Spectroscopic Measurement of Leaf Water Status

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Abstract – A leaf drying experiment was carried out in the laboratory in which simultaneous spectral reflectance in the 350-2450 nm region, and leaf weights, were measured at 10 second intervals over a 40 minute period. As the leaf water weight dropped from approximately 60 to 38%, a nearly-linear rise in reflectance at all wavelengths beyond 1000 nm was observed. A principal components analysis of the time series of spectra in the 2000-2500 nm wavelength region showed that over 99% of the variance in the spectra, that were individually scaled to have a sum equal to that of the mean spectrum and subsequently mean corrected, was in the first component. This result shows that it is feasible to determine leaf water content remotely with an imaging spectrometer independent of the surface irradiance effects caused by topography.

INTRODUCTION

The remote detection of plant water stress from drought has been a major research goal for a number of years for crops [1, 2] and forests [3, 4]. Of importance here is the relative water content (RWC) that is defined as the water volume of a leaf divided by the maximum water volume at full turgor [4]. The objective of this study was to develop an algorithm to determine leaf water content in the physiologically important range of values, independent of brightness associated with surface topography and taking into account the natural variability among vegetation types.

LABORATORY METHOD

The laboratory measurements consisted of acquiring reflectance spectra of an illuminated single large leaf, overlying a white Halon standard, positioned on a balance with 10^{-3} gm digital readout precision. The fiberoptic-bundle, spectrometer input probe had a foreoptic that restricted the view to a 5° full angle and was pointed vertically at the leaf. The illumination consisted of two, 50 W quartz- halogen reflector lamps situated on opposite sides of the sample, approximately 45° off normal. The measurement configuration is shown schematically in Fig. 1.

The lamps were positioned at a distance of approximately 20 cm from the sample in order to dry the leaf to approximately 60% of its original weight in approximately 40 minutes. After the measurement cycle was completed, the leaves were further dried in an oven at 60°C overnight and re-weighed to obtain the dry weight. The reason that only one leaf was used in the experiment, rather than a stack of leaves that would more realistically represent the reflectance of a canopy, was that the drying rate could be controlled only for a single leaf. The spectrometer used was a FieldSpec™-FR (Analytical Spectral Devices, Boulder). The spectrometer acquires a reflectance spectrum spanning the wavelength range 350-2450 nm in 0.1 seconds.

SPECTRAL MEASUREMENTS

A data set for a leaf consisted of 240 spectra, each of which is made up of the average of 50 individual spectra, and time stamped so that for any given measurement spectrum, a leaf weight and water content were retrievable. Fig. 2 shows the spectrum of a Basswood (*Tillia americana* L.) leaf at the beginning of the measurement cycle. The reason for the high reflectance in the infrared plateau around 800 nm is that only one leaf is being measured, and the leaf is lying on a white Halon standard that reflects essentially all the transmitted light back through the leaf. In a canopy the maximum reflectance would be lower.

NEAR INFRARED REGION RESPONSE

The region beyond 1000 nm exhibits a steadily increasing reflectance as a function of time for all wavelengths. This can be explained by the fact that water absorbs strongly at all wavelengths in this region.

The behavior of the reflectance at the absorption maxima for three water features at 1191 nm, 1444 nm, 1927 nm are shown in Fig. 3. The reflectances shown in Fig. 3 increase nearly linearly with decrease in water content of the leaf. However, for purposes of remote sensing, only the absorption feature at 1191 nm is available for determination of liquid water content, since the features at 1444 nm and 1927 nm are hidden by deep atmospheric water vapor absorption features, that are saturated in these regions.

The region 2000-2400 nm exhibits significant change in shape as drying occurs, as shown in Fig. 4. In particular, the features associated with cellulose and lignin appear as separate peaks in the dry spectrum and as a single peak in the initial spectrum in the drying sequence [5]. In order to better display the spectral behavior with time, the spectra have been arranged in a three-dimensional plot shown in Fig. 5. It is interesting to note that the strong features that appear at the end of the drying cycle, and are associated with the dry leaf spectra, do make their appearance throughout the drying cycle and, in a very subdued form, even in the first fresh leaf spectrum. This fact makes possible the determination of the chemical composition of fresh leaves by applying first and second difference techniques to the spectra [5].

DATA ANALYSIS

As shown in Fig. 3, the change in leaf water status is evident and retrievable from the depth of the water absorption feature at 1191 nm, but the change with water status is small, requiring very high signal-to-noise ratio in the sensor and an initial band depth, possibly for each species. Therefore, it is important to use an extended segment of the spectrum with a sufficient number of spectral bands to increase the apparent signal-to-noise ratio, and make use of the changing shape of the spectrum as the leaf dries. We propose a technique for spectroscopic measurement of leaf water status based on the diagnostic changes seen in the shape of the reflectance curves in the 2000 to 2400 nm spectral region. It should be possible to use imaging spectrometry data in this infrared atmospheric window region to infer leaf water status.

The dimensionality and nature of the drying-induced spectral changes in the 2000-2400 nm spectral region were examined with a principal components analysis. We resampled the 400 spectral channels covering this 400 nm range to 200 channels, recreating the 2 nm sampling interval of the instrument. The mean spectrum was subtracted from each spectrum, centering the data on the origin. Then the covariance matrix, eigenvalues and associated eigenvectors were calculated. The overwhelming dominance of the first eigenvalue indicates a nearly linear progression from the first spectrum to the last. The path followed by the spectra of the drying leaf in spectral-space is essentially linear. Fig. 6 shows the first eigenvector which points in the direction of spectral change of the series of drying-leaf spectra.

Fig. 7 illustrates the projection of each of the 240 spectra, from wettest to driest, onto the first eigenvector. There is a nearly linear progression of the first eigenvector projections of the spectra. The slope of this line is many times greater than those shown in Fig. 3, indicating the substantial increase in sensitivity that results from a joint analysis of many spectral bands.

SUMMARY AND CONCLUSIONS

The availability of a new, rapid-reading spectrometer has made it possible to develop a high time-resolution image of the spectral reflectance response of a leaf to drying. The simultaneous recording of the leaf weight made it possible to assess the relationship between spectral reflectance and leaf water content quantitatively. At wavelengths longer than 1.0 µm, spectral reflectances increase uniformly as the water content is reduced by drying. The results of a principal components analysis show that, when the leaf is dried, the 2000-2400 nm spectral region exhibits the greatest spectral change, independent of albedo change. This result leads to the conclusion that a quantitative method can be developed to measure leaf water content remotely by imaging spectrometry. A multispectral scanner such as Landsat with one band in this spectral region, or even a scanner with several bands would not provide sufficient data for this method. The level of precision can be expected to be on the order of ±1% with a sensor such as AVIRIS. Further study will be required to assess the level of accuracy that can be expected under the conditions of remote sensing using the proposed principal components method.

ACKNOWLEDGMENTS

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REFERENCES

[1] Bauer, M.E., C.S.T. Daughtry, L.L. Biehl, E.T. Kanemasu, and F.G. Hall, Field spectroscopy of agricultural crops, *IEEE Trans. Geosci. Remote Sens.*, GE-24, 65-75, 1986.

[2] Hunt, E.R., Jr., B.N. Rock, and P.S. Nobel, Measurement of leaf relative water content by infrared reflectance, *Remote Sens. Env.*, 22, 429-435, 1987.

[3] Hunt, E.R., Jr., and B.N. Rock, Detection of changes in leaf water content using near- and middle-infrared reflectances, *Remote Sens. Env.*, 30, 43-54, 1989.

[4] Elvidge, C.D., Visible and near infrared reflectance characteristics of dry plant materials, *Int. J. Remote Sens.*, 11, 1775-1795, 1990.

[5] Martin, M.E. and J.D. Aber, Determining the chemical composition of fresh leaves using near-infrared spectra, submitted, 1994.

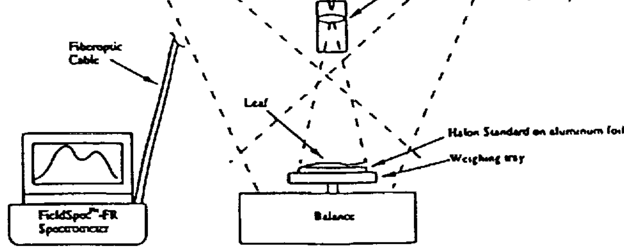

Figure 1. Schematic diagram of the spectral and mass measurements.

Figure 2. First spectrum in the series of 240 spectra

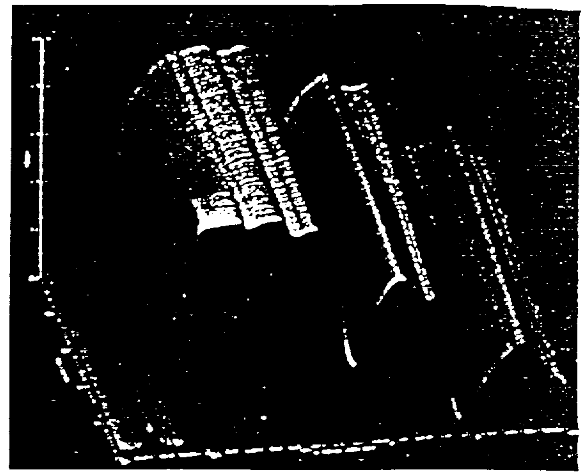

Figure 5. Shaded relief view of the full spectral series. Elevation angle 40 degrees, azimuth angle 10 degrees

Figure 3. Plots of the reflectance levels of the minima of three water features: 1191, 1444 and 1927 nm, top to bottom respectively.

Figure 6. First eigenvector of the 2000-2400 nm spectra, indicating the spectral direction of the drying trajectory.

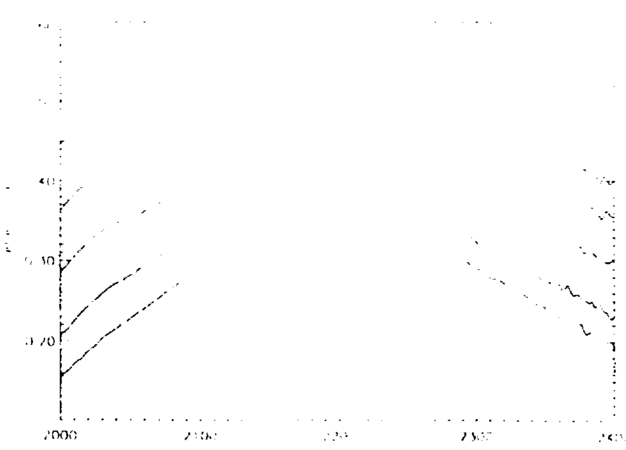

Figure 4. The 2000-2400 nm range, spectra 1, 60, 120, 180, 240.

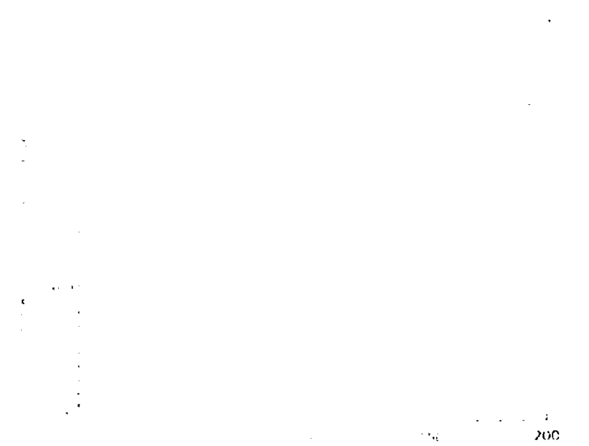

Figure 7. The projection of the data onto the first eigenvector, indicating position along the drying trajectory.