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MEASUREMENT AND MODELING OF THE OPTICAL SCATTERING PROPERTIES OF CROP CANOPIES

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I. Justification of Research

The amount of sunlight specularly reflected by such plants as sunflower, corn, sorghum, wheat, and grass is often so large that canopies of these plants appear white instead of green when viewed obliquely toward the sun.

Specular reflections from the shiny leaves of plants originate at the interface between air and the cuticle wax layer. Unlike the diffuse portion of the light reflected by a leaf, the specular portion of the reflected light is reflected at the first surface it encounters; it never enters the leaf. From the Fresnel equations of optics, the light reflected by such a shiny surface is polarized. The polarized portion of the reflectance may be species dependent and related potentially to the physiological status and development stage of the canopy - to such botanical variables as leaf age and plant water status and temperature regime.

All of this suggests that remotely sensed polarization measurements of a plant canopy will contain information about the leaf surfaces -- information independent of that already identified in the light reflected from the interior of the leaves measured in the various spectral regions. The information is independent because the polarized portion of the reflected light does not enter the leaf to interact with cell pigments, walls or water.

Polarization measurements, although certainly a potential source of useful information about the earth, have never been acquired routinely by satellite-borne imaging sensors as part of earth observation research. The reason is simple; the research area is virgin. Hard evidence in the form of physically-based theories supported by actual data has only recently begun to demonstrate the actual -- not merely potential -- information in such data. More evidence is needed before a dedicated satellite-borne sensor system would be justifiable.

II. Research Objectives

The overall objective is to investigate the potential information in the polarization data of both single leaves and plant canopies. This research is measuring, analyzing, and mathematically modeling the specular, polarized, and diffuse light scattering properties of several plant canopies and their component parts (leaves) as a function of view angle and illumination angle. The potential of these bidirectional radiation properties for ground cover discrimination and condition assessment is being evaluated.

III. Approach

The research approach has proceeded in both empirical and theoretical directions. Measurements performed at our laboratory demonstrate the relationship between polarization data and various optical and botanical properties of both pieces of foliage and plant canopies. The data provide a basis for gaining fundamental understanding of how light is scattered and polarized by a plant canopy. A mathematical model has been developed for predicting the specular and polarized light scattering properties of plant canopies. By exercising the model we have developed better understanding of the potential information in polarization data.

The empirical part of the approach has involved demonstrating our new technique for determining specular, polarized, and diffuse components of the reflectance factor of both leaves and plant canopies. Applying this new technique to our field measurements, we have determined the specularly scattered and polarized light from a plant canopy as a function of view and illumination directions. To these reflectance data, we have appended the ancillary data of the plant canopies for use by ourselves and other investigators developing and testing light-canopy interaction models, such as our specular reflection/polarization model.

A polarization photometer was developed to investigate the potential information in the mean and standard deviation of the polarized/diffuse components of the reflectance factor of leaves, measured individually in vivo at six wavelengths at the Brewster angle. Measurements were made (1) in a survey of plant species and varieties representing crops, forests, "weeds," and horticulture, including as factors (when appropriate) leaf pigmentation, development stage, position of leaf on plant, and position of instrument on leaf, (2) of a corn canopy as a function of its moisture stress, and (3) of a greenhouse-grown wheat innoculated with wheat rust.

IV. Results

We present three results of our research, (1) a theoretical model of the specular-polarized light scattered by a plant canopy, (2) data demonstrating a linear relationship between the relative water content of a leaf and its non-polarized reflectance, and (3) data demonstrating the importance of the variable, angle of incidence, in explaining the polarization of light scattered by plant canopies.

A. Theoretical Model

A model was developed for predicting the amount of light specularly reflected and linearly polarized by the leaves of such plant canopies as wheat, corn, and sorghum. The model is based upon the morphological and phenological characteristics of the canopy and upon the Fresnel equations which describe the light reflection process at an optically smooth boundary separating two dielectrics.

The theory demonstrates that, potentially, measurements of the linearly polarized light from a plant canopy may be used as an additional feature discrimination. Examination of the model suggest that, potentially, satellite polarization measurements may be used to monitor plant development stage, leaf water content, leaf area index, hail damage, and certain plant diseases. The modeling results show that the angles of the polarization analyzer on a radiometer or satellite-borne sensor measuring a ground scene may be predicted from the view and illumination directions.

Applicability of the model of the canopy specular reflectance should extend to many species because leaves - which specularly reflect sunlight - are ubiquitous, unconfined by geography or climate.

The modeling results, Fig. 1, show that for the predictions from the model the single variable, angle of incidence (on the leaf) of the sunlight specularly reflected to the sensor, explains much of the variation, as a function of view direction (both zenith and azimuth), for a plant canopy with a uniform (spherical) leaf angle probability density function. For example, at any specific angle of incidence, 30 degrees, for example, the predicted R_Q, Fig. 1, changes little for zenith view angles less than about 40 degrees, only changing significantly for angles approaching 90 degrees. The physical interpretation of this prediction, Fig. 1, is that at any given angle of incidence there are more specularly reflecting leaves in the field of view of the sensor at large zenith view angles near 90 degrees than near 0 degrees. For example, for the sun on the horizon in the east and for view directions varying from 0 degrees up to the horizon to the north, the angle of incidence will be constant at 45 degrees in all these view directions; however, the number of specularly reflecting leaves in the field of view of the sensor will be least at 0 degrees zenith view angle and greatest at the horizon.

B. Leaf Moisture vs. Reflectance

To investigate if relationships exist between reflectance and moisture-stressed vegetation, measurements were acquired on the leaves of corn, grown in a field under moisture-stressed conditions. (A physiological disturbance of a plant usually results in an increase of reflectance in the visible portion of the spectrum.) Twenty-four hours prior to reflectance measurements, a portion of the field was flood irrigated. Leaves for reflectance measurements came from (a) this irrigated treatment, (b) the field-grown, stressed conditions, and (c) leaves excised from plants subjected to rapid desiccation. The water status of each individual leaf was quantified by measuring the relative water content of each leaf sampled for leaf reflectance measurements.

Fig. 2 depicts the reflectance in the red wavelength band (650 nm) as a function of relative water content (RWC). The results, Fig. 2a, show that when the RWC of these corn leaves increased, the reflectance factor, R, tended to decrease. But within this range of relative water contents sampled (between 50% and 100%), the variaton in the reflectance factor is great - making the usefulness of the reflectance measurements for predicting the relative water content slight. Fig. 2b shows there is no relationship between the polarized component of the reflectance factor, R_Q, and relative water content.

But there is a relationship between the non-polarized component of the reflectance factor and relative water content, Fig. 2c, which increases linearly ($R^2 = 0.77$) with decreasing relative water content. This relationship appeared valid even for relative water contents greater than 80%, a moisture regime for which other investigators have found hemispherical leaf reflectance to be a poor estimator of relative water content. The non-polarized component of the reflectance factor thus appears to be a better predictor of relative water content than the reflectance factor.

C. Plant Canopy Angle of Incidence

In field experiments designed to provide comparisons between the model predictions and polarization data, we measured two plant canopies, each in a variety of view directions as the sun moved, providing illumination in a continuum of directions. More than 200 spectra were acquired on two wheat canopies in the boot (preheaded) and dough (headed) stages of development, and on each date in each of 33 view directions.

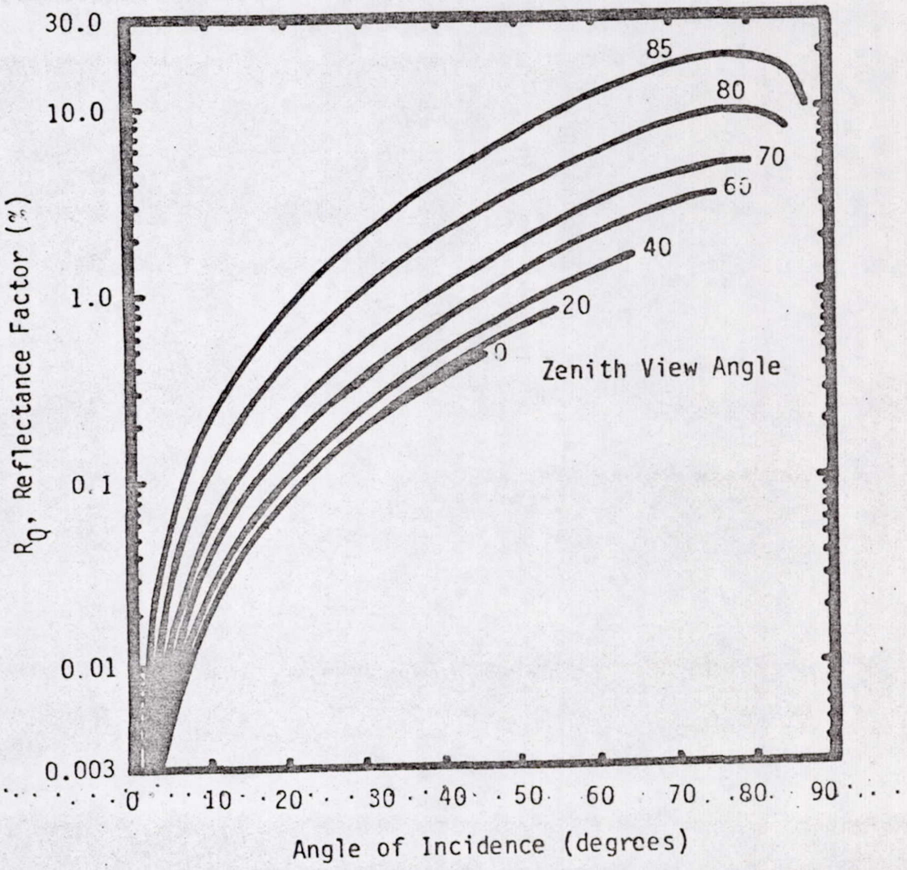
The degree of linear polarization (Fig. 3) at a wavelength of 0.66 um is plotted for 19 June and 17 July for four view zenith angles and angle of incidence, gamma. Regardless of zenith or azimuth view angles, the data points for June 19 fall within a narrow region defining an arc. On July 17 the scatter in the data is generally greater, although those data acquired at a view zenith angle of 60° define a fishhook-shaped curve.

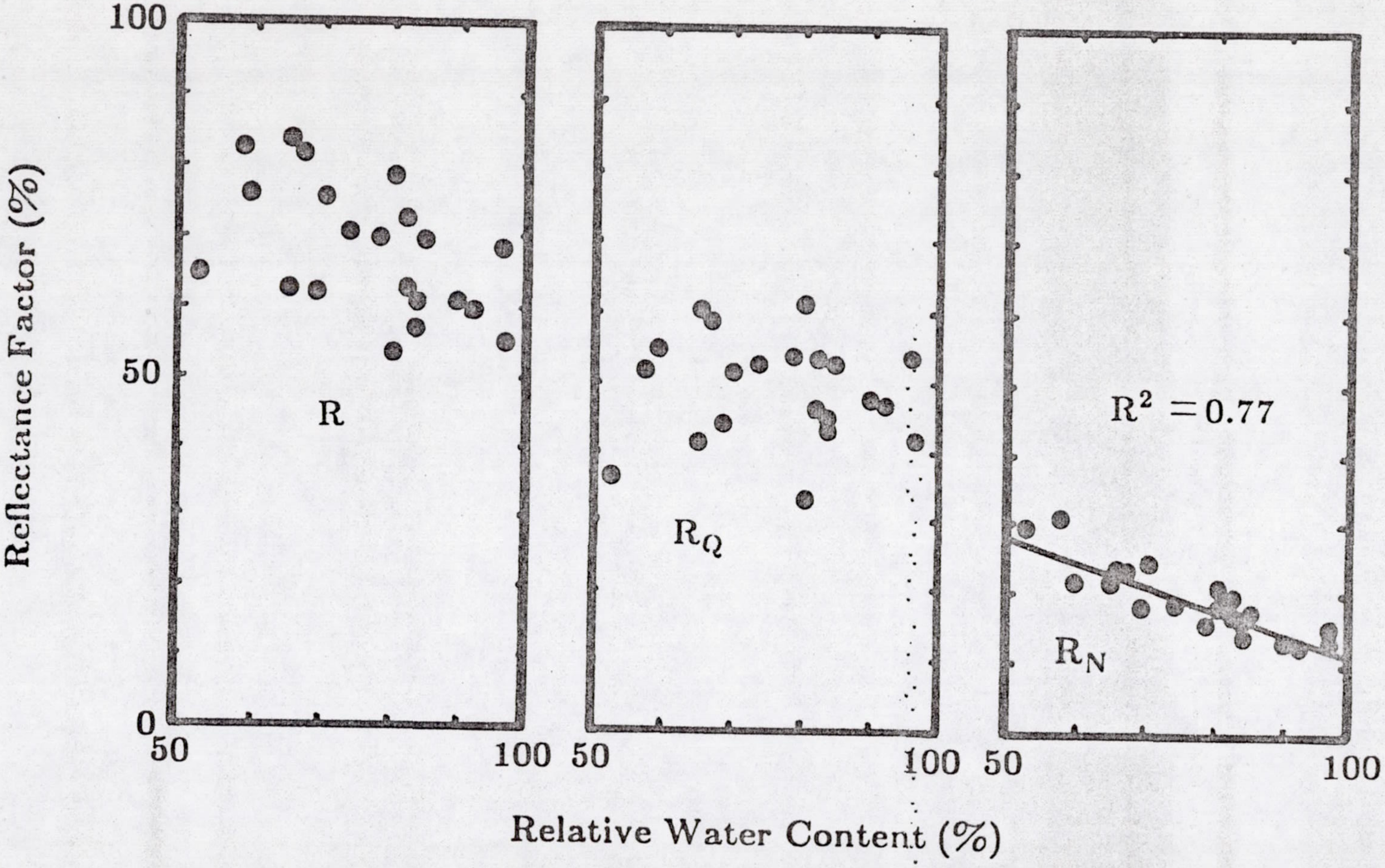
Fig. 3 shows that most of the variation on June 19 in linear polarization as function of the two variables, view zenith and view azimuth angles, is explained by the single variable, angle of incidence, a prediction of the specular/polarization model. The angle of incidence is computed knowing that a small area of shiny leaf must be uniquely directioned to specularly reflect sunlight to an observer. For the headed wheat of JUly 17, the angle of incidence explains the variation in the linear polarization at a zenith view angle of 60° (albeit the arc-shaped relationship of June 19 is a fishhook on July 17) but less well at smaller zenith view angles. The decrease in the degree of linear polarization at large angles of incidence for 60° zenith view angles on July 17 (the hook of the fishhook) is due to the heads (poor specular reflectors) decreasing the visibility of the flag leaves to the radiometer.

V. Conclusions

The specular reflection process has been shown to be a key aspect of radiation transfer by plant canopies. Polarization measurements have been demonstrated as the tool for determining the specular and diffuse portions of the canopy radiance. The magnitude of the specular fraction of the reflectance is significant compared to the magnitude of the diffuse fraction. Therefore, it is necessary to consider specularly reflected light in developing and evaluating light-canopy interaction models for these two wheat canopies. Models which assume leaves are diffuse reflectors correctly predict only the diffuse fraction of the canopy reflectance factor. The specular reflectance model, described here, when coupled with a diffuse leaf model, would predict both the specular and diffuse portions of the reflectance factor. The specular model predicts and the data analysis confirms that the single variable, angle of incidence of specularly reflected sunlight on the leaf, explains much of variation in the polarization data as a function of view-illumination directions.

Design of hardware to remotely sense the polarization of the light reflected by a canopy under a clear sky is simplified by the results of this research. First, the lack of fine structure in wavelength in the polarization spectra suggests that a design with a single wavelength band covering the entire visible wavelength is a possibility. Second, the angle of the polarization analyzer on the polarization sensor does not depend on the data but solely on view/illumination directions and can be set prior to data acquisition.


30.0
10.0
1.0
0.1
0.01
0.003
R_Q, Reflectance Factor (%)
85
80
70
60
40
20
0
Zenith View Angle
0
10
20
30
40
50
60
70
80
90
Angle of Incidence (degrees)


Reflectance Factor (%)
100
50
0
50
100
R
R_Ω
R² = 0.77
R_N
Relative Water Content (%)

(a) (b) (c)

Linearly Polarized Light Reflected by Wheat Canopy
(0.66 μm)

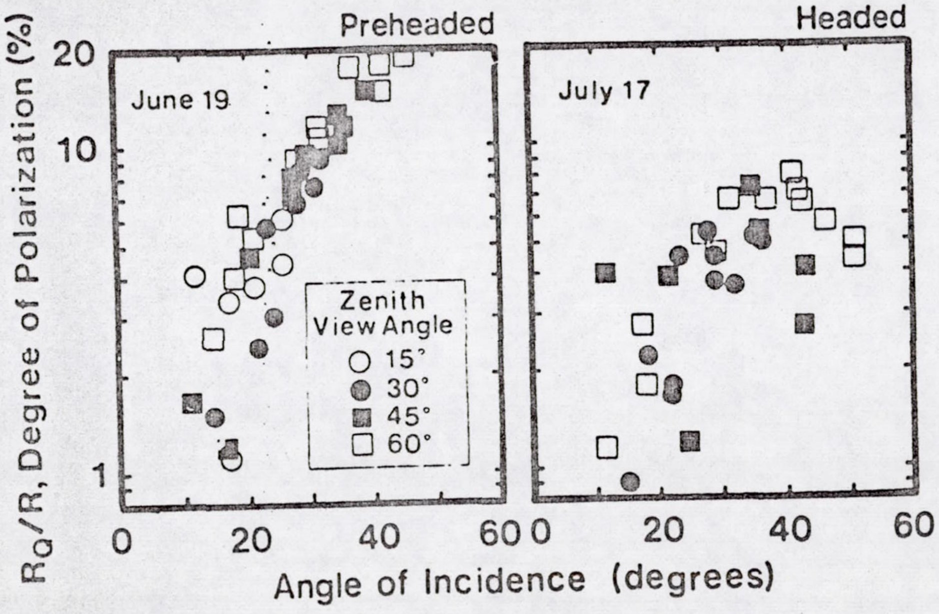


Fig. 3