SENSING, SPECTRA AND SCALING: WHAT'S IN STORE FOR LAND OBSERVATIONS?

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ABSTRACT

Bill Pecora's 1960's vision of the future, using spacecraft-based sensors for mapping the environment and exploring for resources, is being implemented today. New technology has produced better sensors in space such as the Landsat Thematic Mapper and SPOT, and creative researchers are continuing to find new applications. However, with existing sensors, and those intended for launch in this century, the full potential for extracting information from the land surface is far from being exploited.

The most recent technology development is imaging spectrometry, the acquisition of images in hundreds of contiguous spectral bands, such that for any pixel a complete reflectance spectrum can be acquired. Experience with AVIRIS has shown that, with proper attention paid to absolute calibration, it is possible to acquire apparent surface reflectance to 5% accuracy without any ground-based measurement. The data reduction incorporates an educated guess of the aerosol scattering, development of a precipitable water vapor map from the data and mapping of cirrus clouds in the 1.38 µm band. This is not possible with TM.

The pixel size in images of the earth plays and important role in the type and quality of information that can be derived. Less understood is the coupling between spatial and spectral resolution in a sensor. Recent work has shown that in processing the data to derive the relative abundance of materials in a pixel, also known as unmixing, the pixel size is an important parameter. A variance in the relative abundance of materials among the pixels is necessary to be able to derive the endmembers or pure material constituent spectra. In most cases, the 1 km pixel size for the Earth Observing System MODIS instrument is too large to meet the variance criterion. A pointable high spatial and spectral resolution imaging spectrometer in orbit will be necessary to make the major next step in our understanding of the solid earth surface and its changing face.

INTRODUCTION

The introduction of spaceborne remote sensing techniques to the geological sciences owes more to the vision of William T. Pecora than any other individual. Bill Pecora, in his position as Chief Geologist, then Director of the U.S. Geological Survey and later as Undersecretary of the Department of Interior, promoted research in photogeology and remote sensing that led to the establishment of the Earth Resources Observation Systems Program (EROS) in 1966 and the development of the specifications for the first Earth Resources Technology Satellite (ERTS-1), later called Landsat-1. It is ironic that ERTS-1 was launched on July 23, 1972 just three days after Bill Pecora's death.

Twenty-six years ago in an address to the 27th Annual Meeting of the American Congress on Surveying and Mapping, Pecora commented: "Even as the skeptics of a few years back scoffed at the idea of airplanes and aerial photography for the uses which are common today, so some modern skeptics have their doubts about the potential of acquiring useful earth data from space. Nevertheless, there is not only potential, but the time is near when it will be possible and feasible" (Pecora, 1967). As we move to apply modern technology to the next major steps in acquiring truly quantitative information about the earth's surface, we still face those modern skeptics of 26 years ago that have their doubts about the potential of remote sensing. In this case we are dealing with skeptics of imaging spectrometry, a technique that promises to make it possible to acquire quantitative information from remote observations of the earth. In the rest of this paper, I will argue that we need a modern version of Bill Pecora's vision to promote research using this technique and to convince NASA and other agencies that the technology is available and the time is right to fly imaging spectrometers in space that will acquire all the information theoretically available in the solar signal reflected from the earth's surface.

IMAGING SPECTROMETRY

At the beginning of the last decade, eight years after the launch of ERTS-1, it was already understood that significantly more information was available in high resolution spectra of the Earth's surface, particularly for minerals, than would be available in data from the Landsat thematic mapper (Goetz and Rowan, 1981). Diagnostic overtone and combination-overtone vibrational features in the spectra of minerals in the 1-2.5 µm wavelength region require instruments with a resolution (full-width-half-maximum) of 20 nm, dictating a wavelength sampling of at least 10 nm. Landsat thematic mapper has bands of 60-260 nm width that are not contiguous. A spectrum acquired by TM in the solar reflected portion of the spectrum contains six points between which only straight lines can be drawn.

The emerging technology of the eighties in the areas of optics, detectors, electronics and computing made possible the development of imaging spectrometer sensors. Imaging spectrometry is defined as the collection of spatially registered images in many narrow, contiguous spectral bands throughout the solar reflected portions of the spectrum. Although the spectral range is not a limitation to the definition, in practice there is not enough energy outside the 0.4-2.5 µm region to warrant the construction of narrow band imaging spectrometer systems. The imaging spectrometer concept is outlined in Figure 1.

Mapping surface mineralogy was the primary goal in early studies using imaging spectrometry. Figure 2 shows laboratory spectra of a number of OH and CO_3 bearing minerals that are amenable to direct identification with imaging spectrometers.

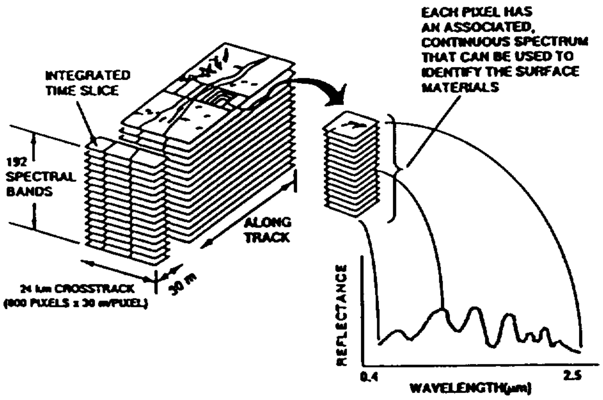

Figure 1. Imaging spectrometry concept (Goetz and Davis, 1991).

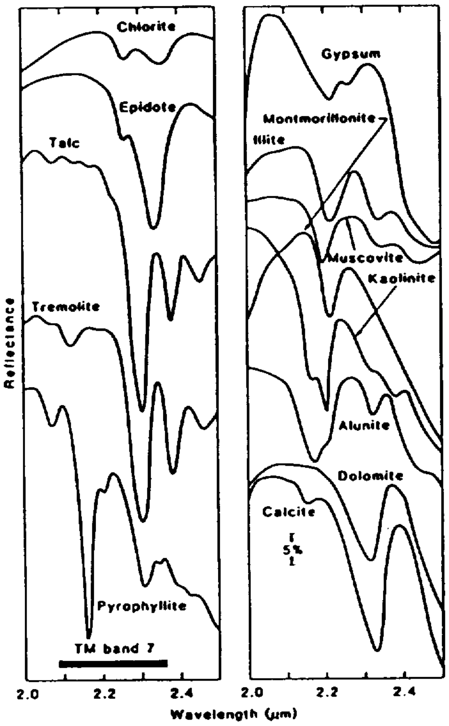

Figure 2. Selected laboratory spectra of minerals containing overtone vibrational absorption features for Al-OH (2.6-2.22 µm), Mg-OH (2.3-2.35 µm) and CO_3 (2.3-2.35 µm). The TM band 7 bandwidth of the Landsat thematic mapper is also shown (Goetz et al., 1985).

In 1983 the first data acquired by the airborne imaging spectrometer (AIS) showed that direct identification of surface mineralogy could be made from an airborne platform with a minimum of data processing, since the diagnostic features showed high contrast and were unique (Goetz et al., 1985). The success of AIS led to the development of an imaging spectrometry program at the NASA Jet Propulsion Laboratory that was to culminate in a spaceborne sensor called the High Resolution Imaging Spectrometer (HIRIS) (Goetz and Davis, 1991). Although HIRIS is no longer part of the NASA Earth Observing System program, the precursor airborne system AVIRIS (Airborne Visible/Infrared Imaging Spectrometer), flown in the ER2 at 20 km altitude (Vane et al., 1993), has provided the basis for new scientific applications in a variety of disciplines (Vane and Goetz, 1993).

The AVIRIS performance characteristics are shown in Table 1.

Table 1. AVIRIS Performance Characteristics (after Vane et al., 1993)

Spectral	
Wavelength Range	400-2500 nm, 4 spectrometers
Average Sampling Interval	10 nm
Spectrometer FWHM	10 nm
Radiometric	
Radiance Range	0 to max. Lambertian
Digitization	10 bits
Accuracy	2-3%
Geometric	
Platform	ER-2
Altitude (above sea level)	20 km
Field of view (FOV)	33°
Image width (614 pixels)	10.5 km
Image length (max)	1000 km
Instantaneous FOV (IFOV)	1 mrad
Ground IFOV	20 m

The applications of imaging spectrometry data just recently beginning to appear in the reviewed literature include high spatial resolution atmospheric water vapor measurements (Gao et al., 1992) and cirrus clouds (Gao et al., 1993) snow and ice studies (Nolin and Dozier, 1993) vegetation studies including canopy biochemistry (Gamon et al., 1993, Roberts et al., 1993, Elvidge et al., 1993, Goetz et al., 1992) surface water studies and particular lakes and coastal ocean environments can now be studied in more detail regarding the suspended material (Carder et al., 1993, Hamilton et al., 1993). Not to be overlooked are geological applications to mineral mapping (Mustard, 1993, Kruse et al., 1993, Crowley, 1993). In each of the applications new, more useful, and in many cases quantitative data are being derived concerning the Earth and atmosphere composition because new data analysis techniques have been developed to take advantage of the narrow, contiguous, spectral bands acquired by AVIRIS.

IMAGING SPECTROMETER VERSUS MULTISPECTRAL DATA

The advent of calibrated imaging spectrometer data spurred a renewed interest in making quantitative corrections for the influence of the atmosphere on the data without making simultaneous ground measurements. The principal absorber in the atmosphere is water vapor that is not a well mixed gas and therefore the total column abundance can vary dramatically across a scene. This is particularly true if significant elevation differences fall within a scene. Water vapor affects more than sixty percent of the solar-reflected portion of the spectrum as shown in Figure 3.

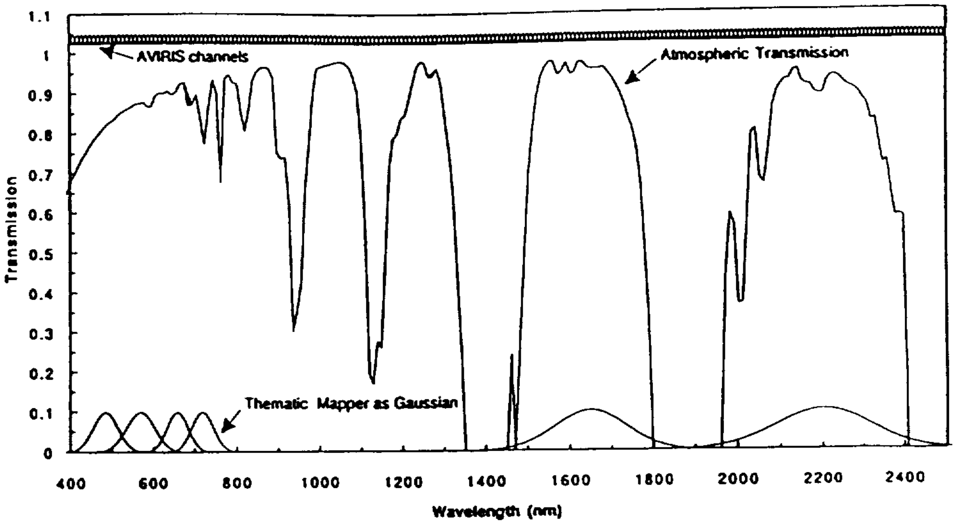

Figure 3. Atmospheric transmission for 2.7 cm column precipitable water vapor along with the band passes for AVIRIS and Landsat thematic mapper.

Because contiguous spectral bands are acquired by AVIRIS, it is possible to derive the total column perceptible water from the shapes of the absorption features at 940 and 1140 nm. Unlike the bands at 1400 and 1900 nm, the two shorter wavelength bands do not saturate under normal conditions. Techniques for determining column perceptible water have been developed by Gao and Goetz (1990, Gao et al., 1993, Carrère and Conel, 1993) the precision of the technique is 3-5% under clear conditions over land. The removal of the featured water vapor features is essential to increasing the useful portion of the spectrum for analysis of surface materials. In particular, water vapor removal allows analysis to be carried out up to the edges of the major 1400 and 1900 nm water vapor features.

The search for good approximations of the effect of atmospheric scattering and transmission on apparent surface reflectance from Landsat has occupied workers in the field since the launch of ERTS-1 (Moran et al., 1992, Richter, 1990, Kaufman and Sendra, 1988, Slater et al., 1987, Ahern et al., 1977, Otterman and Fraser, 1976, Vincent, 1972). The techniques range from those as simple as dark object subtraction, requiring no external data input, to radiative transfer models requiring optical thickness values from educated guesses or ground measurements. Markham and Barker (1985) mentioned the sensitivity of TM 5 (1.55-1.75 μm) to water vapor in the atmosphere.

None of the investigations have attempted to quantify the effects of column water vapor content on the retrieval of apparent surface reflectance, nor the effects of changes in atmospheric parameters within a scene. Neither effect can be estimated from Landsat TM data themselves and, therefore, it has been necessary to assume that a surface measurement at one point can be used to calibrate the entire scene. The effects of water vapor differences across the Landsat scene have been modeled by Goetz (1993) showing that TM bands four, five and seven are the most directly affected by water vapor as shown in Figure 4.

The effect of water vapor is to reduce the area under the band pass curve assuming uniform surface spectral reflectance and uniform exo-atmospheric solar radiance, the change in area will cause an equivalent change in derived apparent surface reflectance. The reduction in curve area as shown in Figure 4 also causes a spectral shift in the band pass center which is significant only for band five as shown in Figure 5.

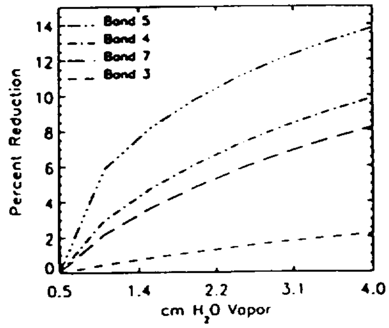

Figure 4. Changes in relative transmission of Landsat TM bands for atmospheric water vapor ranging from 0.5 cm to 4.0 cm column precipitable water (Goetz, 1993).

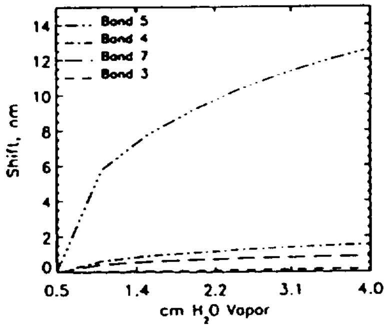

Figure 5. Shift in the effective center of the TM band pass caused by changes in atmospheric water vapor (Goetz, 1993).

When individual bands are affected by water vapor, so are indices derived from them. NDVI is made up of TM bands 3 and 4, and the index is particularly affected at low NDVI values as shown in Figure 6.

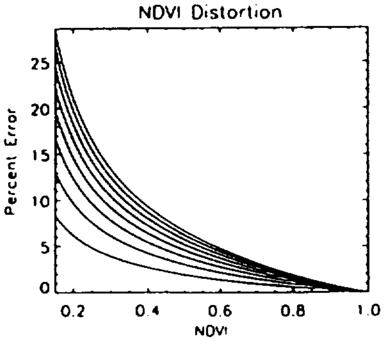

Figure 6. Effects of varying amounts of precipitable water vapor, ranging from 0.5-4.0 cm on NDVI (Goetz, 1993).

Another major source of error in Landsat TM images are unseen cirrus clouds. Cirrus can change the apparent surface radiance in TM bands by as much 20% without being detectable in an image that has significant reflectance variation such as an urban scene. By judicious selection of the proper AVIRIS band, cirrus clouds can be identified and separated uniquely from other ground return (Gao et al., 1993, Goetz, 1993). In the deep 1400 and 1900 nm water absorption features, photons from the sun are completely absorbed below 6 km altitude in the atmosphere. Cirrus form at the 6 km level and since there is very little water vapor above the clouds, excellent images of cirrus clouds alone can be made at 1.38 and 1.88 µm. Figure 7 shows images taken over water inside and outside the 1.4 µm water absorption band.

QUANTITATIVE ANALYSIS TECHNIQUES

Imaging spectrometry holds major promise to make the art of remote sensing quantitative. Multispectral imaging systems by nature undersample the spectrum and, therefore, not all of the information available in the solar reflected signal can be extracted from the data. Because, as discussed above, it is not possible to make proper allowances for differential atmospheric absorption and scattering across the scene, the quantitative results are not obtainable. Imaging spectrometry offers the possibility of producing quantitative results although there are still limitations. Unmixing techniques (Boardman, 1993) make it possible to identify the spectra of pure materials within the scene and determine there relative abundance for each picture element. Other techniques such as spectrum matching (Gao and Goetz, 1993) can be used to identify spectral features of minor components that are otherwise masked by major components such as water in land canopies.

Vegetation Biochemistry

Changes in ecosystem processes such as productivity and decomposition may be expressed in the canopy foliar chemistry resulting from altered carbon allocations, metabolic processes and nutrient availability (Melillo et al., 1982) understanding carbon balance on land over large regions requires quantitative determination of leaf constituents such as lignin and total nitrogen from imaging spectrometry. The quantity and organic chemical composition of litter produced by the canopy are important controlling factors in the processes of decomposition, mineralization and nitrification (Pastor and Post, 1986) significant in foliar nitrogen/lignin ratios may indicate corresponding changes in the composition rates affecting nutrient and trace gas fluxes (Goodroad and Kenney, 1984). Canopy lignin concentrations were successfully estimated using data from the airborne imaging spectrometer (AIS) and were subsequently used to derived images of annual nitrogen mineralization rates in a Wisconsin forest ecosystem (Wessman et al., 1988, Wessman et al., 1989)

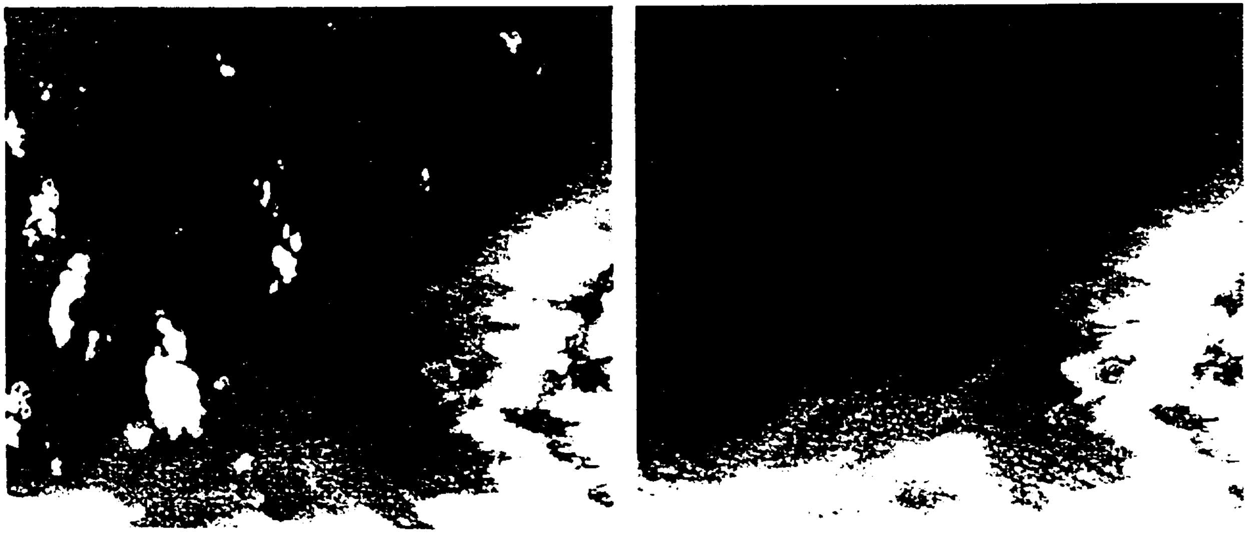

Figure 7. AVIRIS images taken in the window region and in the water absorption feature at 1.28 µm (left) and 1.38 µm (right) over the Gulf of Mexico. Both the upper level cirrus and the lower level cumulus clouds can be seen in the window region while only the upper level, extensive cirrus clouds are seen at 1.38 µm. (After Gao et al., 1993)

Liquid water is the major component of fresh green leaves. It can account for approximately 40-90% of the fresh weight of green leaves. Other biochemical components such as lignin, starch, cellulose and sugars make up the rest. Leaf water is highly absorbing in the region beyond 1.0 mm and strongly affects the reflectance spectrum of green leaf material. It was commonly believed that the absorption spectrum of a leaf could be accounted for completely by water alone (Knipling, 1970; Parish, 1985) new evidence suggests that biochemical constituents do influence the shape of the reflectance curve and can be accessed when the effective leaf water on the spectrum is removed (Goetz et al., 1990, Goetz et al., 1992, Gao and Goetz, 1993)

By simulating the effects of liquid water within the leaf through spectra of glass beads in water, as shown in Figure 8, it is possible to subtract out the water spectrum and the residual spectrum very closely resembles that of the spectrum of a dried leaf and shown in Figure 9.

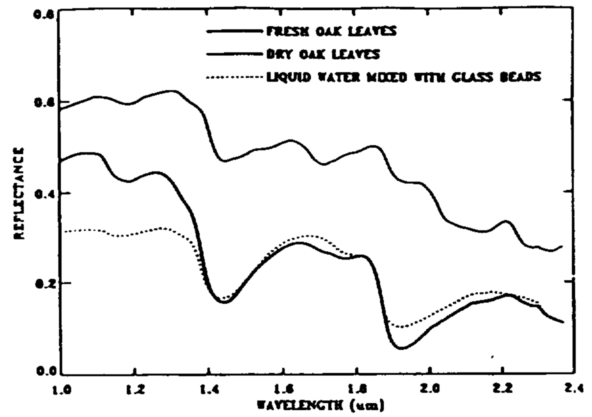

Figure 8. Laboratory reflectance spectrum of fresh oak leaves, dry oak leaves and water mixed with glass beads. (from Goetz et al., 1992)

Unmixing

The large number of contiguous spectral bands in imaging spectrometers makes it possible to identify as many materials as there are spectral bands. Experience shows that, within an AVIRIS scene there can be as few as three and as many as fifteen different identifiable materials (Boardman, 1993). By using concepts of convex geometry, it is possible to surround an n-dimensional set of data points in such a way that the vertices of the simplex become the pure "endmember spectra" even though no pixel within the image was pure. The lines connecting the vertices are mixing lines between two of the endmembers. Therefore, for each pixel it is possible to determine the relative abundance of each the endmember materials within the pixel. All abundances must sum to one. Figure 10 demonstrates the technique.

New developments in unmixing techniques will undoubtedly lead to more quantitative exploitation of imaging spectrometer data.

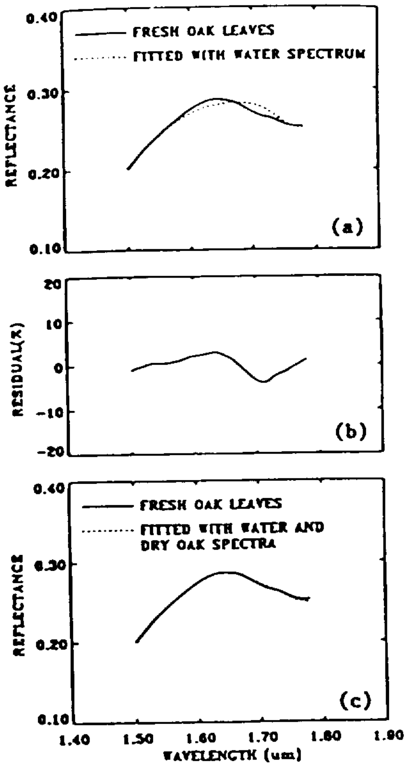

Figure 9. Match of the fresh oak leaf spectrum in the 1.5-1.78 µm region with the water spectrum in Figure 8 (b) Residual spectrum between the two spectra in (a). (c) Match of the first oak leaf spectrum with a combination of the water and dry oak leaf spectra in Figure 8. (from Goetz et al., 1992).

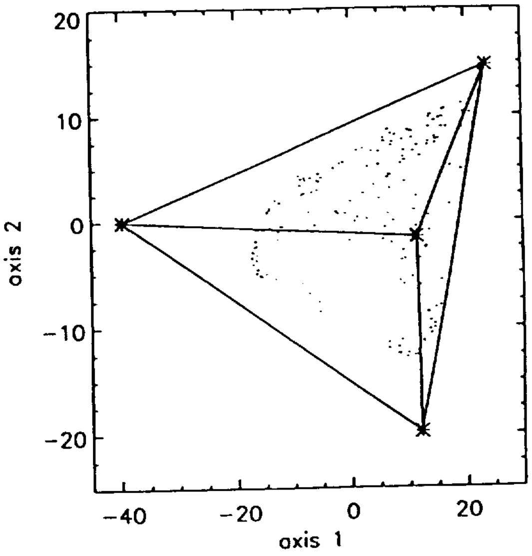

Figure 10a. Best fitting simplex surrounds the vertices of the convex hull of the data. Third axis is perpendicular to the paper.

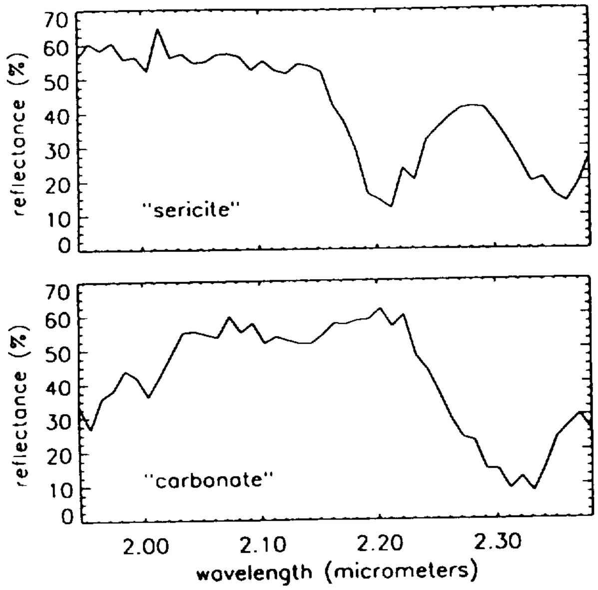

Figure 10b. Two of the derived end members identified as sericite and carbonate. Carbonate is the middle vertex in 10a, sericite is the bottom vertex, shade is to the left (Boardman, 1993)

SCALING

The question of scaling, or bluntly put, spatial resolution lies at the core of the debate about the requirements for remote global observations (NASA, 1986) each natural process manifests itself at a particular spatial scale. If the resolution of the observation, either spatially or temporally, is not sufficient to detect the effects of the process, then only the aggregate result of a number of processes will be measured. If the processes are nonlinear such as the radiance produced by surfaces at different temperatures, the aggregate measurement could be misinterpreted. Nonlinear processes might include gas exchange, nutrient cycling or other biological processes. The spatial resolution must be matched to the processes being studied. The 20 m pixel size of AVIRIS has been found barely sufficient in a grass land study at Jasper Ridge, California (Gamon et al., 1993). Pixel sizes of 50-100 m were sufficient to measure biological productivity in the Konza Prairie FIFE experiment (Davis et al., 1992) because the geomorphological scale or the periodicity of the swales was on the order of 200-300 m. Phytoplankton blooms in the coastal zone are by nature patchy. Many types of fish larvae and zooplankton cannot survive on the average phytoplankton concentration in the ocean and depend on these patches for survival. The patchiness has scales of several hundred meters as predicted by theory (Platt, 1972) and measured in one dimension by Fasham and Pugh (1976). Instruments designed for global measurements such as MODIS and SeaWiFs have imaging systems with 1 km pixels and are not able to detect the patchiness which results in important processes in the food chain.

Unmixing techniques require a variance in the relative abundances of materials among mixed pixels. This variance establishes the dimensions and directions of the simplex planes that are made to surround the transformed data (Boardman, 1993). It is unreasonable to expect that unmixing techniques can be applied equally well to sensors with 1 km pixels that are many times the natural scale of the landscape.

Imaging spectrometry that provides high dimensionality in the spectral domain can best be exploited if the spatial scale is matched to the scale of the phenomenon or process being observed. Unfortunately, this places a major burden on data acquisition and transmission systems as well as requires significant computing capability to handle the masses of data. Fortunately, technological developments are leading to much greater capabilities in data storage, wider bandwidth, data transmission, and faster computing platforms.

FUTURE DIRECTIONS

Imaging spectrometry is now coming into its own and many papers are becoming to appear in the refereed literature speaking to the applications (Vane and Goetz, 1993). A new airborne instrument is being developed by the Naval Research Laboratory called HYDICE that will be operational in September 1994. (Rickard et al., 1993) The HYDICE design is a derivative of that proposed for HIRIS (Goetz and Davis, 1991) and will have greater spatial resolution and signal-to-noise ratio than AVIRIS as shown in Table 2. Although HIRIS will not fly as part of the Earth Observing System missions, derivatives of the instrument concept using new optical and detector technologies and flown as a single instrument on a small spacecraft in a low earth orbit could implemented as a mission at a small fraction of the cost of the original proposal. Spaceborne systems are the only practical means by which multi-temporal observations of multiple sites can be made. Multi-temporal observations must be made if we are to properly understand the canopy chemistry signatures and their natural variance.

Table 2. HYDICE Expected Performance Characteristics

	Spectral
Wavelength Range	400-2500 nm 1 spectrometer
Average Sampling Interval	10 nm
Spectrometer FWHM	10 nm
	Radiometric
Radiance Range	0 to max. Lambertian
Digitization	12 bits
Accuracy	0.9-2.4%
	Geometric
Platform	C-141
Altitude (above sea level)	6 km
Field of view (FOV)	8°
Image width (310 pixels)	1 km
Image length (max)	TBD
Instantaneous FOV (IFOV)	0.5 mrad
Ground IFOV	3 m

In 1976 Bill Pecora said "today we face perhaps the gravest, certainly the most stimulating challenge in the history of conservation. It is the challenge to build a quality society-one in which we manage not just to preserve the delicate balance between the need of our people and the natural resources of our land, but actually to improve the heritage of our Nation" (Pecora, 1967). That observation is just as relevant now as it was twenty-six years ago, and we have a much more sophisticated and capable technology to help meet that challenge than was available 1967. However, we still need the political will, the resources and vision to move ahead and build our future with the tools we already possess. Right now we could use Bill Pecora's help.

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