Thermal Infrared (2.5- to 13.5-μm) Directional Hemispherical Reflectance of Leaves

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ABSTRACT: Previous biconical reflectance measurements of 13 different plant species have shown that leaves display spectral signatures in the 8- to 14-μm atmospheric window that vary with species. Directional hemispherical reflectance measurements of six species reported here document the absolute magnitude of such spectral features for the first time. If half of the spectral contrast in leaf spectra is preserved in emittance from a broad-leaf planophile canopy, then at least some broad-leafed species could be mapped remotely by using currently available airborne instrumentation.

INTRODUCTION

EARLY MEASUREMENTS of the infrared spectral reflectance of leaves were broad band in nature and presented in tabular form because of their low spectral resolution (Gates and Tantraporn, 1952; Wong and Blevin, 1967). However, they seemed to show that plants were close to being black body emitters and that spectral signatures were similar for most species.

Subsequently, Gates (1980) published more detailed leaf spectra for three species; these spectra seemed to differ from species to species, but the spectral resolution and method of acquisition were not described. However, maximum leaf reflectances were of the same order (1 to 6 percent) as those of the previous work.

More recently, Salisbury (1986) and Salisbury and Milton (1987) published high resolution leaf spectra showing distinct differences in the spectral signatures of 13 different species in the 8- to 14μm atmospheric window. However, these measurements were made in biconical reflectance, which is not quantitatively convertible to emittance by means of Kirchhoff's Law as is directional hemispherical reflectance (Wong and Blevin, 1967; Nicodemus, 1965). Thus, it was uncertain whether the spectral features measured in the laboratory were of sufficient magnitude to be detected by remote sensing techniques. The purpose of this paper is to publish the first quantitative, high-resolution, directional hemispherical reflectance spectra of leaves, which show the magnitude of species-specific spectral features in the 2.5- to 13.5-μm wavelength region.

INSTRUMENTATION

Spectra were acquired at 4-cm^{-1} resolution by using a Nicolet 5DXB[†] interferometer spectrometer, an integrating sphere, and a mercury-cadmium-telluride detector cooled to liquid nitrogen temperature. Data were collected from 2.08 to 13.5 μm and stored in digital form.

The gold-coated integrating sphere was constructed by Labsphere of North Sutton, New Hampshire. The interior coating is a proprietary rough gold surface having good diffuse properties and a total reflectance of about 95 percent (Willey, 1987). The sphere is 12.7 cm in diameter, and has a 2.5-cm illumination port at 10° from the vertical and a 2.5-cm sample/reference port at the bottom of the sphere. The 2.5-cm detector port is in the side of the sphere; the detector chip has been baffled to eliminate direct viewing of either the sample or the specular "hot spot" on the sphere wall. A port at the specular angle was filled during these measurements with a plug having a surface curved to match the interior of the sphere.

A relatively large sample port was used, despite the reradiation penalty involved (Hisdal, 1965), because we found it desirable to keep the size of the beam illuminating the sample relatively large. When the beam was condensed to a 0.1-cm spot size in another reflectance attachment, progressive spectral changes (increasing reflectance, especially from 3.5 to 5.5 μm) clearly showed heating[*] and dessication of the leaf surface to be taking place. Measurements in another reflectance attachment using a beam spot size of 0.875 cm showed no dessication effect. Thus, the 1.54-cm spot size used in these measurements is more than large enough to avoid leaf damage and the resulting spectral artifacts.

Performance of the sphere was measured by comparing the reflectances of Halon, a diffuse gold surface, water, and a black body cone with that of a fresh, front-surface aluminum mirror. When the reflectance value for Halon at 2.22 μm determined by Weidner and Hsia (1981) was used as a reference, the reflectances of both the diffuse gold surface and the aluminum mirror were found to be 95.8 percent over most of the spectral range measured here. However, the aluminum mirror surface declined slightly (1 percent) in reflectance from 3.3 to 2.5 μm. These results are consistent with other measurements of the diffuse gold surface and specular aluminum (Willey, 1987).

Leaves have a very low reflectance in the thermal infrared, so that sphere performance at low reflectance was an important question. Fortunately, the spectral reflectance of water at near-normal incidence has been established (Pinkley *et al.*, 1977). Their measurement at 4 degrees off of the vertical (center ray) was a bidirectional measurement at the specular angle. If we assume that all reflected radiation from a water surface is specular, which in theory it should be, our directional hemispherical reflectance at a 10-degree angle from the vertical should be nearly identical. The two curves are, indeed, the same within 0.1 percent, except their peak at 3.15 μm exceeds ours by 0.3 percent. We consider this excellent agreement.

Finally, a black body cone was placed over the sample port to check the zero level. When the ±0.0 percent noise was averaged out, the apparent reflectance measured was 0.02 percent.

EXPERIMENTAL PROCEDURE

A fresh aluminum mirror was placed at the sample port, and a reference or background reflectance was run. Then a leaf was

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[†] Trade names are used for information purposes only and do not imply an endorsement by the U.S. Geological Survey.

[*] The source used for the reflectance measurement is a tungsten filament heated to about 1,250°C. Although there is not much power in the source beam (less than 1 watt), there is enough to slightly heat the sample surface when the beam is condensed. However, the source beam is frequency-modulated by passage through the interferometer head before it reaches the sample, allowing electronic discrimination between reflected source radiation and emitted (unmodulated) sample radiation.

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placed at the port, and the sample reflectance was measured. A ratio of sample to reference produced a reflectance spectrum of the sample. In principal, this spectrum could be corrected for the less than 100 percent reflectance of the reference material and for the reradiation error caused by the relatively large sample size (Hisdal, 1965). These corrections are, however, both small and opposite in sign. Thus, in practice, the uncorrected spectra (like those for water) appeared to be as accurate as any that could be obtained and are presented here.

The radiometric stability of the instrument on regulated power was excellent over a period of hours, as was demonstrated by periodically running a new reference and determining a ratio against the old one stored in memory. A straight 100 percent line was repeatedly produced. Thus, a new reference was typically acquired in the morning and again in the afternoon.

As a matter of convenience, leaves for five of the six species were excised from trees in the vicinity of the laboratory. The petioles were kept in water until they could be measured (no more than 2 hours) and were wrapped in wet tissue during measurement.

To check the validity of this procedure, the spectra of philodendron (*Philodendron sp.*) leaves were measured at three stages: attached to the plant, recently clipped, and 2 hours after clipping. The spectra were identical.

Sugar maple (*Acer saccharum*) leaves were collected some 50 miles from the laboratory, near Frederick, Maryland, the nearest source for this species. They were put on ice and their petioles were kept wet until they were measured, within 6 or 7 hours. Earlier measurements (Salisbury and Milton, 1987) have shown that such treatment preserves original spectral behavior.

RESULTS AND DISCUSSION

Figure 1 shows directional hemispherical reflectance spectra of six different broad-leafed tree species. These spectra are shown from 2.5 to 13.5 μm for plotting convenience, but data to 2.08 μm are available on request.

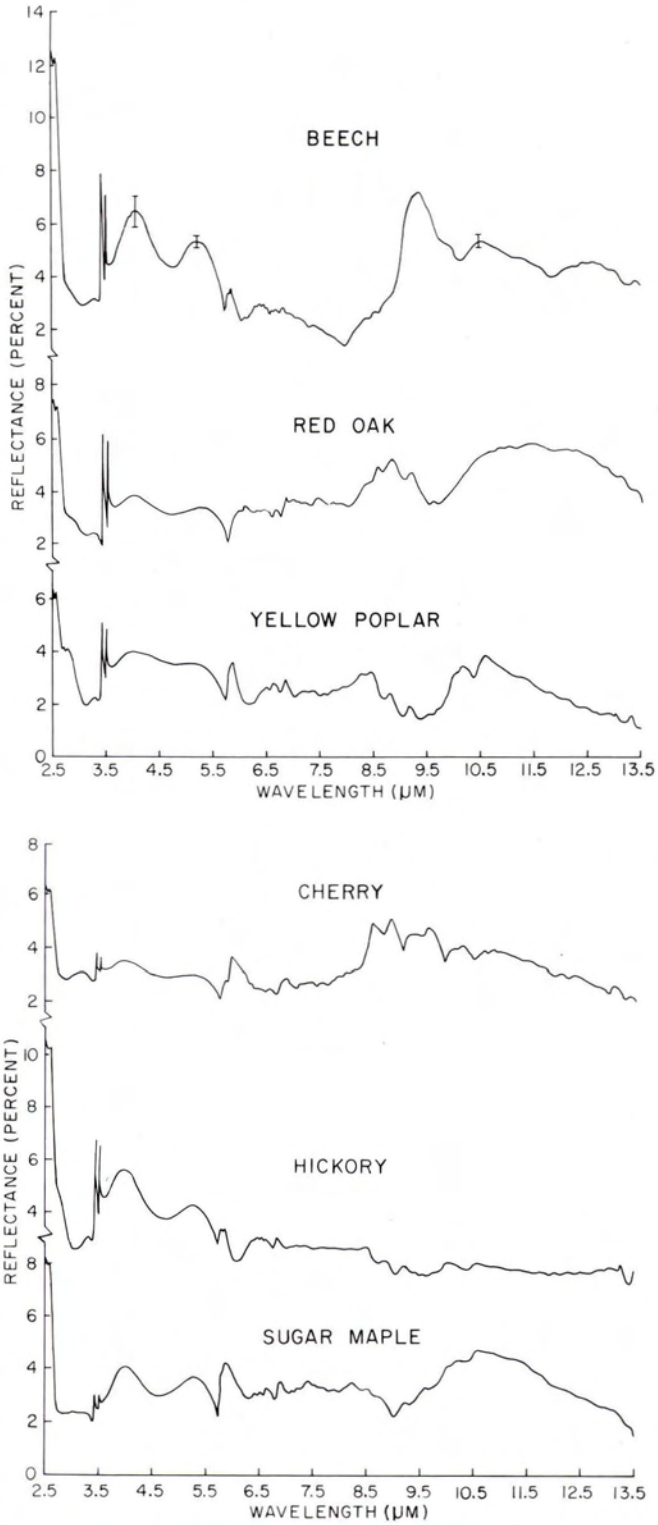

FIG. 1. Directional hemispherical reflectance spectra of leaves of six different broad-leafed tree species: beech (*Fagus grandifolia*); red oak (*Acer rubrum*); yellow popular (*Liriodendron tuliperfera*); cherry (*Prunus serotina*); hickory (*Carya glabra*); and sugar maple (*Acer saccharum*). Each spectrum is an average of the spectral reflectance of at least ten leaves, and each leaf spectrum is derived from an average of 100 interferograms. Bars show the variance of beech leaf spectra at three wavelengths. This variance is typical of other leaf spectra as well.

All leaves display a low continuum reflectance on which are superimposed spectral features. Wong and Blevin (1967) attributed this strong continuum absorption largely to water, and others have accepted this conclusion (Salisbury, 1986). However, when a leaf is thoroughly dried, the principal effect is seen at wavelengths shorter than 6 μm (Figure 2). Figure 2 shows that the epidermis is signficantly transparent at 2.5 to 2.8 μm and 4.0 to 5.6 μm, but substantially opaque and absorbing at longer wavelengths. In the shorter wavelength intervals, the loss of water (and water absorption) allows scattering at cell boundaries to markedly increase reflectance. However, reflectance and the spectral features remain relatively unchanged at longer wavelengths, except for a decrease in reflectance near 10 μm that slightly increases the spectral contrast. The lack of significant spectral effect of drying in the 8- to 14-μm region explains why earlier biconical measurements in the 8- to 14-μm region showed that early senescence had relatively little effect on the spectral behavior of leaves (Salisbury and Milton, 1987).

The spectral features displayed in Figure 1 in the 8- to 14-μm region are qualitatively the same as those previously described from biconical measurements, where they are of the same species (Salisbury, 1986; Salisbury and Milton, 1987). They were shown to result from specular first-surface reflectance, apparently from the cuticle (Salisbury, 1986). It was hypothesized that these features were reflectance peaks analogous to the specular reflectance peaks of minerals (reststrahlen bands) associated with strong fundamental molecular vibration bands. In the case of leaves, these spectral features were thought to be associated with the strong hydrocarbon vibration bands of the waxy cuticle. The spectra shown in Figure 1 support this view, because the extended wavelength range shown here includes two strong,

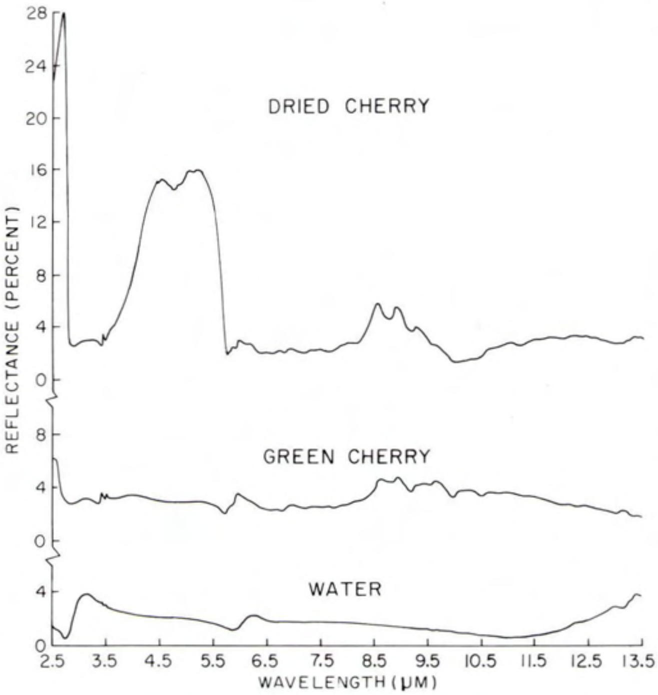

FIG. 2. Directional hemispherical reflectance spectra of tap water and of a cherry leaf before and after drying for 48 hours in a stream of dry air (dewpoint −60°C). The water spectrum has been smoothed to eliminate water vapor fine structure between 5.5 and 7.0 μm. (Note the doubling of the *Y*-axis in comparison with Figure 1.)

sharp peaks near 3.4 μm that are due to carbon-hydrogen fundamental stretching vibrations. Again, these are reflectance *peaks*, indicative of strong first-surface reflectance.

In the wavelength intervals where the cuticle and the epidermis are relatively transparent, shown by regions of high reflectance for the dried leaf between 2.5 and 2.8 μm and 4.0 and 5.6μm in Figure 2, volume scattering would be expected to dominate over first-surface reflectance. In such a case, absorption bands are represented by troughs instead of peaks (Salisbury *et al.*, 1987a). These bands are presumably caused by the underlying structural leaf material and do not vary much from leaf to leaf. In contrast, the reflectance peaks in the 8- to 14-μm region do vary with species, as do the compositions of cuticular waxes (Kramer and Kozlowski, 1979). Thus, these data are consistent with the origination of these spectral features in the cuticle. Interestingly, none of the spectral features appears to arise from water, despite the superficial resemblance of a feature near 6 μm to the water band caused by the H-O-H bending vibration. Not only is the feature offset in wavelength, but it also survives in the dried leaf in Figure. 2.

It is, of course, the magnitude of the species-specific spectral features in the 8- to 14-μm region that is of the most interest from a remote sensing viewpoint. Figure 1 shows that these features have a spectral contrast that varies from about 1 percent for hickory (*Carya glabra*) to nearly 6 percent for beech (*Fagus grandifolia*), the average being a little more than 2 percent. Emittance from a single leaf may reach an observer directly or may be partially absorbed and partially reflected by its surroundings, typically the underside of an overlying leaf. This leaf surface will, in turn, radiate to its surroundings. This complex process of radiative transfer is made even more so by the fact that upper and lower leaf surfaces may exhibit different spectral behaviors (Salisbury and Milton, 1987). The end result, however, is likely to be the same as it would for emittance or reflectance from rock and mineral powders; as scattering increases, spectral contrast decreases (Salisbury and Eastes, 1985). For broad-leafed canopies having a high leaf area index and predominantly horizontal (planophile) leaf habit, we estimate that spectral contrast will be approximately half what it is for a single leaf (Salisbury and Milton, 1987). We base this conclusion primarily on a field measurement of canopy reflectance in the visible, in which the magnitudes of scattered and unscattered (specular) reflectance were measured (Salisbury *et al.*, 1987). Numerous complications are introduced by variations in canopy geometry (especially wind affected) and the fact that the leaves of some species have different spectral signatures on their bottoms as opposed to their tops; however, our original estimate of canopy spectral contrast still seems valid as a first approximation.

Such spectral differences, however, have not yet been detected for vegetation in the airborne Thermal Infrared Multispectral Scanner (TIMS) data, or in ground-based infrared measurements. However, most TIMS flights have been made in the western United States over desert areas or over areas covered by coniferous vegetation. Because the geometry of a coniferous canopy should maximize scattering, spectral contrast would be minimal; also, desert vegetation is not a good target from the viewpoint of leaf area index.

Ground-based measurements of canopy spectra have so far been displayed at 110 percent full scale, so that a 1 or 2 percent spectral effect would be lost in the noise, which in any event appears to be of that magnitude (Hoover and Kahle, 1987). There is a clear need for high-quality ground-based and airborne measurements of appropriate vegetation targets to verify the detectability of leaf spectral signatures in canopy emittance. The potential for remote species mapping, at least of broad-leafed species, warrants a serious effort. The data presented here indicate that such measurements might well start with a stand of beech trees, the spectral signature of which should be apparent in data acquired by current instrumentation.

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