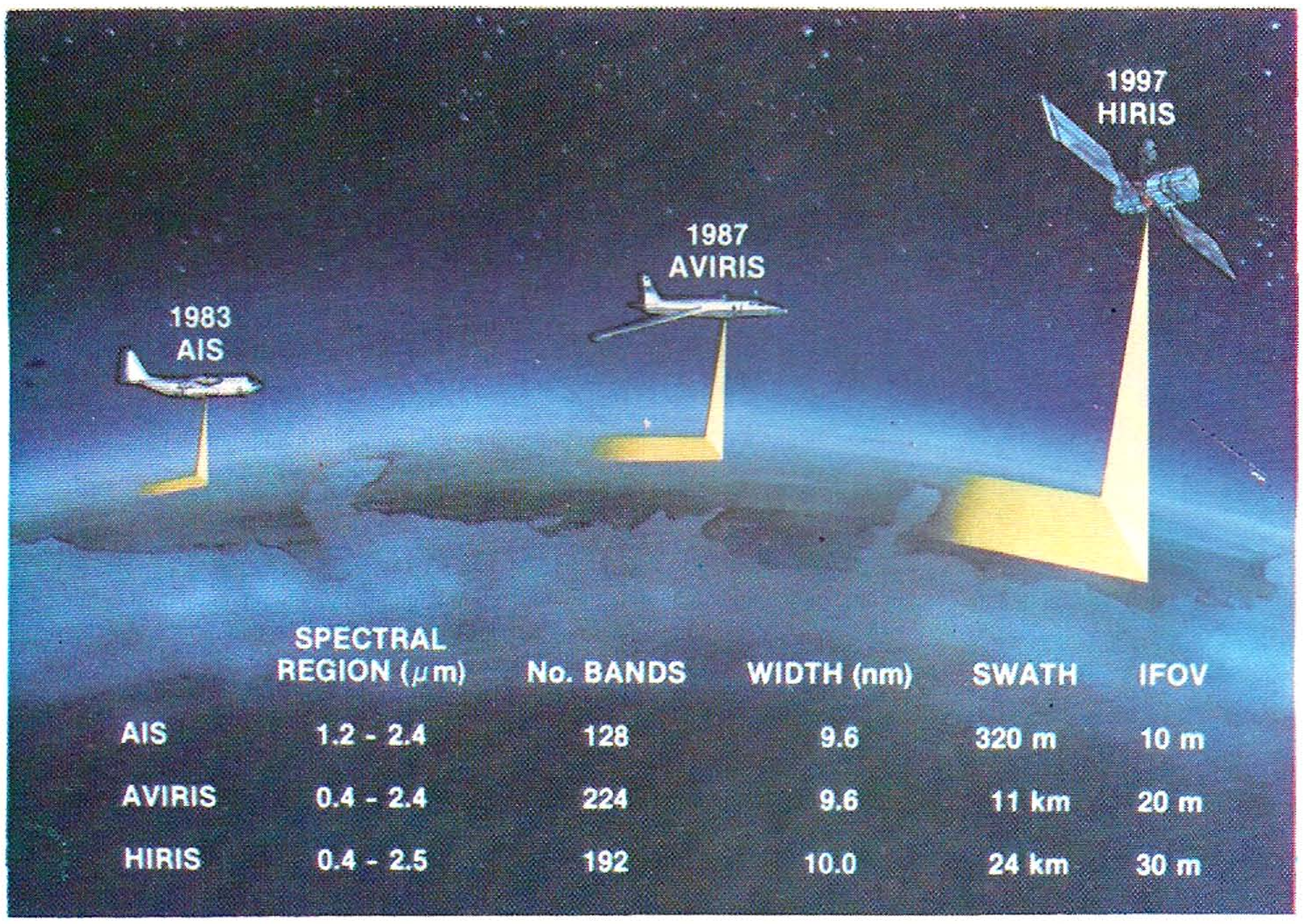

Fig. 2. Historical development of the three major research imaging spectrometers as developed at the JET Propulsion Laboratory.

(Fig. 1). The philosophy in the development of imaging spectrometry has been to provide full spectrum capability with the understanding that only portions of the spectrum are necessary for any particular discipline. This philosophy obviates the need for committees to determine which spectral bands will be chosen for a multispectral scanner. In the following pages, several examples will be used to demonstrate the power of the imaging spectrometry techniques for quantitative remote sensing studies of the Earth.

2. BACKGROUND

The development of imaging spectrometry for earth remote sensing began in 1980 at the Jet Propulsion Laboratory, Pasadena, California. The impetus for this development was derived from Landsat studies, and in particular, field reflectance measurements in the 0.4-2.5 μm region which showed that much information was available in the spectrum that was not being acquired by the most modern development of that time, the Landsat Thematic Mapper. The development of the Shuttle Multispectral Infrared Radiometer (SMIRR) (Goetz *et al.* 1982), showed that, from orbit, it was possible to do direct mineral identification, given closely spaced contiguous spectral bands.

The advent of area-array detectors that operated beyond the 1.0 μm region made it possible to consider a full spectrum imaging spectrometer. The development of imaging spectrometers at the Jet Propulsion Laboratory is shown schematically in Fig. 2. It is interesting to note that the spectral sampling interval has remained at approximately 10 nm while moving from the Airborne Imaging Spectrometer (AIS) flown at 4 km altitude to the High Resolution Imaging Spectrometer (HIRIS) flown at 705 km, while the spatial coverage has increased dramatically and the pixel size has moved from 10 to only 30 m as the altitude of the platform has increased by a factor of 175. The AIS was developed as a proof-of-concept instrument for infrared area-array detectors. It provided the first images, albeit only 320 m wide that proved the concept of direct mineral identification (Goetz *et al.* 1985).

The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) (Vane 1987) was developed to provide scientific data rather than as a technology demonstration. For that reason, the technology that was available in 1984 at the beginning of the project was used. AVIRIS is an optomechanical, whisk- broom scanner utilizing scanning foreoptics, fiber-optic connections to four spectrometers, and line array silicon and indium antimonide detector arrays. The total combination provides 224 spectral channels between the wave lengths 0.4-2.45 μm.

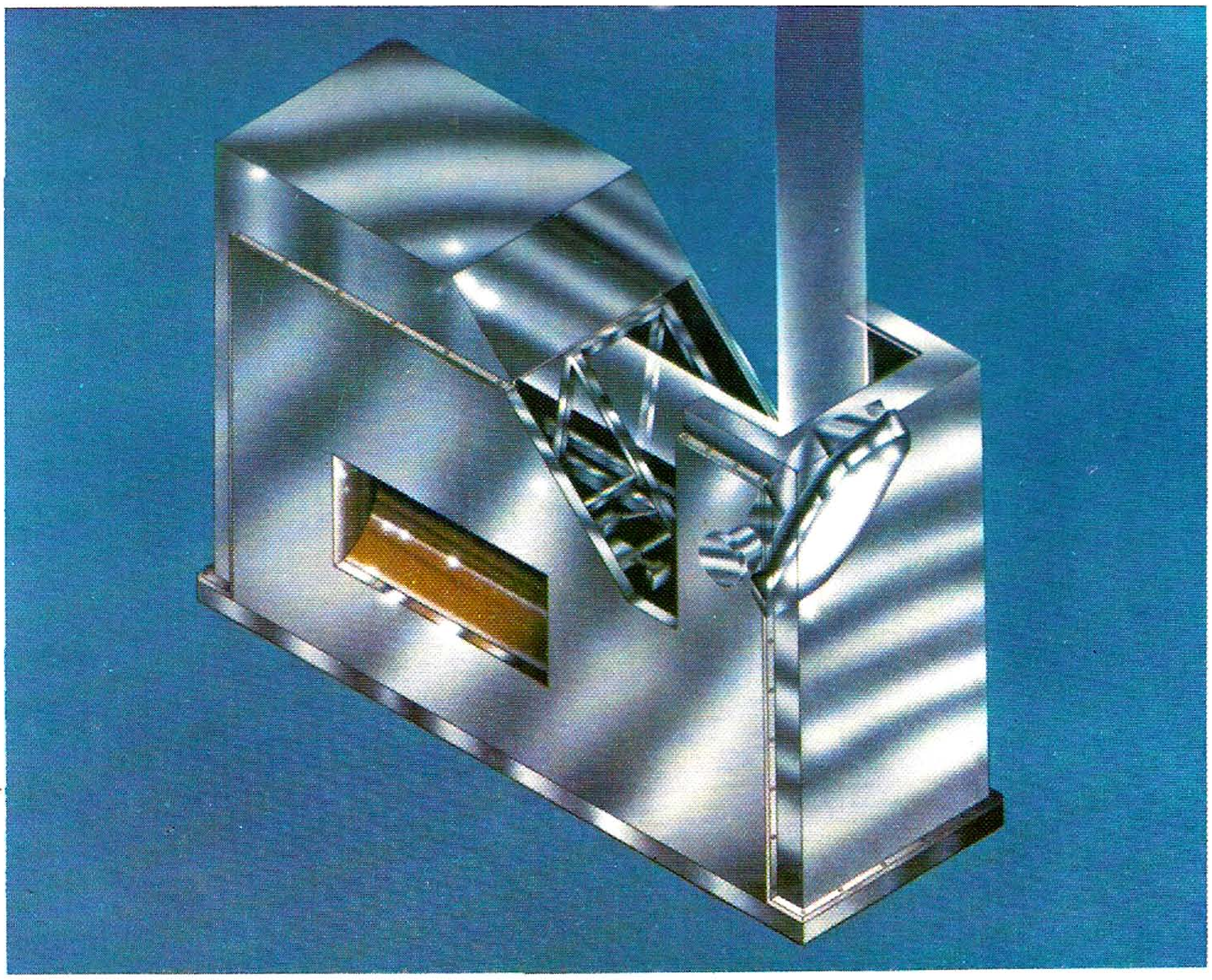

Fig. 3. Artist's rendition of the High Resolution Imaging Spectrometer (HIRIS). The dimensions are 1.2 m high x 0.9 m wide x 2.3 m deep.

In 1984 the Shuttle Imaging Spectrometer Experiment (SISEX) was proposed but eventually it was cancelled as a result of the Challenger accident. However, the SISEX design provided the basis for HIRIS which is now slated for launch in 1998 as part of the Earth Observing System (EOS).

3. HIRIS INSTRUMENT

HIRIS is currently expected to fly on the first polar orbiting platform of the EOS in 1998. Fig. 3 shows an artists conception of the instrument which has the dimensions 1.2 m high x 0.9 m wide x 2.3 m deep. The mass is 450 kg and it consumes an average 300 watts of power. Fig. 4 shows the HIRIS functional block diagram which includes a schematic of the prism spectrometer. The VNIR detector covers 64 wavelength bands and the SWIR, 128 for a total of 192 spectral bands between 0.4 and 2.45 µm. The average bandwidth is 10.7 nm but can range from 8-14 nm in width as a result of the nonlinear wavelength dispersion characteristics of the prisms. The overall speed is f/5.4.

The HIRIS estimated signal-to-noise ratio performance is given in Fig. 5. The performance is significantly better than for AVIRIS and this is achieved by using area- array detectors. The integration time per pixel is approx. 4.3 ms. However, the performance over the full wavelength region is still not optimal, for instance, for water measurements near 0.4 µm and for mineral identification near 2.4 µm. The solution is to use image motion compensation, taking advantage of the pointing mirrors to increase the integration time. This is shown schematically in Fig. 6. The image is acquired ahead of the spacecraft and completed behind the spacecraft. In the case of "IMC8" the 24 km swath length of the image is acquired as the spacecraft traverses 192 km on the ground. This increase in integration time results in an increase in SNR between 8 and the square root of 8 depending on the relationship between detector/ preamplifier noise and signal shot noise. The resulting SNR curves using IMC8 is shown in Fig. 7. For a solar zenith angle of 25° and a surface albedo of 50%, SNR values of more than 1,000 are achieved in the region .5-1.6 µm. These high values will, for instance, make possible vegetation biochemistry studies not previously considered feasible.

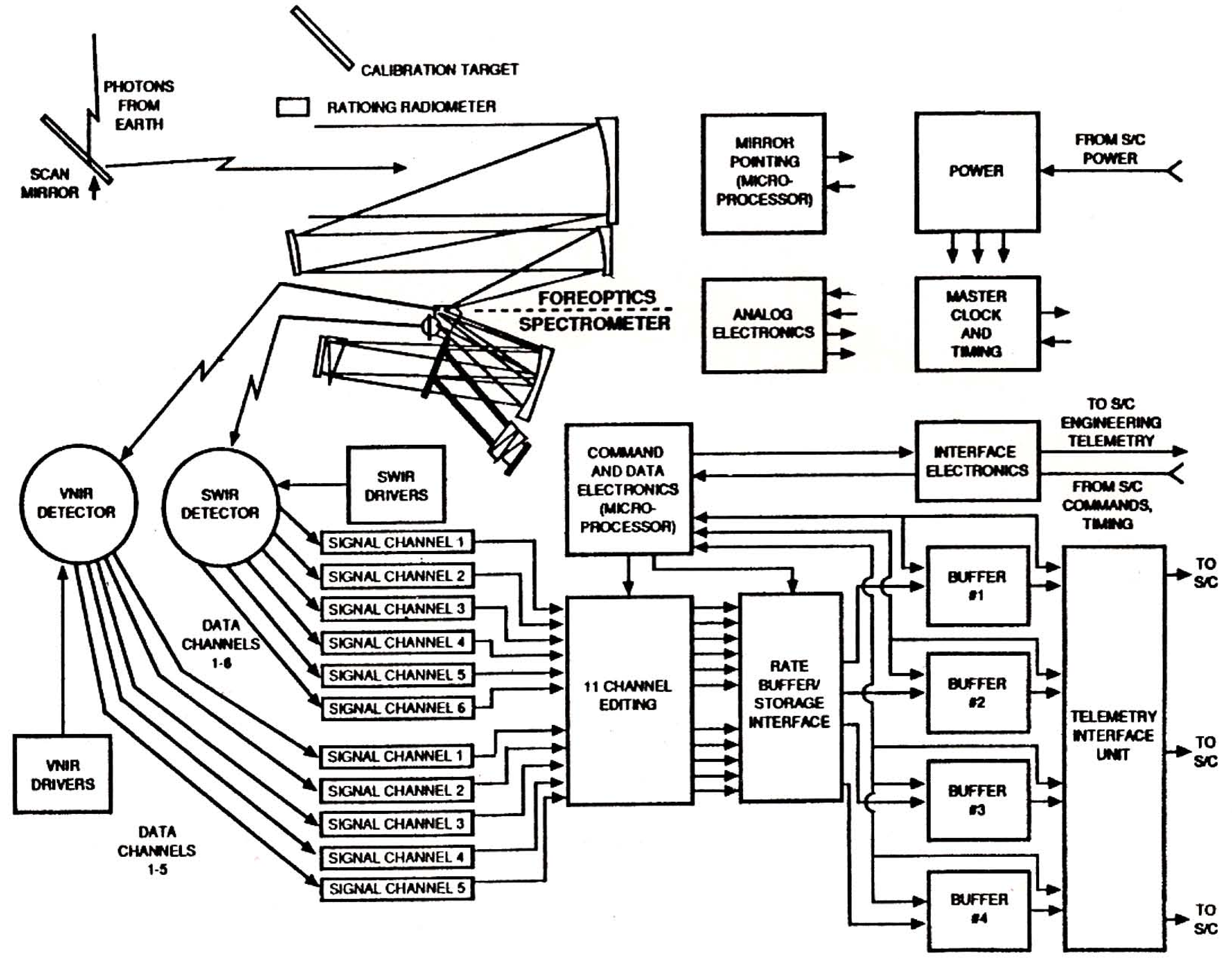

Fig. 4. HIRIS functional block diagram.

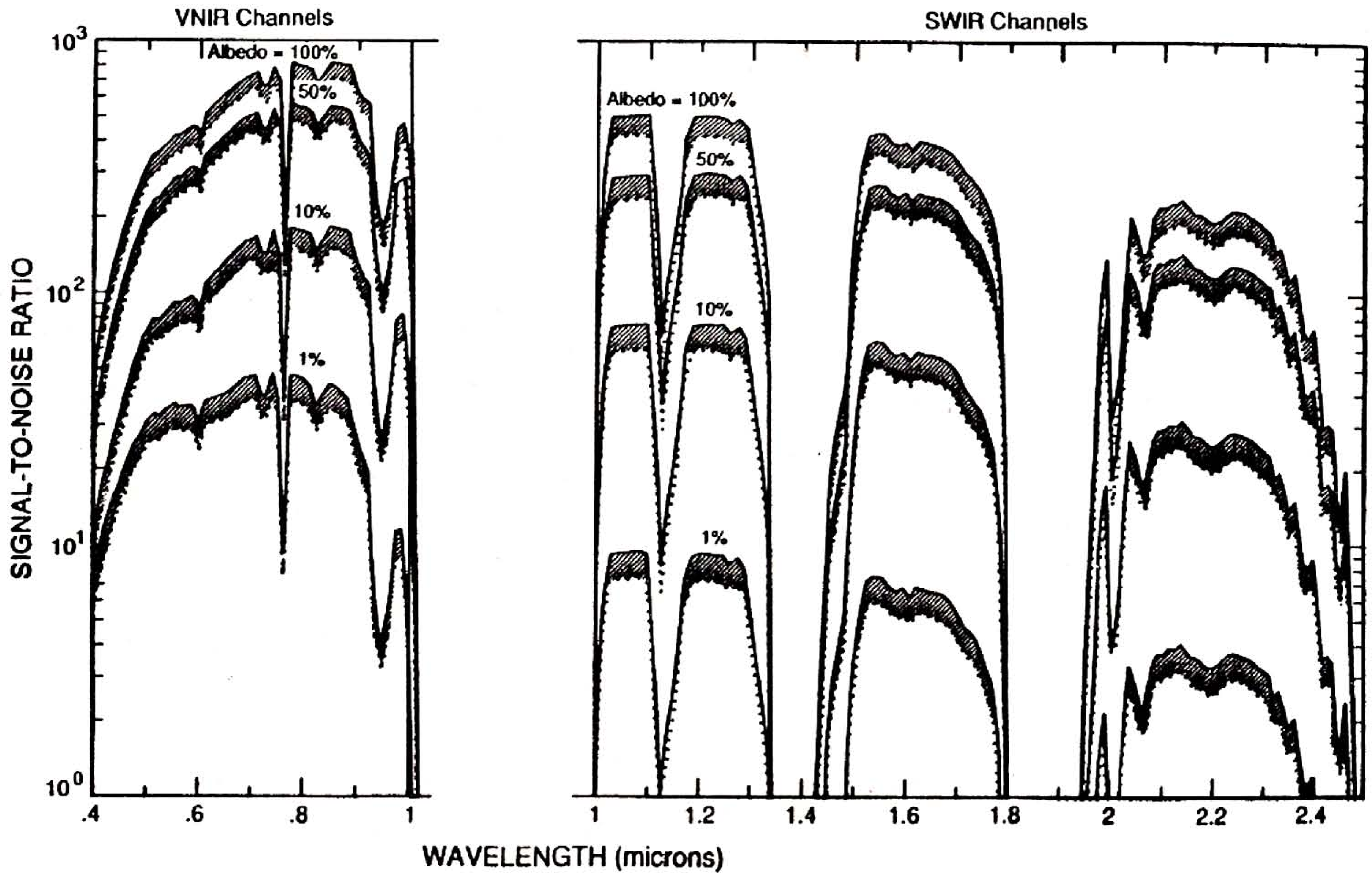

Fig. 5. HIRIS estimated signal-to-noise performance without image motion compensation. Solar zenith angle 25°, look angle 5°. The dotted line represents the signal-to-noise ratio performance for the silvered mirror reflectivity that has been reduced by 3% for each surface. This degradation might be expected over the lifetime of HIRIS.

4. IMAGING SPECTROMETRY APPLICATIONS TO GLOBAL CHANGE STUDIES

Studies of global change are not confined to climate change. For the first time there are planned systematic studies of the land and ocean surface on a global scale as part of the Earth Observing System. Two imaging spectrometers with complementary capability will be flown. The Moderate Resolution Imaging Spectrometer (MODIS) is actually two instruments MODIS-T (tilt) and

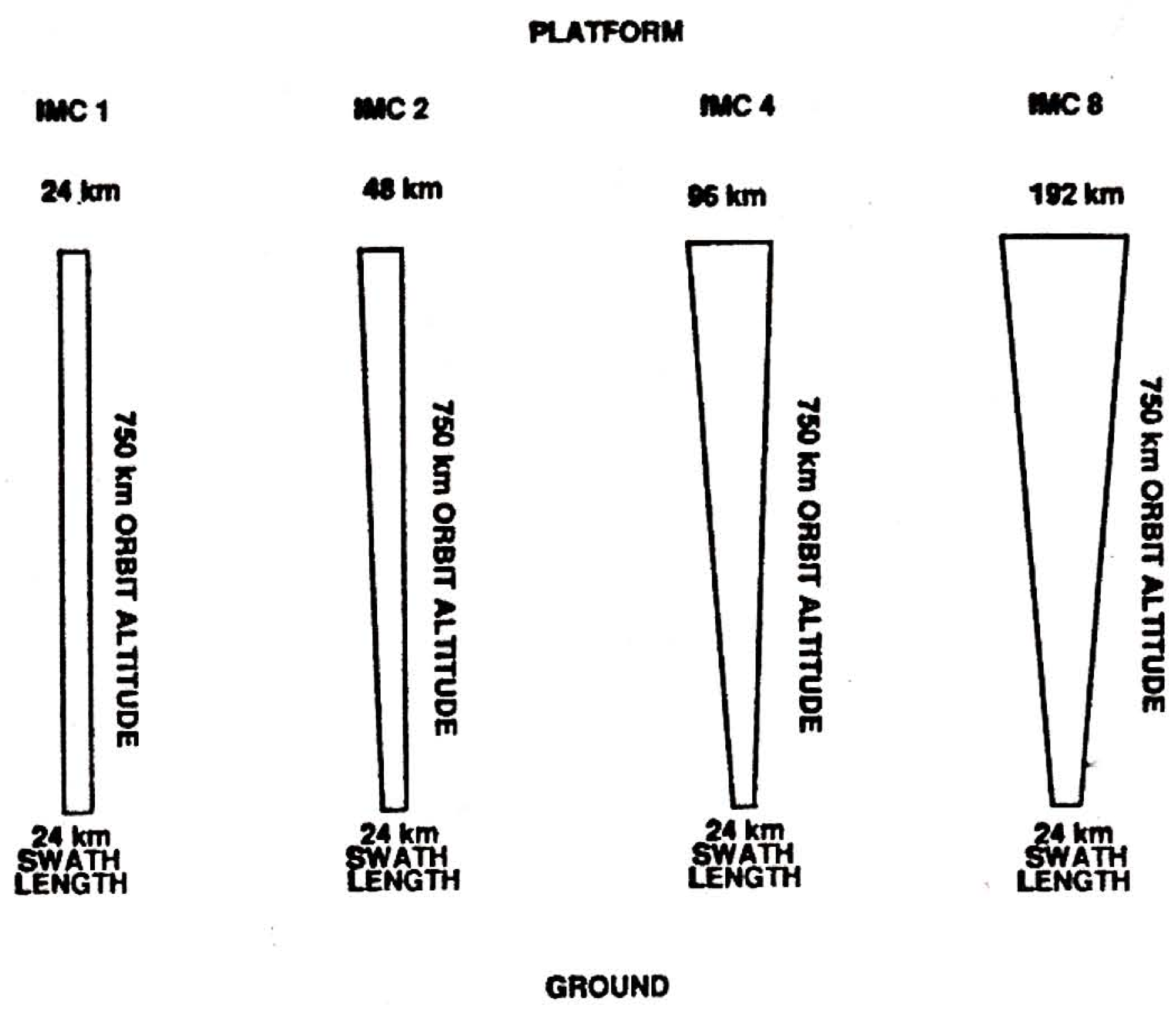

Fig. 6. Diagrammatic representation of the orbit swath length and angles required to create image motion compensation up to a factor of 8.

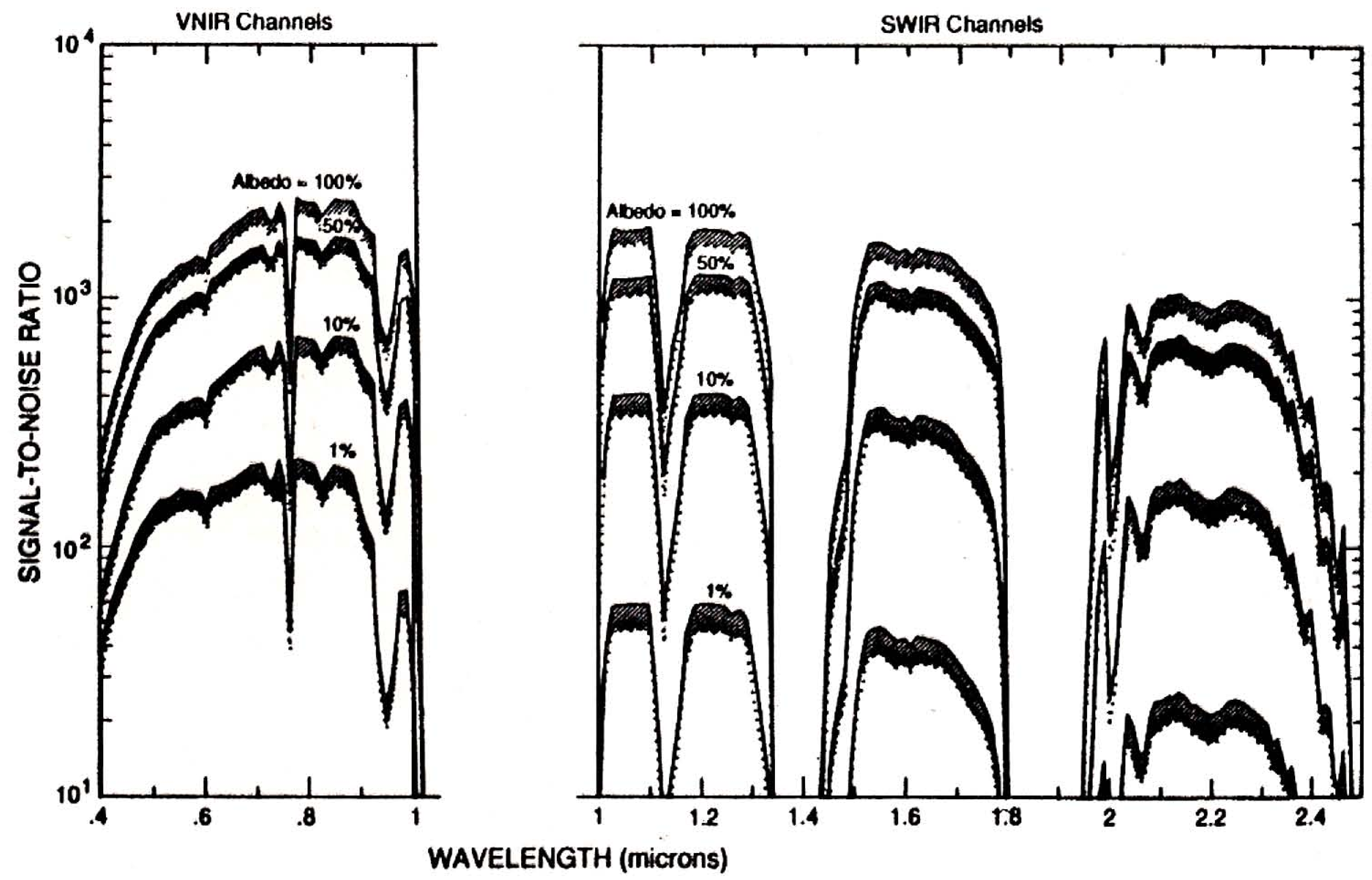

Fig. 7. HIRIS estimated signal-to-noise ratio performance for IMC8 under the same conditions as given in Fig. 5.

MODIS-N (nadir) (Salomonson *et al.* 1989). The second is HIRIS discussed above. The two instruments have significantly different objectives and therefore vastly different capabilities.

MODIS is viewed as the primary instrument with which to develop long term global data bases to establish the Earth's present state and to delineate trends in global change. MODIS will monitor the entire globe every two days for a minimum ten year period which will make it possible to separate trends from short term natural variations. Terrestrial studies, amenable to being addressed by low resolution imaging radiometer include: rate of tropical deforestation and type and rate of regrowth; aerial distribution and effect of acid rain on boreal forests at high latitudes; rate and extent of desertification at the edge of the world's deserts; update of global vegetation maps; extent of freeze or drought damaging crop plants and natural communities; land cover change and its effect on terrestrial biophysical systems; continental changes in snow cover with associated changes in albedo; and derived products including standing green biomass, intercepted photosynthetically active radiation, and net primary productivity.

Oceanographers will utilize MODIS visible data to characterize the global distribution of phytoplankton biomass and its temporal and spatial variability. Oceanic and global measurements of primary productivity and their temporal variation will be possible. Thermal infrared data will be used to study variability in sea surface temperature as related to physical processes on the climatological and physical dynamics scales. Mesoscale ocean circulation features, such as warm and cold rings and jets, can be observed and their development followed for months or years using ocean color and thermal infrared data.

HIRIS plays a different role than MODIS because it obtains data at at least 250 times the aerial resolution of MODIS and has complete spectral coverage in the 0.4-2.45 µm region. Because the HIRIS instrument data rate is so high (405 Mbs) and only 100 Mbs can be transmitted to the platform data system, HIRIS is by definition a sampling instrument.

The high spatial resolution of HIRIS makes it ideally suited for extending measurements made at the human scale to those made by MODIS. HIRIS can therefore be used for process studies which include the estimation of fluxes, nutrients, solutes, and sediments. It is also suited for the development of models and their validation.

HIRIS allows studies of interfaces such as the land-wetland-ocean interface, the tundra- boreal forest interface, the urban-grassland and grassland-forest interface. In these regions, the rates of change are the highest and it is expected that HIRIS will detect these changes long before the average changes are detected by MODIS. Important fluxes take place at small scales and require high spatial resolution to detect them. HIRIS is not suited to making complete global measurements but rather can be used for sampling in areas where models are being developed for the integration of the effects of small scale processes.

The scaling of processes remains an important question in remote sensing of the global environment. HIRIS operates at the intermediate scale between the human and the global, and thus is essential to link studies of processes at the surface of the Earth to the global monitoring program that is one of the functions of EOS. Some of the fundamental questions in earth system science revolve around the scale dependence of processes and the scale invariance in others, along with the interaction of processes that occur at fundamentally different scales. Experimental measurements can investigate processes at the detailed level in which the transport of nutrients, sediments, gases and solutes occur. These relate to the uptake of carbon dioxide and nitrogen by plants, a release of water vapor and organic compounds by plants, the movement of sediment in rivers, the elution of chemicals from the seasonal snowpack. Since some of these processes are nonlinear, it is important to understand the scaling process and to develop mixing models so that data acquired at coarse resolution can be properly interpreted. Thus, the intermediate scale of HIRIS is essential to link understanding of Earth surface processes to the global monitoring program, that is one of the functions of EOS.

5. ATMOSPHERE

One of the primary goals in the EOS program is understanding climate change, and a necessary aspect is the radiation balance. This balance depends on the makeup of gases in the atmosphere but also to a great extent on the clouds. While HIRIS does not create the necessary global data set, it can contribute to understanding scaling processes and in some cases produce data of much higher precision than can be acquired by MODIS. Fig. 8 shows the atmospheric transmission of water vapor for various values of total column precipitable water vapor. Water vapor affects over half of the spectral region from 0.4- 2.45 µm and, as such, must be understood on a pixel by pixel basis in order to remove its effect and acquire true surface radiance. Of course in the 1.4 and 1.9 µm water vapor bands, no energy reaches the surface in the saturated regions and therefore it is not possible to compensate for water vapor transmission in these regions.

Gao and Goetz (1990) have developed a technique for high precision determination of total column water vapor in AVIRIS data using the 0.94 and 1.14 µm unsaturated water vapor bands. Their technique yields precisions on the order of 3% for regions containing topographic variations less than 50 m. Fig. 9 shows a water vapor image over the Cuprite mining district in Nedava in which elevation changes of 300 m are present within the image. The blue areas represent low water vapor values, approximately 0.8 cm and are correlated with the higher elevations. The red values correspond to approximately 1.1 cm precipitable

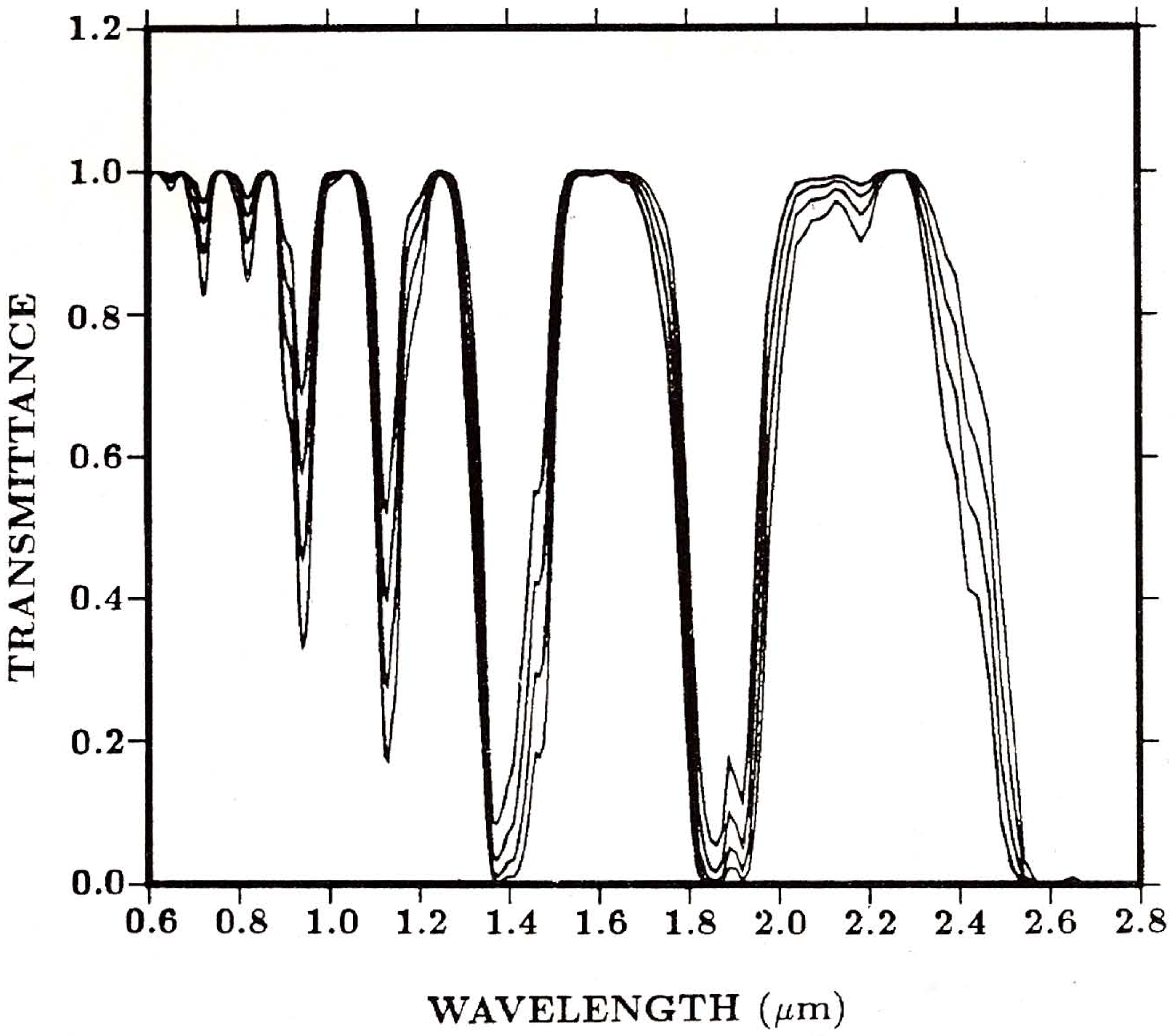

Fig. 8. Spectral atmospheric transmission associated with various amounts of water vapor.

water and are correlated with the low areas in the image. This technique is sufficiently sensitive to detect elevation changes of approximately 50 m. This method makes it possible to reduce the spectrum of each pixel to account not only for water vapor but also for O_2, CO_2 and CH_4, the additional major contributors to atmospheric absorption in the 0.4-2.45 μm region.

Clouds play a major role in the radiation balance in the Earth's atmosphere. A 4% increase in average cloudiness would be equivalent to halving the amount of CO_2 in the atmosphere from a radiation balance point of view. Low resolution sensors such as AVHRR can produce cloud cover data for the globe but there are still ambiguities in determining the fractional cloud cover within a pixel. A very recent study (Gao and Goetz 1990b) shows that it is possible with AVIRIS data to differentiate among clouds and bright surfaces by making water vapor images. Since the clouds, in most cases, lie above the surface within an image, elevation derived from water vapor measurements can be used to separate the clouds from the surface. An example is shown in Fig. 10 which is a single-channel AVIRIS image of a portion of Roger's Dry Lake, California. The surface is clearly visible at the left and clouds cover the area on the right but in the intermediate area it is not clear whether the cloud shadows are falling on the surface or on a lower cloud deck and in many cases the surface is brighter than portions of the cloud deck. The method most often used in separating clouds from the surface is by simple thresholding (Wielicki and Welch 1986) assuming that the clouds are always brighter than the surface. When this technique is applied to Fig. 10, the fractional cloudy area of the scene is calculated to be 25% (Gao and Goetz 1990b). By measuring the water vapor content for each pixel, a new image can be created as shown in Fig. 11. Low water vapor values are light, high water vapor values are dark. The light areas extend over approximately half the image and thresholding applied to this processed image yields the fractional cloudy area of 56%.

6. WATER

The high spectral resolution of AVIRIS/HIRIS makes possible the determination of chlorophyll and accessory pigments in marine and fresh waters in both Case I and Case II waters. The development of new models is necessary to utilize the contiguous spectral bands throughout the visible and near- infrared portions of the spectrum (Carder *et al.* 1985; Pilorz and Davis 1990). With AVIRIS/HIRIS it is possible to map chlorophyll concentration patches which have sizes on the order of

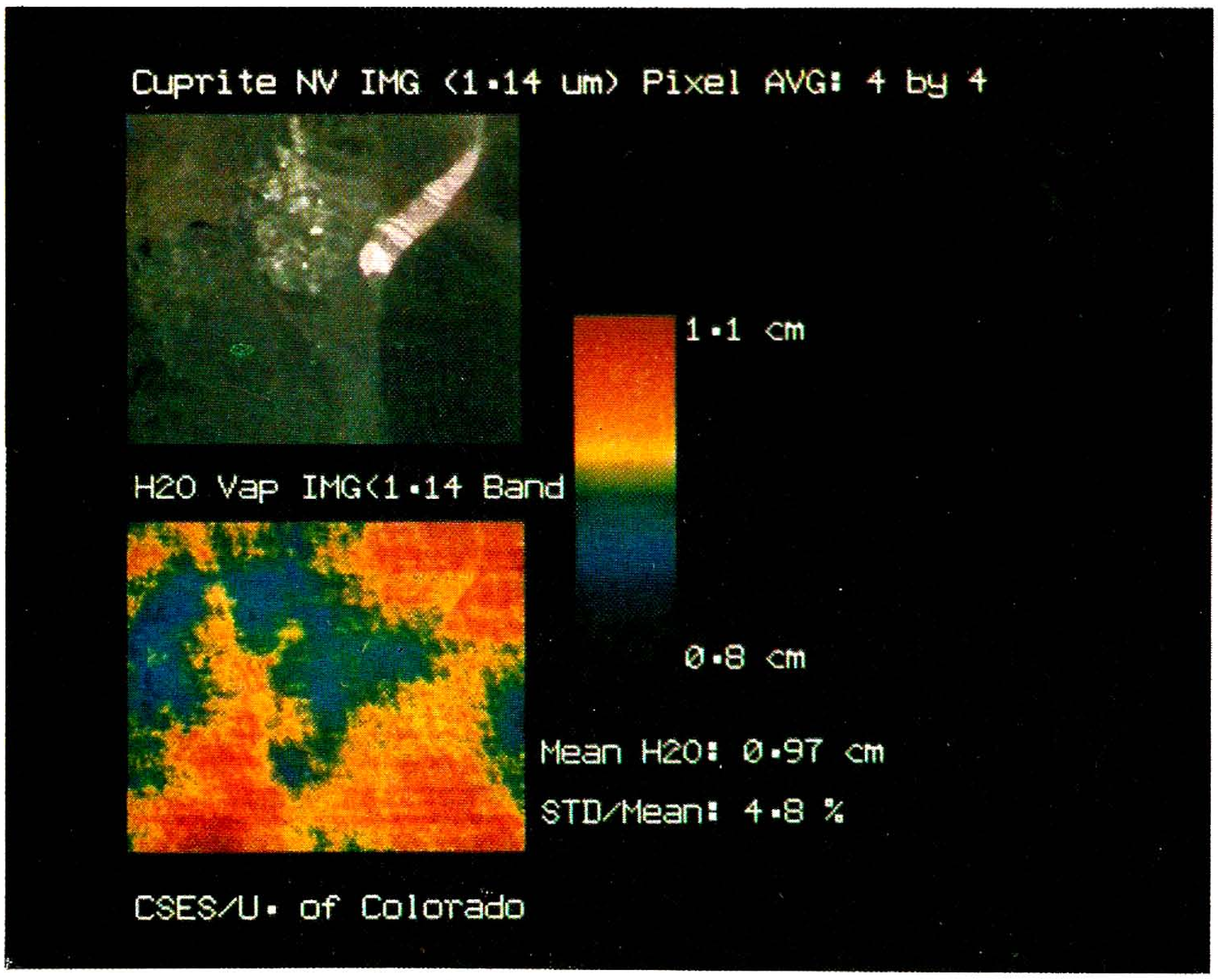

Fig. 9. Total column precipitable water vapor image of the Cuprite, Nevada mining district showing variations associated with elevation but independent of surface albedo (Gao and Goetz 1990).

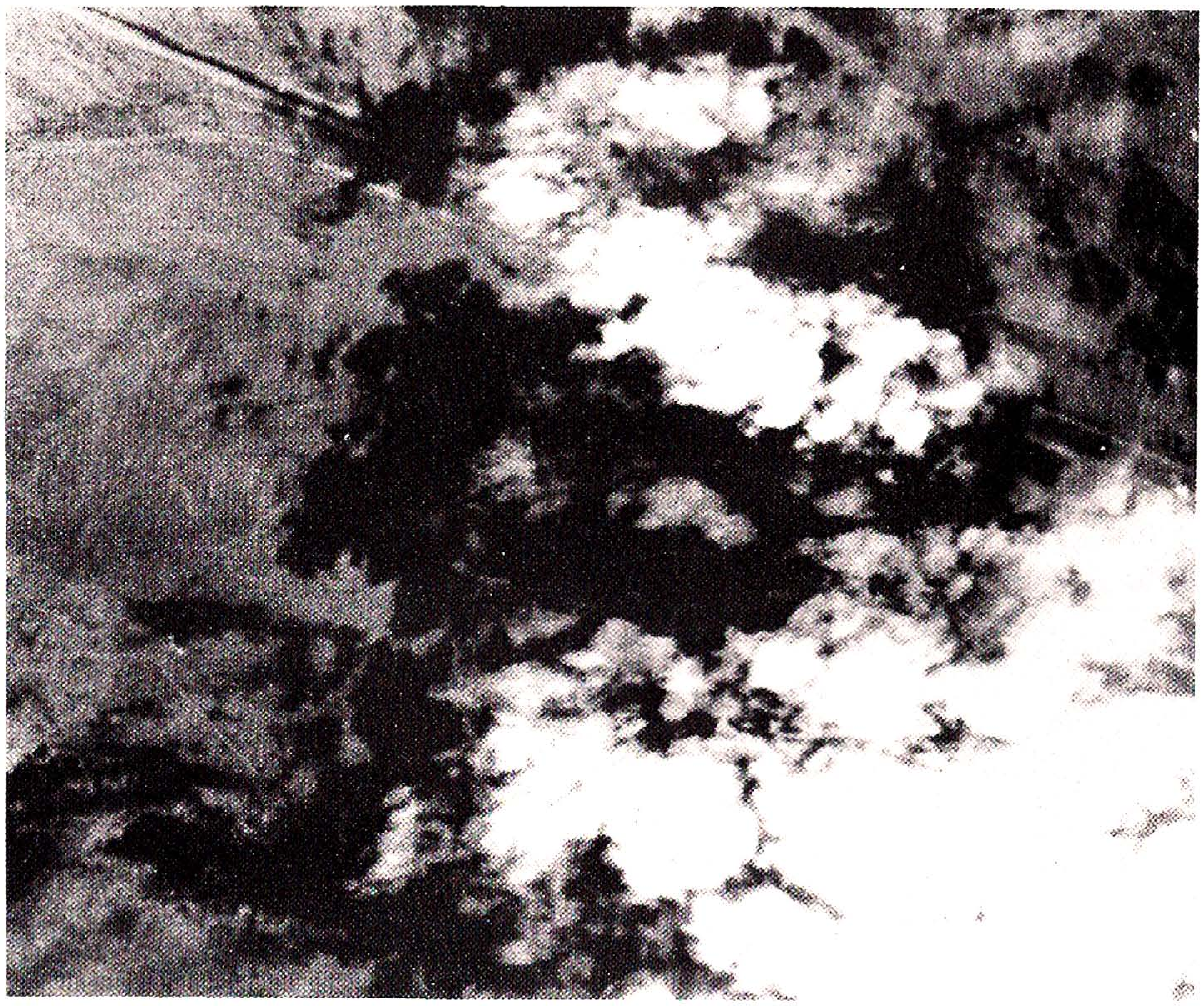

Fig. 10. A single band AVIRIS image (0.704 μm) of Roger's Dry Lake, California. The data were collected on a partly cloudy day on September 1, 1988. Some dark areas are low reflectance clouds as opposed to cloud shadows or low reflectance surface regions (Gao and Goetz 1990b)

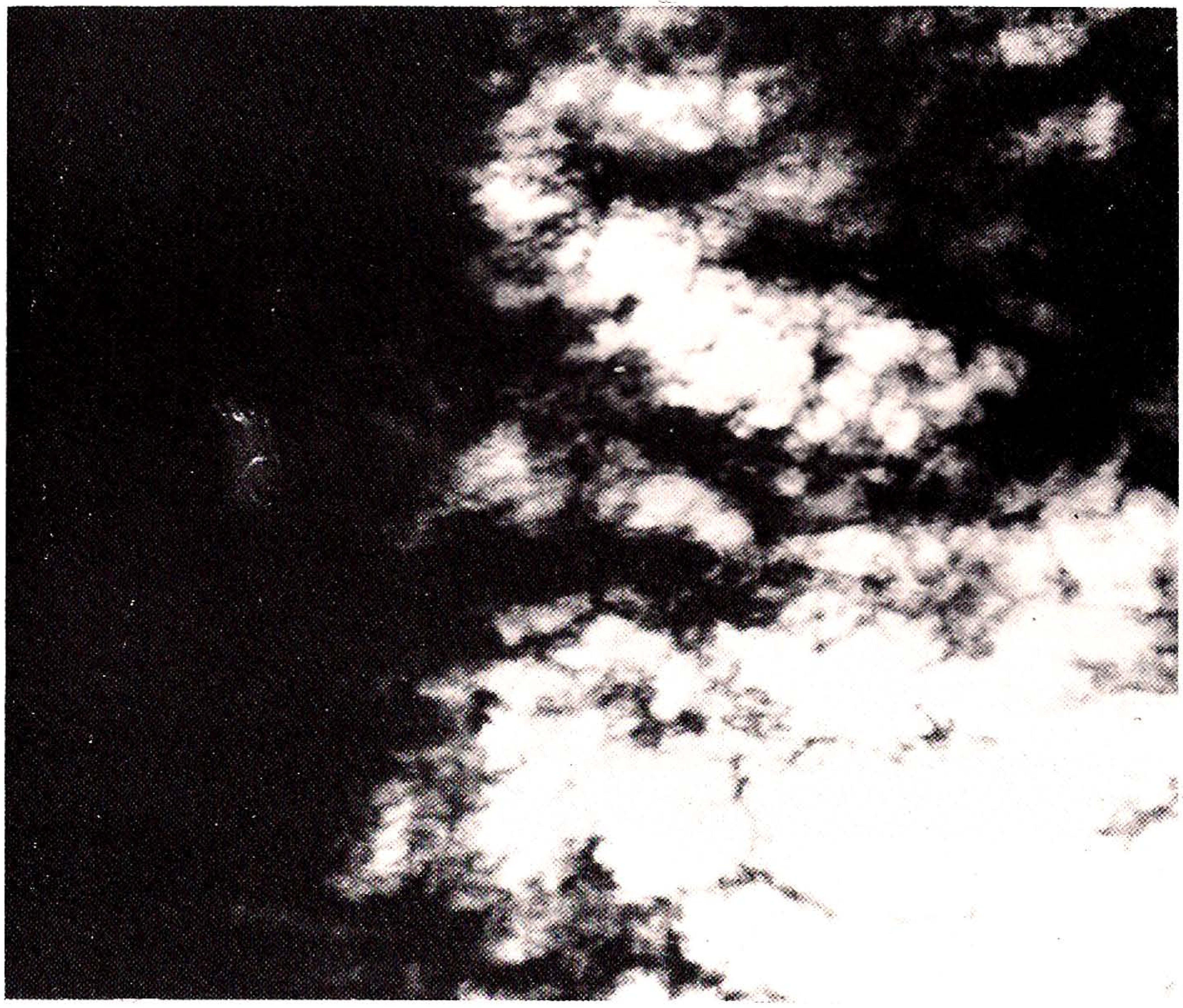

Fig. 11. Band ratio image consisting of the sum of AVIRIS bands at 0.94 and 1.14 μm divided by twice the AVIRIS image at 1.04 μm. Light areas are clouds, dark areas, the surface (Gao and Goetz, 1990b).

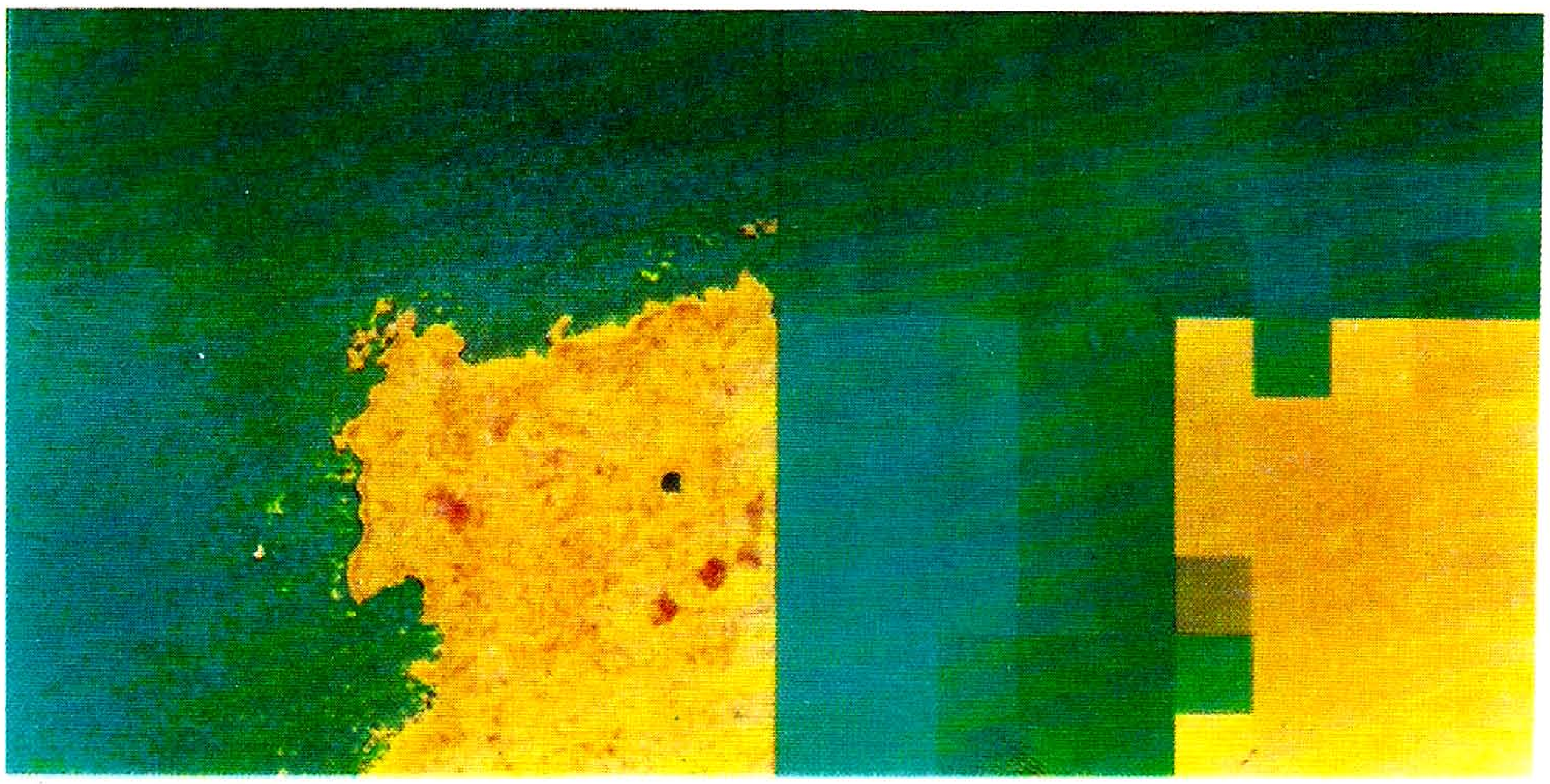

Fig. 12. On the left, an AVIRIS image of Monterey Peninsula, California, processed according to the CZCS algorithm for chlorophyll content. The blue areas have chlorophyll contents of approximatelly 1.0 μg/l grading to the yellow areas with a chlorophyll concentration of approximately 10 μg/l in the water. The righthand image shows a simulated MODIS-T image created from the image on the left (Pilorz and Davis 1990).
Image courtesy of C. Davis, Jet Propulsion Laboratory.

60-200 m. The two-dimensional patchiness in ocean chlorophyll content can be observed with AVIRIS data as shown in Fig. 12 (Pilorz and Davis 1990). Fig. 12 also shows a simulated MODIS-T image of the same region to emphasize the need for high resolution imaging particularly if the processes being studied are non-linear. High spatial resolution is needed to develop mixing models for the low resolution global monitoring sensors.

7. VEGETATION

Only recently has it been shown that high spectral resolution for remote sensing can provide quantitative information from leaf canopies. This field is still very young and growing. Two conditions must be met if imaging spectrometry is to be useful in the analysis of terrestrial ecosystems. First there must be strong relationships between canopy characteristics and the rates at which processes important to the biosphere occur. Second, it must be possible to measure these canopy characteristics remotely using high spectral resolution data.

Because of the inherent complexity of biological systems, the field biological sciences have lagged behind many of the physical sciences in identifying the key processes and attributes that control the systems under study. Only in the last several years has information begun to appear at the ecosystem level. That suggests that broad generalizations of the type required for biospheric studies may be derivable. These cover the major processes of photosynthesis, primary production, herbivore consumption, and decomposition as well as the general detection of stress.

Plant communities alter their allocation of carbon, and thus the nutrients available for herbivory consumption, between primary products such as cellulose and secondary, woody and defense related compounds, depending on the relative availability of carbon (through photosynthesis) and nutrients. Of particular importance in temperate systems is lignin, a complex amorphous polyphenol that is very resistant to insect attack. Recent studies (Waring and Pitman 1985; Larsson *et al.* 1983) have shown that reduced tree vigor increases the susceptibility to insect attack, and thus can be reversed by thinning or fertilization. The lignin content of foliage may be a sensitive indicator of the carbon status of the community and of the potential for insect outbreak.

The spectral reflectance of fresh vegetation was characterized over 30 years ago by Gates *et al.* (1965) and Gausman *et al.* (1969). They established the importance of leaf pigments, leaf water and internal scattering on the reflectance and transmittance properties of leaves. The pigments, in particular chlorophyll a and chlorophyll b, are primarily responsible for the reflectance characteristics in the visible region 0.4-0.7 µm. Plants appear green because of the pigment absorption in the blue and red portion of the spectrum. Beyond 1.2 µm, leaf reflectance is dominated by the absorption properties of water.

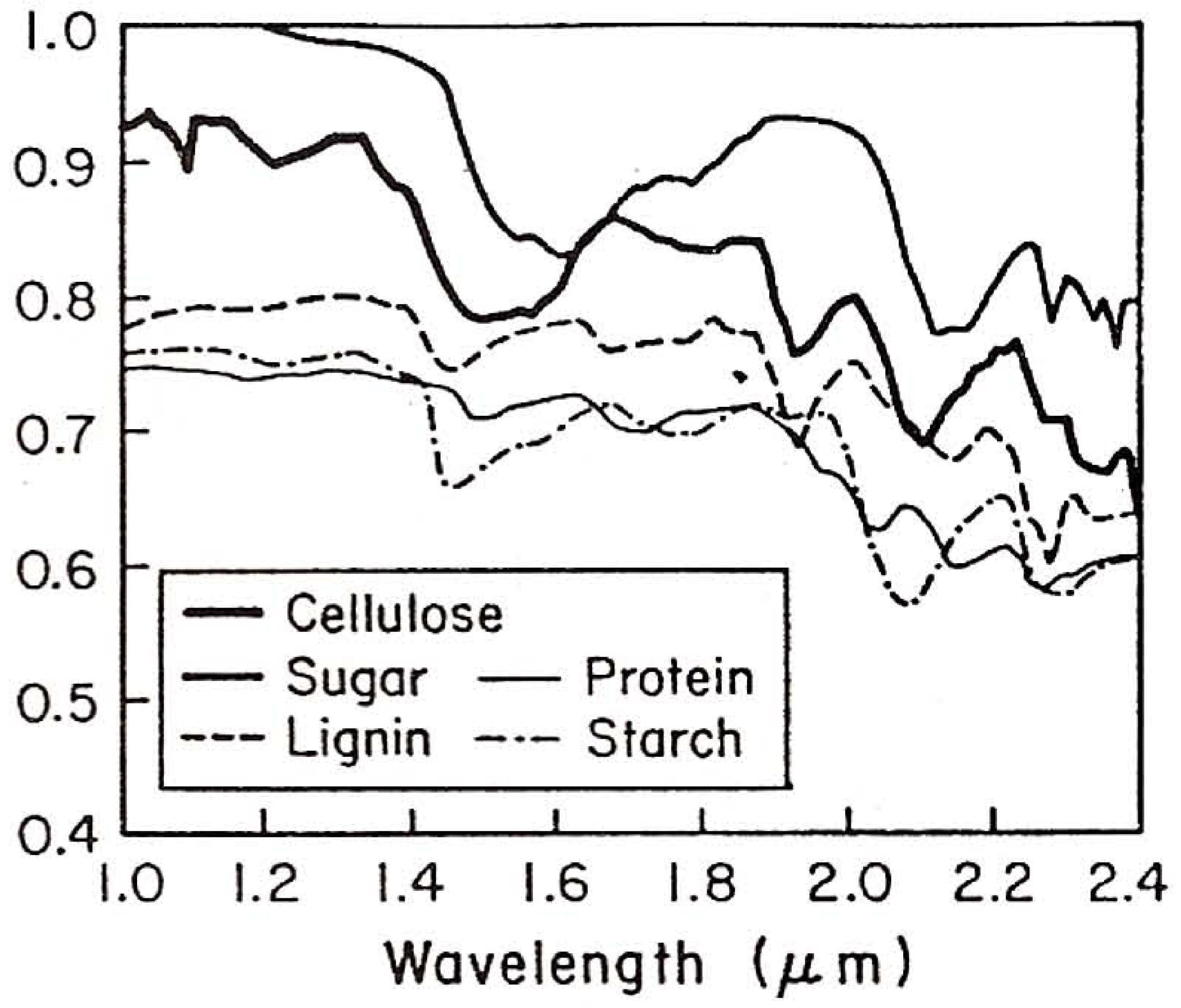

Fig. 13. Spectral reflectance of individual leaf biochemical components.

Liquid water has four overtone combination bands at 0.97, 1.19, 1.45 and 1.94 µm (Curcio and Petty 1951). Water also affects the spectral reflectance between the absorption bands. Organic compounds that make up the leaf, such as protein, lignin, starch, sugar, also contribute to the reflectance characteristics, albeit in subtle ways that are not apparent unless the contribution of liquid water is removed from the spectrum. Organic compounds absorb in the middle infrared and ultraviolet regions at fundamental stretching and bending vibrations of small strong molecular bands between hydrogen and carbon, oxygen, and nitrogen. The absorption bands observed in the short wavelength infrared are associated with overtones of the fundamental stretching (C-H, N-H, and O-H bonds) (Hergert 1971; Hirschfeld 1985). Carbon compounds of importance include lignin cellulose and carbohydrates. The reflectance spectra of individual leaf components is shown in Fig. 13. In the past, only spectra of dry leaves could be used to derive the relative concentration of components (Peterson *et al.* 1988). Unfortunately, in most remote sensing applications, the interest is in determining leaf biochemistry leaves in canopies.

Recent work (Goetz *et al.* 1990) has shown that it is possible to extract the dry leaf spectrum from fresh green leaves by modeling the liquid water contribution and removing it. Fig. 14 shows laboratory spectra of oak leaves, both fresh and dried, along with the spectrum for liquid water. By using a non- linear least-squares fitting technique between the water spectrum and the fresh leaf spectrum, Gao and Goetz (1990) created a residual spectrum outside the major water features shown in Fig. 15. The residual spectra match the dry oak leaf spectrum shown in Fig. 14

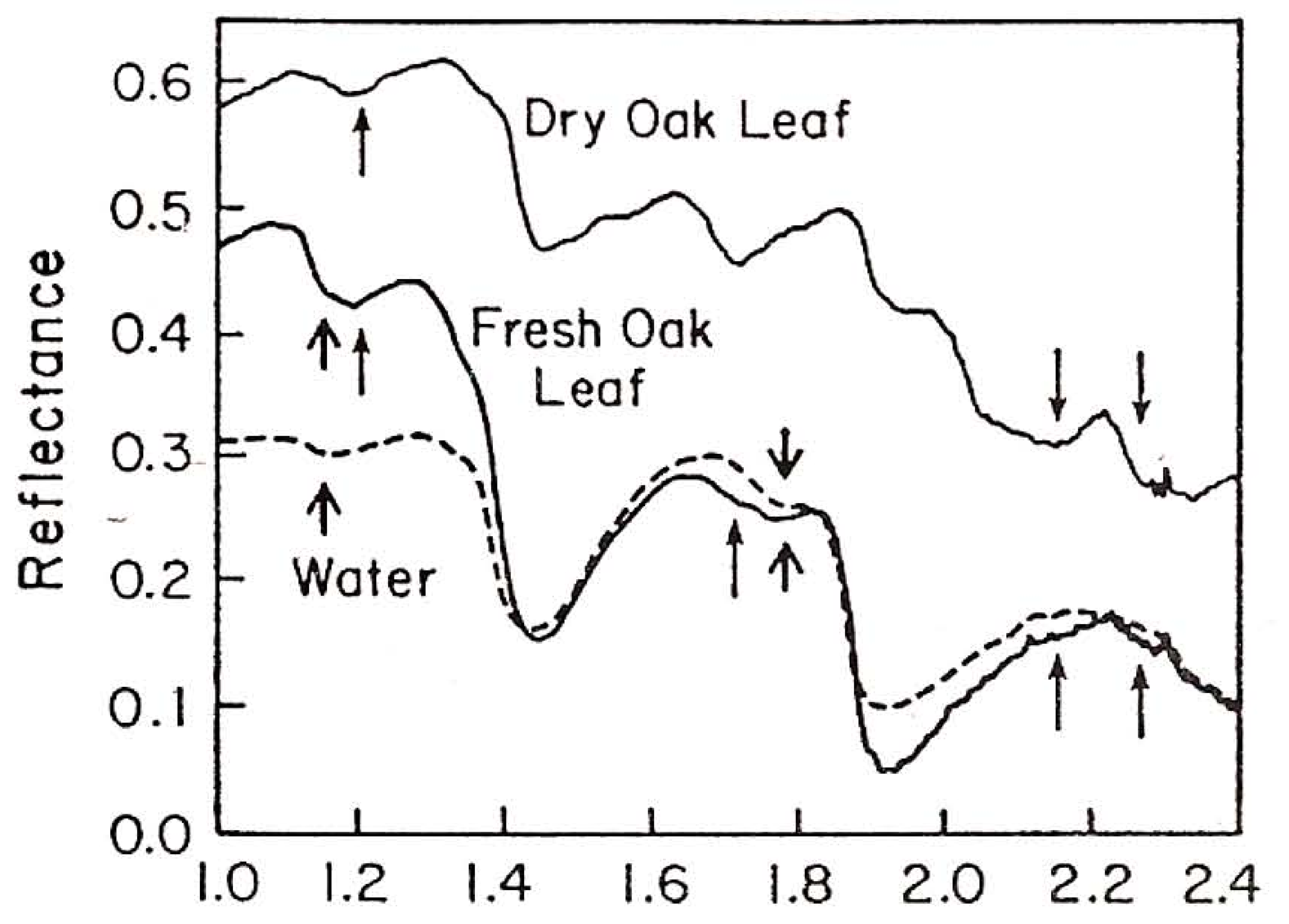

Fig. 14. Reflectance spectra of an oak leaf, both dry and green and the spectral reflectance of a water and glass bead combination that most closely matches the green leaf spectrum (Goetz et al. 1990).

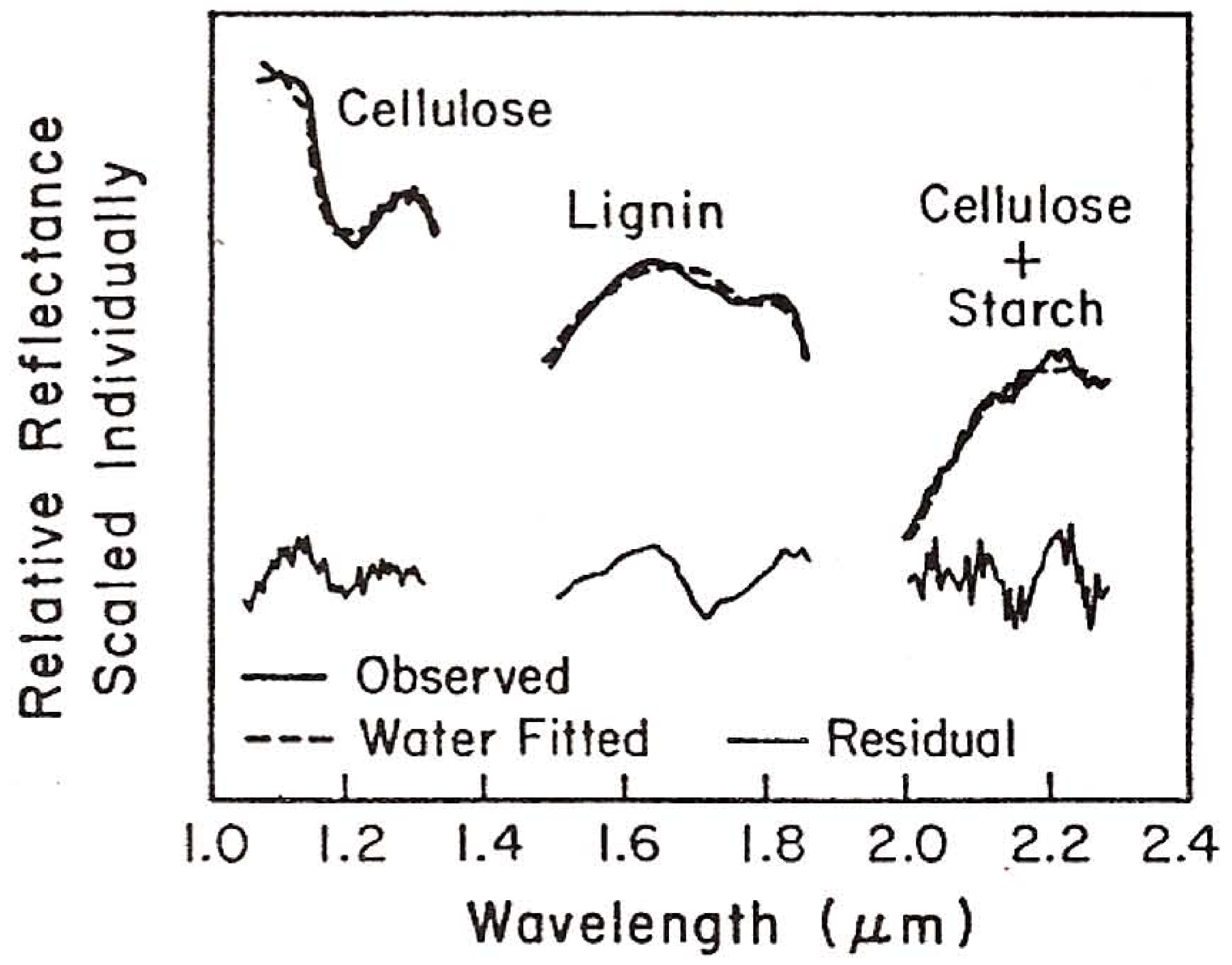

Fig. 15. Green oak leaf spectrum matched to the water spectrum and differenced to provide the residuals. The residuals should be compared with the dry leaf spectrum in Fig. 14 (Goetz *et al.* 1990).

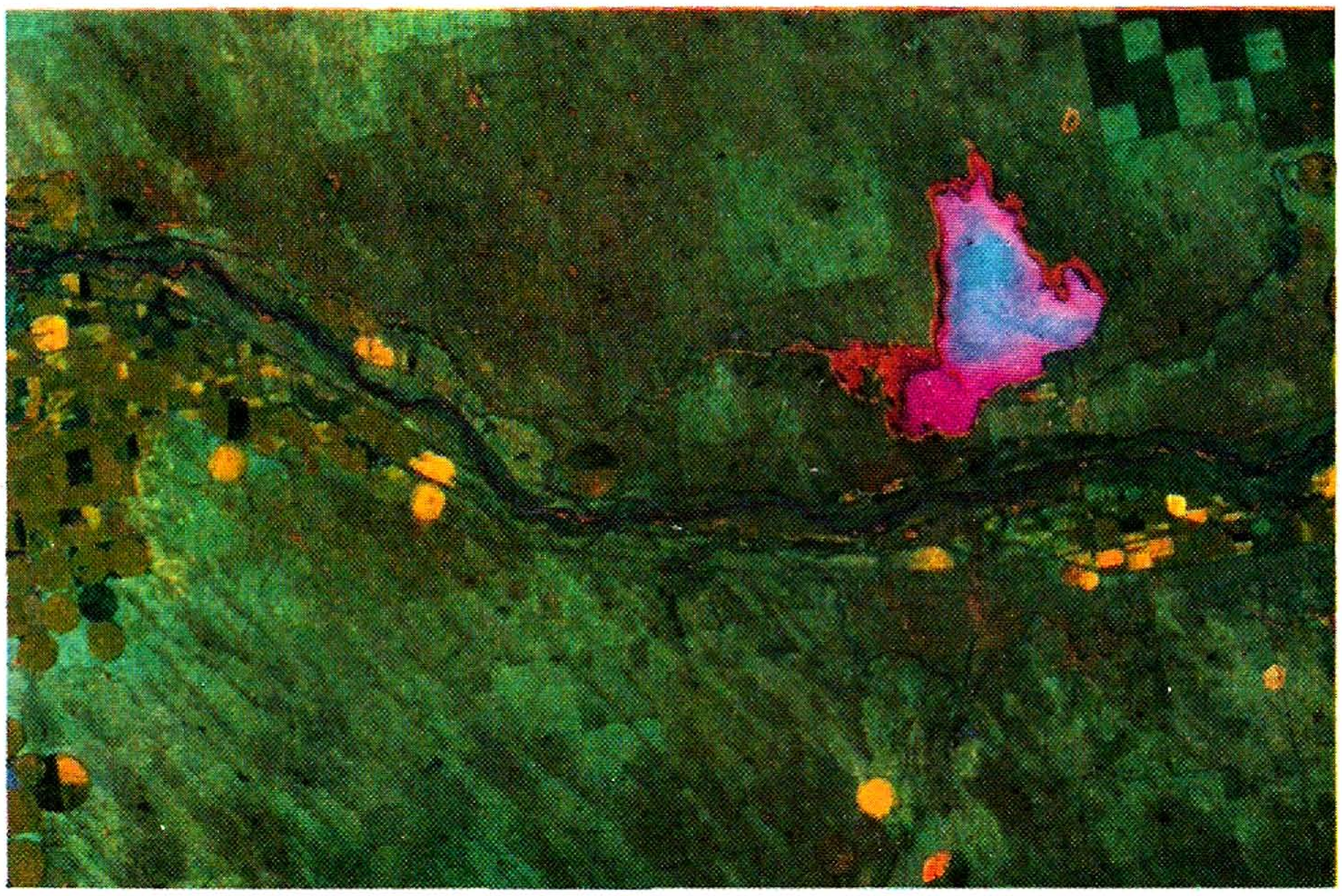

Fig. 16. Principal components 5, 3, 2 displayed as a red-green-blue respectively of a Thematic Mapper image of a region near Greely, Colorado. In the lower half of the image are elongated parabolic dunes, anchored by vegetation, that were active as recently as 3,000 years ago during a period of average global temperatures of 1°C higher than today (Forman *et al.* 1990).

quite well. These matches give confidence that it will be possible to carry out quantitative spectroscopy using the residual spectra.

8. GEOLOGY

Imaging spectrometry owes its development to the early interest in direct mineral identification through reflectance spectrometry (Goetz *et al.* 1985). Recent work has shown that the early predictions were borne out (Zamudio and Atkinson 1990; Kingston 1990; Taranik *et al.* 1990; and Rubin and Lyon 1990). Direct identification of surface mineralogy using imaging spectrometry is now a reality.

A new challenge for imaging spectrometry is to monitor surface changes that bear important relationships to questions of global change. A current study in the High Plains of the U.S. has shown that during the Holocene there were several periods of atmospheric warming which was manifested in the reactivation of stabilized dune surfaces over hundreds of thousands of square kilometers in a region extending from Canada to Texas and Colorado to Central Nebraska and Kansas (Forman and Maat 1990; Forman *et al.* 1990). The dune features are shown on thematic mapper images (Fig. 16) and multitemporal and multispectral studies have shown that these dunes are stabilized by vegetation and the identification of the dunes depends not on the topography but rather on the vegetation density. HIRIS will be used to identify accurate spatial cover of vegetation in order to predict reactivation. Similar studies will be conducted elsewhere on the Earth in climate sensitive regions such as central China. The potential disruption of human activity associated with the reactivation of the dunes in these climate sensitive regions is enormous.

9. SUMMARY

Imaging spectrometry has now reached the stage of being a quantitative tool with applications in all the major disciplines of earth science. Both research and commercial systems are available to create data from airborne platforms and, within this decade, HIRIS will provide high spatial and spectral resolution data from orbit. This quantum leap advance in remote sensing will make it possible to study physical and biological processes on a global scale that can support the development predictive models for global, human induced environmental change.

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