URBAN, FOREST, AND AGRICULTURAL AIS DATA: FINE SPECTRAL STRUCTURE

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ABSTRACT

Spectra acquired by the Airborne Imaging Spectrometer (AIS) near Lafayette,IN, Ely,MN, and over the Stanford University campus,CA were analyzed for fine spectral structure using two techniques: the ratio of radiance of a ground target to the radiance of a standard and also the correlation coefficient of radiances at adjacent wavelengths. The results show ramp-like features in the ratios. These features are due to the biochemical composition of the leaf and to the optical-scattering properties of its cuticle. The size and shape of the ramps vary with ground cover.

INTRODUCTION

The Airborne Imaging Spectrometer (AIS), developed at the Jet Propulsion Laboratory (JPL), offers the unique capability to obtain high spatial resolution, high spectral resolution, and high radiometeric resolution data from an aircraft-borne (NASA C-130) sensor. The instrument provides a synoptic image of any specific ground scene at each of 120 infrared wavelengths between 0.9 (or 1.2) and 2.4 μm. During an extensive data acquisition campaign organized by personnel at JPL during the summers of 1983 and 1984, data were obtained by the AIS instrument over three flightlines: one an agricultural and forested region near Lafayette, IN; an area near Ely, MN, representing the boreal forest; and a rural-urban-residential area including the Stanford University campus in California. Results of an analysis of these data are presented here.

While the AIS instrument does not acquire data in the spectral regions between 0.4 to 0.9 μm, future imaging sensors having high spectral resolution will acquire data in these regions. To anticipate promising areas of future research involving these planned sensors, results of an analysis of high spectral resolution data acquired with an Exotech Model 20C field spectroradiometer are also presented. The data include two spectra from each of more than 250 benchmark soils from locations across the United States as well as more than 800 spectra of four wheat canopies measured in various development stages and sun/view directions and at various times during the day. These spectra and supporting documentation are available in a data library at LARS/Purdue University.

BACKGROUND AND JUSTIFICATION

Is there fine structure in infrared spectra of foliage? There is reason to believe that in the infrared wavelength region, plants may absorb in narrow spectral bands defined by the structural properties of the organic molecules near the surface of the foliage -- by the resonant frequencies of the translational and rotational vibration modes of the simple bonds (e.g., C-H, C=C, $C-CH_3$, N-H, $C-NH_2$, etc.) in the larger molecules. For these atoms connected by a covalent bond, the fundamental resonant frequency generally is located at wavelengths longer than 2.5 µm, beyond the wavelength range of the AIS and other passive airborne or spaceborne remote-sensing instruments.

In the 0.7 to 2.4 µm wavelength region (which includes the 1.2 to 2.4 µm range of the AIS), the absorption bands are overtones and harmonics of the fundamental resonant frequencies of these simple structures. The magnitude of the absorption in such a wavelength band usually is not large. And it tends to vary with wavelength, being generally smaller, if the band is located at shorter wavelengths (higher frequency), farther from the fundamental resonant frequency. By the visible wavelengths, this type of light absorption -- involving vibration of organic, covalently bonded atoms -- is nonexistent and light absorption is due to electronic transitions in such organic pigment molecules as chlorophyll.

The observability of the narrow absorption bands may be enhanced if the foliage surfaces are good specular reflectors in the infrared. This is because the magnitude of the specular reflection is determined in part by these absorption properties. And for some plant canopies, the specularly reflected light is a significant part of the total reflected light. For a leaf, the specularly reflected light originates at the interface between air and the cuticle, the multi-layered, wax-covered skin of the leaf. The properties of the cuticle, its topology and chemical composition, are species and possibly variety specific and change with leaf age, plant development stage, plant water status and temperature regime. Because the specularly reflected light never enters the leaf to interact with cell walls or water, its magnitude depends solely on the properties of the cuticle. The magnitude varies with the complex index of refraction of the cuticle and with the optical roughness properties of its surface. Thus, the magnitude would vary in and near a particular narrow absorption band, if these bands exist.

In summary, justifying the search for fine detail in the spectra of vegetation is the potential to discover a new source of information for discriminating species and assessing their condition. The radiometric magnitude and the location in wavelength of absorption in narrow spectral bands, if present in the spectra, may provide such information.

Despite these arguments, narrow absorption bands might not appear in spectra of foliage measured by the AIS instrument. The reasons are identically those explaining, for example, why the sharp absorption

peak at 0.68 μm of chlorophyll measured in vitro does not appear in high resolution spectra of plant canopies. For absorption in the infrared, the many candidate bonds provide a rich plethora of absorbing regions at often adjacent wavelengths. While many molecules throughout the plant will contain any specific bond, for example, C-CH₃, the absorbing wavelength region of each will not be the same, but rather modified depending on the structural characteristics of the parent molecule and adjacent environment. The absorbing region of wavelengths will be broader for the aggregate of molecules than that for any one molecule. And in canopy spectra, the prominence of the absorption region may be reduced if other bonds absorb at adjacent wavelengths.

Additionally, whether or not absorption is evident in narrow wavelength bands in the AIS spectra will depend on the magnitudes of the instrument noise relative to the absorption "signal" in the spectra as well as the natural variability of the spectra of the scene as a function of wavelength. Almost certainly the change in the spectra due to an absorption band will be small (probably less than 5% of value). Substantial evidence has not been reported for the existence of narrow absorption bands in spectra of individual leaves measured with the Beckman DK-2A spectrophotometer with integrating sphere attachment. Compared to the DK-2A, the AIS has better spectral resolution and has the additional advantage of imaging a synoptic view of the scene. Thus, the AIS is an important tool for readdressing the question -- does foliage preferentially absorb in narrow wavelength bands -- at increased spectral and radiometric resolution.

RESULTS

To analyze the AIS data for fine spectral structure, the spectral and image analysis system located at the Jet Propulsion Laboratory, Pasadena, CA, was employed to determine, for test fields containing between 50 and 32,000 pixels, two variables (Figs. 1-3) as a function of wavelength: (a) a ratio -- the uncalibrated radiance (as indicated by the digital number, DN) averaged for a test field divided by the DN of a standard -- a large uniform vegetated area in the flightline, and (b) the correlation coefficient of the DN values of adjacent bands. Analysis of the spectroradiometer data of the 500 soil spectra and more than 1200 vegetation spectra involved calculation of the correlation coefficient of data at adjacent wavelengths. A description of procedures used to acquire these data is available.

Figures 1-2 show that the ratio varies as a function of both cover type and wavelength, showing large variations over small wavelength intervals in the two large water absorption bands at approximately 1.4 and 1.9 μm. On each side of these bands the ratio (Fig. 1) varies with wavelength often as an increasing or decreasing ramp, depending upon the cover type in the test field. Plots of ratios (not shown) representing other areas in both the Lafayette and Ely flightlines display similar ramps. The average DN of a large area of deciduous forest served as the standard, or denominator, of the ratio in

Figure 1. The results (Fig. 2) show that the ratios of several cover types of the urban area do not vary with wavelength. This means that the DN values of the cover types vary in conjunction with the DN values of the standard, a large grass area on the Stanford campus. Unlike the results, Fig. 2, the results, Fig. 3, do show variation with wavelengths; the ratios representing clay tile rooftops on the campus (Fig. 3) have minima between 2.05 and 2.15 μm. In the Stanford data, the DN values of some pixels, generally near the extreme left and right edges of the flightline, are saturated with a DN of 2.55. Care was taken to exclude such pixels from the analysis. The minima (Fig. 3) represent the only evidence of fine structure discovered in the analysis of the Stanford flightline.

The results of the analysis of the vegetation and soils acquired by the Exotech spectra radiometer show that the correlation coefficient of data at adjacent wavelengths varies as a function of wavelength. Large variations in the values of the correlation coefficient occur in the vicinity of the water absorption bands at 0.95, 1.15, and 1.4 μm. For the vegetation, additional anomalies are located at 0.56 - 0.60 μm near the peak of the green region and at 0.70 - 0.75 μm at the red edge. The only anomaly found in the soils data was due to the ferric oxide absorption band near 0.9 μm.

DISCUSSION

The results (Fig. 1) contain ramp features in the data showing that the spectra of other foliage areas in the flightline vary with wavelength differently than does the spectrum of the forest, the standard whose DN value served as the denominator of the ratio. The variation is not random with wavelength but instead appears to represent fundamental characteristics of the foliage areas. Furthermore, the ramps appear due mainly to chemical and physical properties of the light-scattering foliage -- not to geometric factors related to the canopy architecture -- or to sun-view angle effects (these three factors determine the amount of light scattered by a plant canopy).

The ramps show that the biochemical constituents and/or the optical-scattering properties of the foliage surfaces vary with ground cover. The variation is small and represents a secondary factor in understanding the mean reflectance of all the vegetation in the flightline. Yet when the ratio technique is employed to effectively remove the mean from the data, this secondary factor becomes a primary source of variation between ground covers in the flightline.

The argument that canopy geometry is not the primary cause of the ramp feature is simple; if it were, curves of the ratio would never cross and probably they would have a shape different from that of the ramps (Fig. 1). To prove the point, let us initially assume that the canopy geometry is the primary cause of the ramps in the plots of the ratios. Then we will demonstrate a contradiction. So assume that the light-scattering properties of each infinitesimal piece of foliage in the flightline are identical. Assume that the only difference between

ground covers is due to geometric factors related to canopy architecture (e.g., size of leaf, leaves per unit volume, leaf area per unit volume, etc.). Then the bidirectional reflectance factor (BRF) of the plant canopies would depend only on these geometric factors and on the sun-view direction. For the specific sun-view direction of our flightline, only the geometric factors would determine the BRF of the plant canopies. These geometric characteristics would determine the amount of light, singly and multiply scattered, arriving at the sensor. Under these circumstances, the plots of BRF would be nested; no two curves would cross. Furthermore, two ratios would never cross. As the ratios (Fig. 1) do cross, our initial assumption is not valid; the optical-scattering characteristics of the foliage do vary with species as a function of wavelength. As a second reason why the initial assumption is wrong, consider the region, 1.4 - 1.9 µm, between the large water absorption bands. Again, if the light-scattering properties of all foliage were identical and only geometric differences distinguished canopies, then the amplitude variation of a specific ratio as a function of distance from an absorption band should be similar to the variation with distance in wavelength from other bands. Yet Fig. 1 shows this is not the situation. The ratio (Fig. 1) shows an abrupt rise (or fall) to about 1.5 µm followed by our "ramp" -- a slow fall (or rise) to approximately 1.8 µm. There is no abrupt rise (or fall) near 1.8 µm. Since the geometry of a canopy is not a function of wavelength from 1.5 to 1.8 µm and since light absorption by foliage in each band is comparable, we should see this abrupt rise (or fall) with decreasing wavelength near the 1.9 band. We do not. Thus, for both reasons -- the shape of the ratio curves and the fact that they cross-- we conclude that the geometry of the canopies is not the primary factor for understanding why the ramps exist in the results (Fig. 1); instead the secondary biochemical properties and light-scattering surface properties of the foliage are the important factors.

Three biochemical and physical factors appear potentially important to understanding the appearance of the ramp features in the data: (a) specular reflection; (b) absorption/scattering by the constituent carbohydrates, fats, and proteins in the foliage; and (c) absorption/ scattering by the distributed air and water (protoplasm) in and between the cells in the foliage.

Specular reflection requires an optically smooth boundary between two dielectrics--thick compared to the wavelength of incident light. Typically the surface of a leaf is never optically smooth but instead supports structures capable of scattering light according to the size criteria established by Rayleigh and Mie. While the amount of light scattered by the structures on the surface is dependent on wavelength, it is probably of limited importance for remote sensing purposes in the wavelength region 1.2 - 2.4 µm. More important is the optical thickness, the skin depth of the multiple layers containing the epicuticular wax, the cuticle and the cell wall and membrane. All have comparable indices of refraction in the visible wavelength region but not necessarily throughout the infrared. The thickness, more or less three micrometers, is comparable to the wavelength of the incident

light -- more so at 2.4 than 0.9 μm. Because of these structural characteristics, a leaf might be expected to be a better specular reflector in the visible wavelengths than at 2.4 μm. And at some wavelengths, the surface will no longer be a specular reflector. In the transition zone between these extremes (which could include the region 0.9 - 2.4 μm), the amount of specularly reflected light will decrease to insignificance. Thus, one factor to consider in the explanation of the ramp features in the data (Fig. 1) is the spectral location and importance of the specular reflectance transition zone in each species. It may be possible that all or part of the ramp might be explainable as the waning influence of specular reflection as a function of increasing wavelength, a process dependent on leaf optical properties and thus peculiar to each plant cover -- depending on its species/variety and condition.

The second factor to consider in understanding the presence of the ramp features (Fig. 1) is the amount of light absorbed by the constituent carbohydrates, fats, and proteins of the leaf. As discussed in the Background section above, these molecules absorb preferentially with wavelength. While one of the simple bonds composing one of the larger molecules might absorb at one wavelength, the general trend of the absorption spectrum of the aggregate of all carbohydrate molecules is a decrease, albeit erratic, with decreasing wavelength from 2.4 μm. The absorption curves for fats and proteins show similar trends. Thus, a second factor to consider in the explanation of the ramp features in the data is the relative importance of the absorption spectra of these three constituents of the foliage. The importance will presumably change with wavelength. A composite absorption spectrum might aid in explaining all or some portion of the ramp features in the data (Fig. 1). The composite spectrum would include contributions from all three absorption spectra of carbohydrates, fats, and proteins in a linear combination dependent on species, varieties, and plant condition.

The last factor to consider in the explanation of the ramp features (Fig. 1) is the relative importance of air and water (protoplasm) dispersed in the leaf. If the leaf were optically thick and completely water, then the plant canopy would be quite black. But leaves do contain air in irregular sinuous pathways. The physical properties and thus the optical properties of the emulsion of air and water vary with species. As the transition regions near the large water-absorption bands at 1.4 and 1.9 μm are likely regions to observe such species-dependent optical phenomena, the ramp features may be a manifestation of species-dependent water absorption.

Analysis of the spectroradiometer data, determining the correlation coefficient of reflectances at adjacent wavelengths, provides evidence for fine spectral structure in the orange and red edge spectral regions in the wheat spectra and the ferric oxide, $Fe_2 O_3$, absorption band near 0.9 μm in the soils data. As the wheat data contained spectra from four development stages including data acquired before and after heading and when the wheat was ripe (senescent), the correlation analysis process will tend to identify those regions where

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the spectral curves show the maximum change with wavelength and date. Such a region, the red edge, contains an abrupt increase in radiance value between the red and the near infrared before senescence. The increase almost disappears upon senescence as the chlorophyll pigments deteriorate and the red reflectance of the wheat canopy significantly increases. The Collins far-red shift, which has been observed to occur with heading, will add additional diversity to the spectra at the red edge. Thus, the explanation of fine spectral structure at the red edge appears clear. The spectra of the senescent wheat appear to be the contributing factor for finding fine structure at 0.56 - 0.6 μm in the data acquired by the spectroradiometer. Prior to senescence, the wheat spectra have a peak reflectance at 0.56 μm; the peak disappears after senescence and the reflectance increases monotonically with increasing wavelength in the green and red spectral regions. The correlation process is identifying this abrupt change that occurs at senescence.
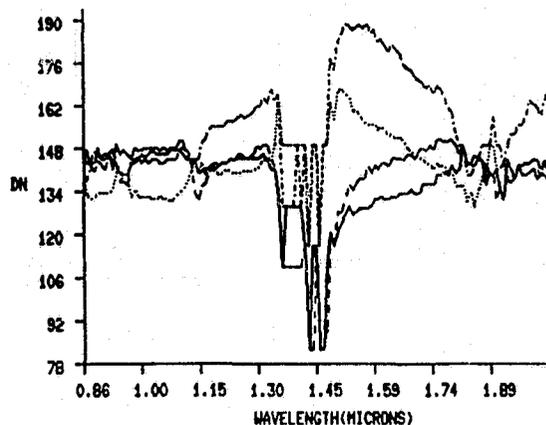
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Fig. 1. Using the AIS data from the Lafayette flightline, the ratios, the digital numbers (DN) of four ground covers divided by the DN value of a deciduous forest used for comparison purposes as a standard, were calculated using the formula: ratio = 50 + 100 * target/standard. As best as can be determined, the four ground covers are alfalfa (top curve at 1.5 μm), deciduous forest (bottom curve), and probably corn and/or soybeans (middle curves).
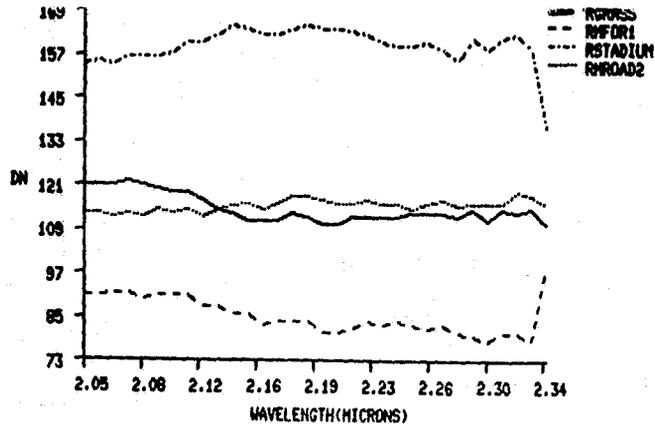
Fig. 2. The ratios of four ground targets in the Stanford flightline were determined from the formula: ratio = 50 + 75 * target/ standard. The ground targets are bleachers in the football stadium (top curve), forest (bottom curve), playing field in stadium (solid curve), and a road surface. A large grass area served as the standard.
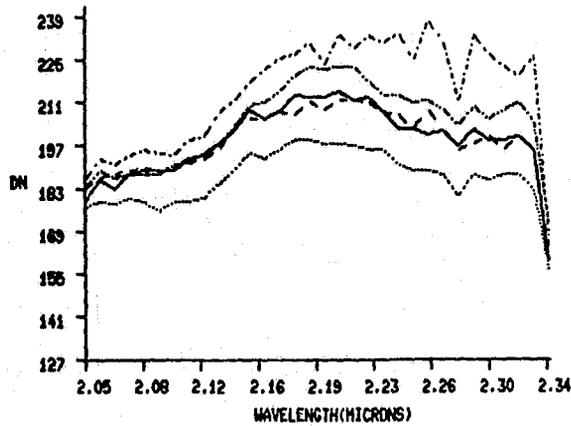

Fig. 3. The ratios of the Stanford data representing four rooftops from the section of the Stanford campus containing red tile roofs were determined from the formula: ratio = 50 + 75 * target/standard. The grass area of Fig. 2 served as the standard.