Should We Expect Anomalous Dispersion in the Polarized Reflectance of Leaves?

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ABSTRACT:

The light scattered by plant canopies depends in part on the light scattering/absorbing properties of the leaves and is key to understanding the remote sensing process in the optical domain. Here we specifically looked for evidence of fine spectral detail in the polarized portion of the light reflected from the individual leaves of five species of plants. Although our initial results showed fine spectral detail in the polarized reflectance at 1350 nm wavelength, further investigation pointed to anomalous dispersion occurring not at the leaf surface but in one of the measuring instruments — in the optical fiber connecting the fore optics to the dispersion optics in the instrument. In such a situation, proper calibration should remove evidence of anomalous dispersion from the calibrated spectra, suggesting that our calibration of the data was flawed.

1. Intoduction

The light scattered by plant canopies depends in part on the light scattering/absorbing properties of the leaves and is key to understanding the remote sensing process in the optical domain.

While this scattered light may be described by the four components of a vector, (intensity, magnitude of linear polarization, angle of plane of linear polarization, and magnitude/direction of circular polarization), significant progress has been achieved toward understanding only the first component, the intensity of the scattered light. Research shows that the magnitude of the linearly polarized light may be a significant part of the light scattered by some canopies (Vanderbilt, et al., 1985).

In this research we measured the intensity and the linear polarization of the light scattered by single leaves, testing the hypothesis that the polarized light scattered by a leaf is attributable to properties of the surfaces of the leaf and does not depend upon the characteristics of the interior of the leaf, such as its resident chlorophyll (Grant, et al., 1987a and 1993). We concentrated analysis efforts on the polarized portion of the reflected light, looking specifically for evidence of fine spectral detail, which, if found, would presumably be linked to the absorbing characteristics of the leaf cuticle. This research extends previous investigations limited to measurements in the 450 to 800 nm wavelength range of the leaves of approximately 20 species typically found in the vicinity of Lafayette, Indiana (Grant, et al., 1987a; 1987b; 1993; Vanderbilt and Grant, 1986).

2. Methods

We measured, Fig. 1, the detached leaves of five plant species — coffee, ficus, philodendron and spathiphyllum, all purchased at a garden store, and cannabis, grown in a greenhouse at the USDA — using two spectroradiometers, an ASD ©FieldSpec Pro (Analytical Spectral Devices, Boulder, Colorado, USA) and a GER 3700 (Spectra Vista Corp., Poughkeepsie, New York, USA). In the experimental protocol, each leaf was observed at approximately Brewsters angle sequentially by each instrument, one instrument periodically replacing the other in the measuring setup, Fig. 1.

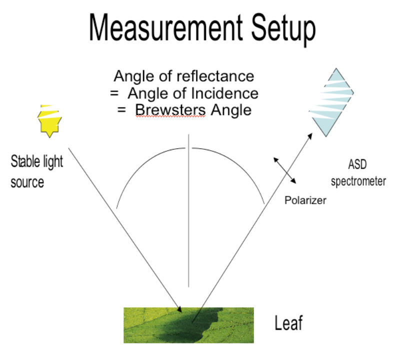

Figure 1. In the experimental protocol, after the ASD ©FieldSpec Pro collected data of a leaf, it was replaced by the GER 3700, which then collected data on the same leaf. Both spectroradiometers observed the leaf through a polarization analyzer at approximately Brewsters angle.

The bidirectional reflectance factor (BRF) and the polarized part of the BRF (BRF_{QU}) of each target i (one of five leaf species or a ©Spectralon calibration surface) (©Spectralon is manufactured by Labsphere, North Sutton, New Hampshire, USA) were calculated from measurements by each instrument at 11 polarizer angles (q=-90,-70,-50,-30,-10,0,10,30,50,70,90), first regressing the data, X(l,i,q), recorded at each wavelength, l, and polarizer angle using eq. 1 with intercept C

$$X(l,i,q = C(l,i) + A(l,i)\sin(q) + B(l,i)\cos(q). \quad (1)$$

Rearranging provides

$$X(l,i,q) = C(l,i) + \{[A(l,i)^2+B(l,i)^2]^{0.5}\} \sin(qq) \qquad (2)$$

where q= arctan[A(l,i) / B(l,i)]. Finally the BRF(l.i) and BRF_{QU}(l.i) for leaf i were calculated

$$BRF(l,leaf\ i) = BRF(l,spec) \frac{C(l,leaf\ i)}{C(l,spec)} \qquad (3)$$

$$BRF_{QU}(l,leaf\ i) = BRF(l,spec) \frac{[A(l,leaf\ i)^2+B(l,leaf\ i)^2]^{0.5}}{C(l,spec)} \qquad (4)$$

where spec refers to ©Spectralon . We assumed the BRF(l,spec)=1.0 for illumination and observation at Brewsters angle.

3. Results

The BRFs of individual leaves measured with each instrument, Fig. 2, appear generally comparable and display variation with wavelength typical of green leaves, revealing a green peak and the effects of chlorophyll absorption in the visible wavelength region and, in the reflective infrared spectral region between 700 and 2500 nm, an infrared plateau and the effects of water absorption.

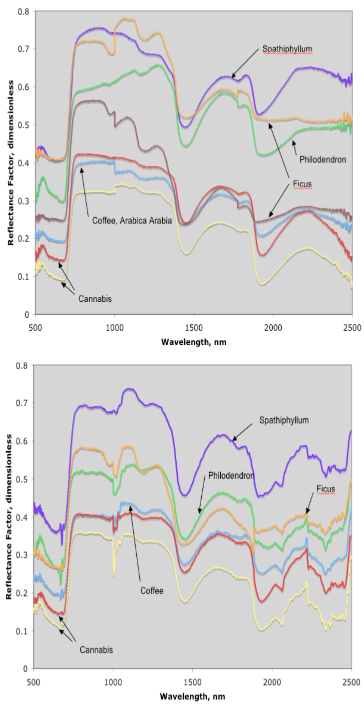

Figure 2. The relative bidirectional reflectance factor was estimated from (a) (left) ASD data and (b) (right) GER data.

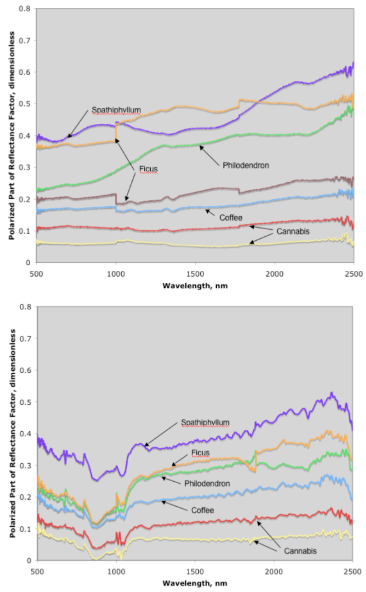

Figure 3. The polarized part of the relative bidirectional reflectance factor was estimated from (a) (left) ASD data and (b) (right) GER data of five leaf species measured as shown in Figure 1.

The BRF_{QU}s of individual leaves measured with each instrument, Fig. 3, are reasonably comparable for wavelengths longer than 1000 nm, but show marked differences at shorter wavelengths where the GER spectra display much greater apparently random amplitude variation – noise - with wavelength than the ASD spectra. In the wavelength range 500 and 800 nm, the ASD results — but not the GER results — compare reasonably well with our prior research results. The general downward trend of the GER spectra with wavelength is in contrast to the generally flat character of the ASD spectra. At wavelengths longer than 1000 nm there are subtle differences near 1350 nm where the GER spectra appear relatively flat while the ASD spectra of most leaves display a miniature trigonometric sine wave atop an otherwise slowly changing response with wavelength.

4. Discussion

The miniature sine wave in the ASD results at 1350 nm, Fig. 3a, is characteristic of the effects of anomalous dispersion, an optical phenomenon that occurs when a light beam is specularly reflected at the surface of an absorbing material (Fowles, 1989). Typically, the magnitude of anomalous dispersion effects after just one specular reflection are small – probably too small to be consequential at present for remote sensing purposes. Thus, in general we do not expect the light singly specularly reflected by leaves to exhibit the effects of anomalous dispersion in remotely sensed data, suggesting that the evidence of anomalous dispersion displayed in Fig. 3a is due to a source other than the leaf surface. The lack of evidence of anomalous dispersion in the GER results, Fig. 3b, supports this view.

Figure 4 displays evidence of a very slight absorption in the ASD optical fiber at a wavelength of approximately 1350 nm, suggesting an explanation for the apparent anomalous dispersion effects evident in the BRF_{QU} of the leaves measured by the ASD but not the GER, an instrument with fore optics connected directly to its dispersion optics and lacking a connecting optical fiber. Based upon the evidence in Figs. 3 and 4, we believe the most reasonable explanation for the anomaly at 1350 nm in the ASD results, Fig. 3a, is that anomalous dispersion at 1350 nm occurred in the ASD optical fiber and not during the specular reflection at the leaf surface. If anomalous dispersion occurred in the ASD optical fiber, which tends to depolarize incident light, the effect should not be evident in Fig. 3a – properly calibrating the ASD data with reference to the ©Spectralon surface should have removed from the spectra, Fig. 3a, evidence of anomalous dispersion. (On the other hand, evidence of anomalous dispersion attributable to leaf surface properties, if pronounced, should appear in properly calibrated ASD and GER spectra.) Thus, in this situation we believe responsibility for the evidence of anomalous dispersion, Fig. 3a, rests with the data analyst (VCV) who most likely calibrated the leaf data using the wrong ©Spectralon data.

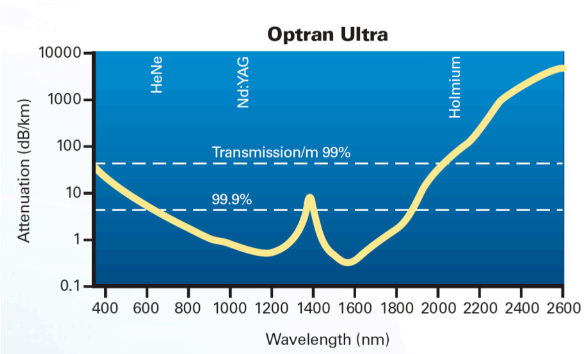

Figure 4. The attenuation of the optical fiber in the ASD instruments shows a minor absorption band at approximately 1350 nm. This figure was obtained from the optical fiber manufacturer, CeramOptec Industries Inc., East Longmeadow, Massachusetts, USA.

Assuming the BRF(l,©Spectralon)=1.0 for illumination and observation at Brewsters angle (see the Methods) is unreasonable for purposes of calculating the absolute values of the BRF and BRF_{QU} of a leaf. However, this assumption is reasonable here because the issue here concerns not the absolute magnitude but the existence of fine spectral detail in the BRF_{QU}; thus, analysis of the relative magnitudes of the BRF_{QU} suffices for this investigation; we incorrectly - but safely - assume the BRF of the ©Spectralon equals 1.0, because we report the relative not absolute BRF magnitudes.

One additional point to be made is that here we have not corrected these polarization results – and should have - for the polarizing effects introduced by the each of the measuring instruments.

5. Conclusions

We do not expect the effects of anomalous dispersion to be evident in the polarized remotely sensed reflectance spectra of leaves until the signal to noise ratio in the measuring instrumentation improves significantly. We believe the evidence of anomalous dispersion found in this research is due entirely to artifacts introduced into the results because a researcher incorrectly calibrating the data obtained from the ASD instrument.

6. References

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