A MODEL OF PLANT CANOPY POLARIZATION RESPONSE

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I. ABSTRACT

Sensors to remotely measure the linear polarization of ground scenes have been proposed for the Multispectral Resource Sampler (MRS), a satellite sensor system proposed to compliment the Thematic Mapper. At present justification for a sensor on MRS to measure scene polarization is limited. This paper discusses a model for the amount of linearly polarized light reflected by the shiny leaves of such crops as wheat, corn, and sorghum. The theory demonstrates that, potentially, measurements of the linearly polarized light from a crop canopy may be used as an additional feature to discriminate between crops. Examination of the model suggests that, potentially, satellite polarization measurements may be used to monitor crop development stage, leaf water content, leaf area index, hail damage, and certain plant diseases. The model adds to our understanding of the potential information content of scene polarization measurements acquired by future satellite sensor systems such as MRS.

II. INTRODUCTION

A series of investigations has shown that remotely sensed Landsat satellite multispectral scanner (MSS) data can be used to accurately identify and measure hectarages of crops over large areas. Experimental global wheat production forecasts have been made by melding crop area estimates derived from Landsat data and estimates of crop yield made by regression models based on historical weather and yield data[1,2]. Despite these successes, there are limits to the present technology; for example, during the Large Area Crop Inventory Experiment (LACIE), there was a tendency for spring wheat to be confused with other small grains such as barley. And potentially in the multitemporal spectral responses of various crops there is information related to crop vigor and growth stage, information needed for various models to predict crop grain yield[3,4]. There is a continuing need to better discriminate between crops and a need to research and develop remote sensing data analysis techniques to predict crop grain yield[4].

Sensors to remotely measure the linear polarization of ground scenes have been proposed for the Multispectral Resource Sampler (MRS), a satellite sensor system proposed to compliment the Thematic Mapper[5]. If polarization sensors are to be included in the MRS, it should be established that polarization measurements of a scene provide nonredundant information exceeding that already found in the scene spectral response, now routinely measured by Landsat MSS with four wavelength bands and soon to be measured by the Thematic Mapper with seven wavelength bands.

At present justification for a sensor on MRS to measure scene polarization is limited. Using data obtained in the laboratory and with an aircraft, Egan, Egan and Hallock, and Egan, et al. found evidence that the degree of linear polarization

Figure 1. Specular Reflection. The camera received specularly reflected sunlight from the bright areas of these wheat flag leaves.

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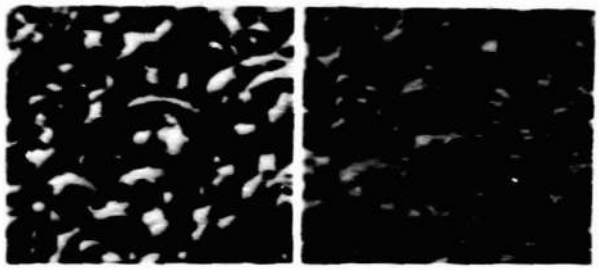

(a) (b)

Figure 2. Polarized Light from Canopy. These photos, taken with a polarizer oriented for transmission of maximum specularly reflected light (a) and minimum specularly reflected light (b), demonstrate that the specularly reflected light is polarized.

of the response of a scene provides additional discriminatory information with which to classify the scene[8,9,10,11]. Egan reached a potentially important conclusion that drying of leaves generally increases their depolarizing properties[11]. Curran used a photographic measurement technique to relate soil surface moisture to the proportion of polarized light in the scene response[12,13]. In an appendix Curran presented data showing a possible link between the percent linear polarization of a canopy and its roughness[12].

This paper discusses a model for the amount of linearly polarized light reflected by a plant canopy. 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 the smooth boundary separating two dielectrics[14]. The theory demonstrates that the linear polarization response of the plant canopy potentially contains information to help discriminate between crops. The theory relates the response to the agronomic condition of the crop--to factors such as growth stage, plant vigor, and leaf area index (LAI).

III. POLARIZATION MODEL

As may be verified with a polarizing filter and camera, the shiny leaves on a plant (Fig. 1) provide the basis for understanding how light is specularly reflected and polarized (Fig. 2) by a healthy, vigorous plant stand. The shiny leaves of many plants, including wheat, corn, and sorghum varieties, have a leaf skin or cuticle covered by a wax layer which specularly reflects light in accordance with the Fresnel equations. Because the light is specularly reflected, the equations show that it is polarized for all but two angles of incidence (0 and 90 degrees). Breece and Holmes found that the bidirectional light scattering characteristics of wheat, corn, and soybean leaves are intermediate to the scattering characteristics of diffuse and specular reflectors, indicating that the specular portion is an important part of the total leaf response[15].

From the laws of optics a leaf segment with a tendency toward specularity portends that a significant portion of the surface area is flat and similarly oriented. Indeed, there is electron micrograph evidence that the wax deposits on glossy leaves may form smooth films on the cuticle or platelets which lie flat on the surface[16,17]. Electron micrographs of a wheat leaf and a corn leaf both reveal irregular acicular wax structures distributed on a flat wax surface much like tree stumps on a flat, clear cut area or a child's jacks scattered on a table[18,19].

A. THEORY

The mathematical model for polarization of light from a wheat canopy is developed in two parts. First, the microscale situation, the polarization response and orientation requirements for a small specularly reflecting area Δa on a leaf (Fig. 3), is analyzed. Second, the microscale results are extended to the macroscale level as measured by a field spectrometer or satellite sensor (Fig. 4). The assumptions are:

1. There exist on the wax surface of each shiny leaf small flat areas, Δa, which specularly reflect light.

2. The wax layer is essentially clear and absorbs little light. This means that for the wax layer the complex index of refraction can be adequately approximated by its real component, a reasonable supposition for the visible spectral region where any light energy absorbed by the wax layer is then unavailable to the chloroplasts to promote photosynthesis. Limited evidence supports this assumption[20].

3. Specular light reflection occurs principally at the air-wax boundary. Comparatively negligible amounts of light are reflected specularly to an observer and from the boundaries between epidermal cell walls, cell membranes, and the various cutible layers. These boundaries have comparable indices of refraction and often appear rough in electron micrographs.

4. The magnitude of polarized light from

sources (moist soil, for example) other than sunlit leaves is insignificant.

Micro Scale Response. On the micro scale level, Fig. 3, sunlight is specularly reflected by one of the small leaf areas to an observer only if the area is properly oriented. The normal to the area must be in the plane and bisect the angle formed by two vectors, the illumination vector ($\vec{E}$) directed from the leaf area to the sun and the observation vector ($\vec{V}$) directed from the leaf area to the observer. In other words the area Δa must be oriented such that the angle of incidence, γ, equals the angle of reflectance and such that the vectors $\vec{E}$, $\vec{n}_a$ (the unit vector normal to Δa), and $\vec{V}$ are coplanar. Only then will specularly reflected light from Δa reach an observer. These conditions form the keystone of the polarization model and are satisfied by the equations,

$$\gamma=\cos^{-1}\frac{\vec{E}\cdot\vec{n}_a}{|\vec{E}|}=\cos^{-1}\frac{\vec{n}_a\cdot\vec{V}}{|\vec{V}|}=0.5\cos^{-1}\frac{\vec{E}\cdot\vec{V}}{|E||V|} \quad (1)$$

The solar irradiance incident on one small area, Δa, is a function of the angle of incidence. If the area Δa specularly reflects light to an observer, then the angle of incidence is uniquely determined

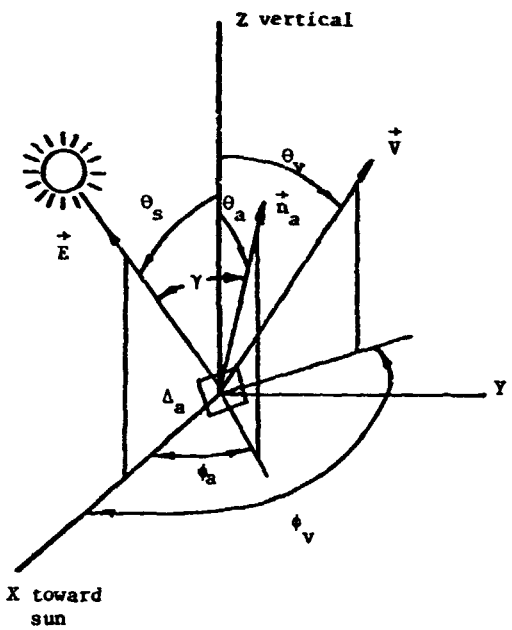

Figure 3. Coordinate System. A small leaf area Δa specularly reflects sunlight toward an observer, $\vec{V}$, if and only if the vectors $\vec{E}$, $\vec{n}_a$ and $\vec{V}$ are coplanar and the angles of incidence (γ) and reflectance are equal.

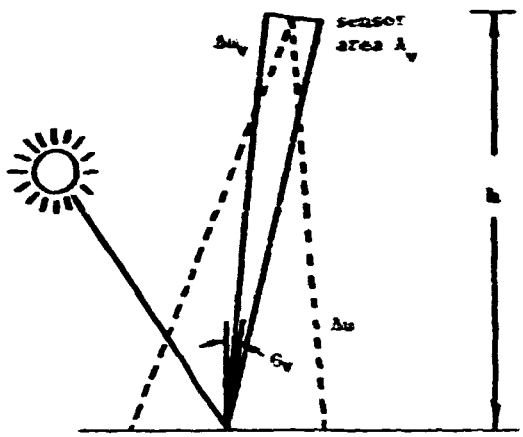

Figure 4. Canopy Response. A sensor measures the canopy response over a solid angle $\Delta\omega$.

by the angles (θ_s,θ_v,ϕ_v), as discussed above. For such an area the radiant flux incident on Δa is $P_s|\vec{E}|\cos\gamma$ where $\gamma=\gamma(\theta_s,\theta_v,\phi_v)$ and P_s is the probability of finding in a small volume an area Δa illuminated directly by the sun as opposed to being shaded by intervening foliage. The probability of finding in a small volume an observable area Δa is symbolized by P_v. In determining P_s and P_v, area Δa is assumed to be either illuminated or shaded, observable or not observable; adumbral effects are not considered[21].

The probabilities, P_s and P_v, are functions both of the (x,y,z) location of the leaf in the canopy and of directions of illumination and observations, respectively. The probabilities will be unity when only leaves are illuminated and observed. For example, P_s and P_v will approach unity for the topmost leaves of a dense, preheaded wheat canopy if the aggregation of these leaves forms a layer one leaf thick at the extreme top of the canopy essentially impenetrable to direct illumination. The probabilities will be less than unity for more typical canopies with some soil and/or non-leaf foliage illuminated and observed and some leaves not illuminated and/or not observed.

Even though the incident sunlight is not polarized, each small area, Δa, polarizes the specular portion of the reflected sunlight provided the angle of incidence is neither 0 or 90 degrees. If Δa is smooth, the magnitude of the light that is specularly reflected and polarized by Δa is described mathematically by the Fresnel equations and Stokes vector and depends only upon the angle of incidence, γ, and the index of refraction of both

the epicuticule wax layer and air[22].

For a smooth surface the portions of the specular reflectance with electric vector perpendicular, $\rho_{sp\perp}(\gamma)$, and parallel, $\rho_{sp\parallel}(\gamma)$ to the plane of incidence are given by the Fresnel equations[22]. The first component of the Stokes vector, S_I, provides the magnitude of light reflected by a surface[22]. The term S_I is the sum of the specularly (S_S) and diffusely (S_D) reflected light from the surface. The second component, S_Q, is the portion of S_I linearly polarized by the surface.

$$S_I = S_D + S_S \tag{2a}$$

$$S_S = (\rho_{sp\perp} + \rho_{sp\parallel})/2.0 \tag{2b}$$

$$S_Q = (\rho_{sp\perp} - \rho_{sp\parallel})/2.0 \tag{2c}$$

[dimensionless]

Most often Δa is not a perfectly smooth surface but instead supports small acicular structures. These structures diffusely scatter light which would otherwise be specularly reflected. To account for the reduced amount of light, specularly reflected by an area Δa which is not perfectly smooth, the Fresnel equations is modified by a factor, K. In general K [dimensionless] is a function of the angles $(\theta_s,\theta_v,\phi_v)$, wavelength, and side (top or bottom) lateral position and direction on the leaf. However, evidence suggests that for any one leaf the wax acicular structures in most cases are homogeneously and isotropically dispersed across the leaf surface[18]. It is assumed here that $K(\theta_s,\theta_v,\phi_v,\lambda)$ is identical for all leaves and is not a function of lateral position and direction on the leaf surface. The value of K varies between zero and one.

Define a probability density function $f_a(\theta,\phi)$ for leaves such that the probability that any one of the leaf areas Δa is oriented within a solid angle $\Delta\omega_a$ about (θ_a,ϕ_a) is $\Delta\omega_a f_a(\theta_a,\phi_a)$[dimensionless]. The units of $f_a = f_a(x,y,z,\theta,\phi)$ are $[sr^{-1}]$. Because the area Δa must be correctly oriented to reflect light to an observer, the Jacobian provides[23]

$$\Delta\omega_a = \Delta\omega_v/4\cos\gamma = A_v\cos^2\theta_v/4h^2\cos\gamma \tag{3}$$

Macro Scale Response. On the macro scale level, Fig. 4, the radiant flux due to specularly reflected sunlight received from leaves in the field of view of a sensor is found by summing the flux contributed by each leaf area Δa in each volume V_j in the field of view. For a Δa the radiant flux specularly reflected into a solid angle $\Delta\omega_v$ by a randomly selected area is the quadruple product of (1) the radiant flux incident on the area Δa, (2) the specular reflectance of Δa, (3) the probability that Δa is correctly oriented to specularly reflect light in a solid angle $\Delta\omega_v$ about direction (θ_v,ϕ_v), and (4) the probability that Δa is observed.

$$\Delta\Phi_{aS} = \overbrace{P_s|\vec{E}|}^{(1)}\overbrace{\Delta a\cos\gamma}^{(2)}\overbrace{KS_S\,\Delta\omega_a f_a(\theta_a,\phi_a)}^{(3)}\overbrace{P_v}^{(4)} \tag{4}$$

For a volume V_j, $\Phi_{V_jS} = \iint_{\text{all leaf area in } V_j} d\Phi_{aS}$ (5)

If the volume V_j is sufficiently small, then the probabilities P_s and P_v are essentially constants everywhere in V_j and will be denoted P_{sj} and P_{vj}. Letting A_j be the leaf area in volume V_j, f_{aj} be the probability density function of leaf area orientation in V_j, and using eq.(3) to substitute for $\Delta\omega_a$, eq.(5) becomes

$$\Phi_{V_j} = P_{sj}|\vec{E}|A_jKS_SA_v\cos^2\theta_v f_{aj}(\theta_a,\phi_a)P_{vj}/4h^2 \tag{6}$$

Summing the specular flux contributions of each volume V_j in the field of view of the sensor to find the specular portion of the flux measured, eq. 7, and the linearly polarized portion of Φ_S, eq. 8,

$$\Phi_S = |\vec{E}|\,KS_S\overbrace{\sum_{\substack{\text{all } V_j \text{ in}\\ \text{field of view}\\ j=1}} f_{aj}P_{sj}P_{v_j}A_j}^{\text{canopy dependent terms}}\overbrace{A_v\cos^2\theta_v/4h^2}^{\text{sensor dependent terms}} \tag{7}$$

(source dependent term)

$$\Phi_Q = |\vec{E}|\,KS_Q\sum_{\substack{\text{all } V_j \text{ in}\\ \text{field of view}\\ j=1}} f_{aj}P_{sj}P_{v_j}A_j\,A_v\cos^2\theta_v/4h^2 \tag{8}$$

The percent linear polarization is proportional to the linearly polarized flux divided by the total flux, the sum of the diffuse and specular fluxes.

$$100\%\Phi_Q/(\Phi_D + \Phi_S) \tag{9}$$

To illustrate the properties of the polarization model, the response of several canopies will be examined.

Example A: Sparse Wheat Canopy. If the properties of the canopy are constants for those layers containing leaves, that is, if $P_{sj}=P_{si}=P_s$, $P_{vj}=P_{vi}=P_v$, $A_j=A_i=A$, and $f_{aj}=f_{ai}=f_a$, $\forall V_j,V_i\in$ field of view

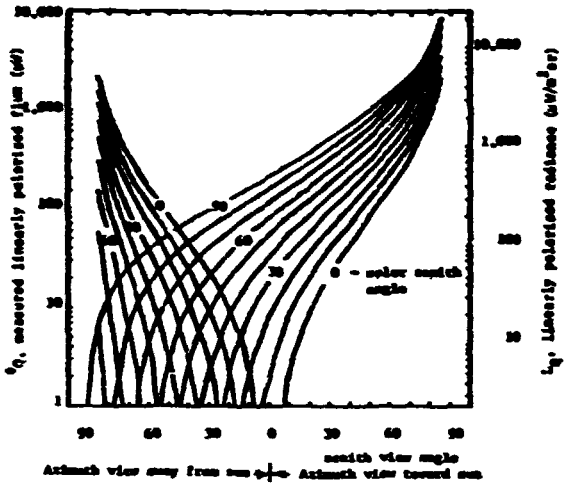

Figure 5. Preheaded Wheat Canopy Polarization Response. Prior to heading the response is zero at the anti-solar point, the "hot spot," and increases with increasing zenith view angle.

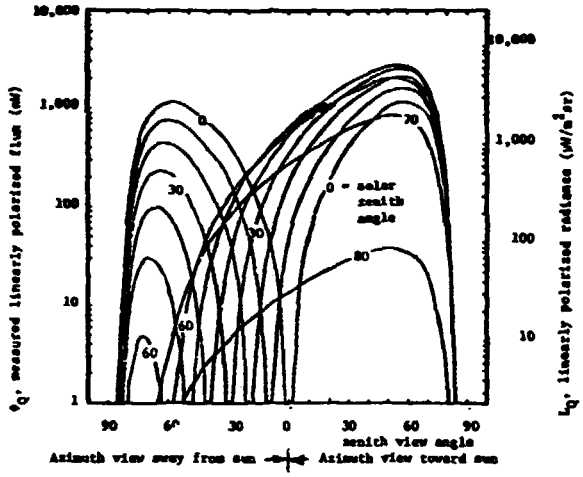

Figure 6. Headed Wheat Canopy Polarization Response. After heading the response remains zero at the anti-solar point, is maximum at intermediate zenith view angles, and approaches zero for near-horizontal view directions where heads and stems obstruct view of polarizing flag leaves.

s.t.$A_j \neq 0$, then

$$\sum_{j=1}^{\text{all } V_j \text{ in field of view}} P_{sj}P_{vj}A_j$$

$= P_sP_v$[total two sided leaf area in FOV]

$= P_sP_v[2LAI][h^2\Delta\omega/\cos^3\theta\omega_v]$

and

$$\phi_S=|\hat{E}|P_s(LAI)KS_Sf_aP_vA_v\Delta\omega/2\cos^3\theta_v \qquad (10a)$$

source canopy sensor

$$\phi_Q=|\hat{E}|P_s(LAI)KS_Qf_aP_v\Delta\omega A_v/2\cos\theta_v \qquad (10b)$$

where LAI is leaf area index. The linearly polarized portion of the total scene radiance is[24].

$$L_Q=\phi_Q/A_v\Delta\omega=|\hat{E}|P_sLAIKS_Qf_aP_v/2\cos\theta_v \qquad (11)$$

Example B: Preheaded, Dense Wheat Canopy. If the probability $P_{sj}P_{vj}\simeq 1$ for V_j in the topmost layer of the canopy and $P_{sj}P_{vj}\simeq 0$ for V_j in all lower layers, then the ϕ_S and ϕ_Q are proportional to the leaf area index only of the topmost layer. A winter wheat canopy measured just prior to heading might have the following characteristics: LAI = 2.0 for top layer containing flag leaves with a wax layer index of refraction = 1.5, f_a = uniform = 0.0796 sr^{-1}, K = 0.9, and $P_S = P_V = 1.0$ for top layer and $P_S = P_V = 0.0$ for all lower layers. The linearly polarized portion of the canopy radiance (eq. 11) and the linearly polarized flux measured by a sensor over such a canopy are shown in Fig. 5. The calculations are for a sensor with a field of view, $\Delta\omega$, of 15° = 0.216sr, entrance optics of area $0.002m^2$, and spectral band of 0.6-0.7μm (red wavelengths). The solar insolation is assumed to be $165.3W/m^2$ in the 0.6-0.7μm spectral band[25].

Example C: Headed, Dense Wheat Canopy. The polarization response of a wheat canopy is expected to change significantly during the heading growth stage (Fig. 2). This is because the probabilities P_S and P_V of a headed wheat canopy, unlike those of a preheaded canopy, are pronounced functions of sun angle and view angle. The product P_SP_V may be estimated for a hypothetical headed canopy with LAI = 2.0 by applying linear regression techniques to data for a canopy with LAI = 1.0 and scaling by a factor of 2.0[26].

$$P_SP_V=.232\exp(-1.17((1/\cos\theta_V)+(1/\cos\theta_S))) \qquad (12)$$

Equation 12, derived assuming P_S and P_V to be independent, provides erroneous estimates of P_SP_V at angles near the canopy hot spot direction where the probability P(leaf observation|leaf illumination) approaches unity. Fig. 6 shows the linear polarization response for a source-canopy-sensor with the parameters of Example B except P_SP_V given by equation (12).

Example D: Percent Polarization Response of Canopy. If the magnitude of the specular flux is either small or large compared to the diffuse flux, then the percent polarization (eq. 9) reduces to

$$\% \text{ polarization} \approx \begin{cases} 100\%\Phi_Q/\Phi_D, \Phi_D >> \Phi_S & (13a) \\ 100\%\Phi_Q/\Phi_S, \Phi_D << \Phi_S & (13b) \end{cases}$$

Both Φ_Q and Φ_S are proportional to the same agronomic factors. When $\Phi_D << \Phi_S$ (which might occasionally be true in the blue and red spectral regions), then there is no agronomic information in the term percent polarization because the agronomic factors in the numerator and denominator of eq. 13b cancel.

IV. DISCUSSION

The model shows the magnitude of the polarization response of a plant stand is related to the solar insolation and the characteristics of the canopy and the sensor. The response depends on the optical and geometric properties of the portion of the canopy in the instrument field of view.

The calculations show that a sensor would measure zero linearly polarized light at the anti-solar point, the canopy "hot-spot," where S_Q and the angle of incidence of the sunlight are both zero. The sensor would measure the maximum amount of polarized light in the solar azimuth direction (Fig. 5), provided the small areas Δa are randomly oriented in azimuth and zenith directions. Otherwise the direction of maximum polarization may be shifted, as might occur when a strong wind preferentially orients the flag leaves of wheat downwind.

The theory shows that when the approximation (eq. 13b) is valid--when the specular flux is much, much greater than the diffuse flux--the percent linear polarization is not directly related to the canopy agronomic properties. This might occur in the chlorophyll absorption region in the red portion of the spectrum viewing at large zenith angles toward the sun azimuth angle. However, even though the percent linear polarization in certain circumstances may contain limited information related to canopy agronomic factors, the magnitude (eq. 8) of the linearly polarized flux is always directly related to the canopy agronomic properties. Thus, the model provides a theoretical basis for the same, but empirically based result noticed by Egan[9].

The agronomic variables LAI, f_a, K, S_Q, P_S, and P_V in the equations (eqs. 8 and 10b) are functions of one or more environmental and/or physiological variables. The leaf area index (LAI) is a function of many variables including species and cultivar, weather, and growth stage. The probability density function $f_a(\theta_a, \phi_a)$ for the orientation of the leaf areas Δa is a function of wind strength and direction, catastrophes (such as hail damage), crop vigor (moisture stress causes corn leaves to roll, cotton leaves to droop), and growth stage (the shapes of healthy green leaves and senescent leaves are not the same). The optical properties of the leaves, K, S_Q, and S_I, are functions of species and almost certainly cultivar, disease (plant pathogens often alter or destroy the wax layer), pubescence (the hairs scatter light which would otherwise be specularly reflected), material on the leaves (dust, pollen, water droplets), and wavelength (the Fresnel equations are functions of the cuticle wax index of refraction, which changes in regular fashion with wavelength). The terms S_Q and S_S are functions of the angle of incidence (view and illumination direction) of the sunlight. The geometrical properties of the canopy, P_S and P_V, are functions of the angles of illumination and observation (lower leaves have lower probabilities of being illuminated and observed at large sun and view zenith angles) and growth stage (wheat heads partially block illumination and observation of flag leaves; the projected area of leaves changes with senescence). Several of these functional relationships will be discussed further in the following paragraphs.

Light polarized by a moist or wet soil surface is a part of the canopy polarization response not considered in the theory. Visual observations suggest that except for wet soil surfaces, the amount of light polarized by the soil is insignificant compared to the amount of light polarized by foliage. Neglecting emergent and sparse canopies, the soil generally has a very low probability of being both illuminated and observed. Thus, the theory presented predicts the polarization response of canopies on dry soils and/or with sufficient foliage to obscure the soil.

Sunlight tends to be specularly reflected and polarized by leaves in the upper portion of plant stands. The probability that a leaf is both visible and directly illuminated by sunlight is often a pronounced function of the (x,y,z) location of the leaf in the stand and of the view and illumination directions. The probability tends to decrease rapidly with increasing depth into the canopy. This means that leaves in the lower portions

of a plant stand will little affect the canopy polarization response. Thus, lower leaf senescence or a disease condition localized to the lower leaves may not be detectable using polarization measurements.

The probability density function, $f_a(\theta_a,\phi_a)$, for the orientation of the leaf areas, Δa, can be calculated (from eq. 10b) for the population of observable, specularly reflecting leaves using polarization measurements sampled from the hemisphere of all possible canopy view directions. Such a density function is needed as input data to certain canopy radiation models which are used to examine the utility of and information in canopy reflectance measurements[27]. To obtain the polarization data needed to calculate f_a, Horvath proposed a field apparatus consisting of a linearly polarized light source co-located with a sensor with a polarization analyzer[28]. Due to the inherent randomness of the leaf structure, the diffuse portion of the reflected light will tend not to be polarized[11]. The specular portion of the reflected light will be polarized, not because of reflection at the leaf cuticle wax layer (0° angle of incidence) but instead because the light source is polarized. To compute f_a the canopy polarization response is measured with the analyzer oriented in two directions, parallel and perpendicular to the polarization direction of the light source beam. It is easily shown that the specularly reflected flux (eq. 10a) is the difference of these two measurements; hence, in a particular direction

$$f_a = |\vec{E}|LAI\ KS_S P_s P_v \Delta\omega A_v / 2\Phi_S \cos\theta_v$$

where $S_S = ((n-1)/(n+1))^2$ for normal incidence, and $P_s=P_v$. A practical limitation to the approach exists. In general values for leaf area index (LAI), the factor K, and the index of refraction (n), are not known; however, properly normalizing to unity the integral with (θ_v,ϕ_v) of the initial estimate of f_a obviates the need to know these terms. But more importantly the need to know or estimate P_s and P_v, usually unknown functions of view directions, cannot be circumvented if f_a is to be calculated. The term $P_s P_v f_a$ includes all the canopy dependent variation due to view angle (assuming the factor K is a constant) and is always calculable.

Depending on its direction and strength, the wind is capable of reorienting the leaves of a canopy and thereby changing the probability density function of leaf area, f_a. The resultant variations from day to day in the polarization response of a field will tend to complicate interpretation of polarization data because these variations represent noise (unless, of course, the probability density function of the orientation of the leaves is to be calculated for each day). The size of these day to day variations, if sufficiently large, might preclude a naive analysis which neglects wind effects; conceivably, wind induced variations in f_a might render an agronomic interpretation of polarization data impossible. There remains the hope, however, that for data taken at one time the wind will affect similarly all the fields in a region containing a particular crop species and cultivar. For such data comparisons between fields of a specific crop variety might remain valid. Therefore, an important question which should be addressed empirically is the following: How uniformly does wind affect polarization data acquired over a region?

Visual observations suggest that blue skylight incident on the canopy affects minimally the magnitude of the canopy polarization response. By the same process discussed in the theory for sunlight, the shiny leaves of a canopy polarize the specularly reflected skylight, a spectrally varying light source already polarized according to observer view direction. The magnitude of the skylight and its effect on the canopy polarization response is greatest in the blue spectral region and decreases into the near infrared. Atmospheric haze, which decreases the solar insolation on leaves, noticeably decreases the specular and polarized light from leaves.

The efficacy and feasibility of a satellite sensor measuring the linear polarization of a scene through the earth's atmosphere has not been considered. Sensor design must consider the path radiance of the atmosphere, a source of linearly polarized light potentially capable of altering or masking the amount of linearly polarized light received from the scene. Even if the polarized portion of the path radiance is excluded, analysis of field spectral radiometer data suggests that for a satellite polarization sensor the signal flux must be increased (the spectral/spatial resolution of a Landsat-type satellite must be degraded probably by a factor greater than 10:1) and/or noise power decreased to obtain a signal to noise ratio approximately equivalent to that of Landsat in the red spectral channel. Including atmospheric effects in the analysis would potentially indicate a practical value of the spatial/spectral resolution of a satellite sensor.

The information in canopy polarization data, when obtained from satellite sensors,

(a) (b) (c)

Figure 7. Polarization Response with Heading. The three photographs, taken at one week intervals before and after heading, demonstrate that the amount of specularly reflected- and therefore polarized-sunlight decreases significantly with heading.

probably will be used in conjunction with other remotely sensed data and will be extracted by analysis of frequent, synoptic data sets, by using the temporal and spatial information to make relative comparisons between the fields in the data for one date and between the dates for one field. One polarization measurement of one field for one date probably will have little value unless it is compared to polarization data for that field and other fields for that date and other dates. This is because it is unrealistic from the model to expect that canopy polarization data will be calibrated in an absolute sense to discriminate a particular crop or to correlate uniquely to a particular agronomic variable. Frequent, synoptic polarization data from a satellite sensor potentially aid in assessing crop vigor and growth stage and in determining areas of hail damage and pestilence, all potentially possible from comparisons between field and across dates. Perhaps daily satellite coverage is feasible using a low spatial and spectral resolution sensor in a geosynchronous orbit.

The canopy polarization response described by the model is a function of wavelength only because the index of refraction of the cuticle wax layer is a function of wavelength. From the physics of the optical properties of materials it is expected that the index of refraction of the wax layer will gradually and monotonically increase with decreasing visible wavelength, displaying no perturbations or "fine structure" with wavelength[14]. However, the model indicates the percent linear polarization of a healthy green canopy will be large in the blue and red spectral regions, small in the green, and even smaller in the near infrared region away from any absorption bands. This is because the total canopy flux, the normalization factor used when computing percent polarization, exhibits a green vegetation response[29].

From the model there appears little need to measure the canopy spectral polarization response with high wavelength resolution in the visible spectral region; a polarization sensor covering the entire visible region or a large portion of it might suffice. Conversely, in the infrared spectral region the cuticle wax layer may absorb in narrow spectral regions defined by the structural properties of the constituent waxes of the layer, by the resonant frequencies of the translational and rotational vibration modes of molecules of the layer[14]. If absorption bands exist, high resolution spectral polarization data may possibly provide information concerning the properties of the cuticle wax layer, properties relatable to crop species and light regime[18].

The linear polarization model may be extended to include the elliptical polarization response of the canopy. Evidence exists that the cuticle wax of some species is birefringent and therefore potentially capable of elliptically polarizing specularly reflected light[18]. However, this evidence does not suggest that the structure of the wax layer is sufficiently organized to elliptically polarize light specularly reflected from a significant amount of leaf area. Egan argues that the amount of elliptically polarized light from a vegetation scene should be negligible because of the inherent randomness of the properties of the vegetation[9]

The connection between leaf polarization measurements and leaf moisture content, noted by Egan, is supported by a morphological model for the structural changes which occur in a leaf undergoing

dehydration[11]. When the leaf water content and leaf thickness decrease and the leaf cells dehydrate and collapse, the surface roughness of the wax layer increases. The leaf surface appears rough in thin sections of senescent leaves and of leaves under moisture stress[28]. As the surface roughness increases, the specular portion of the light reflected by the leaf decreases because there are fewer areas Δa which are similarly oriented. The amount of linearly polarized light reflected by the canopy decreases in company with the decrease of specularly reflected light. These arguments suggest that the canopy polarization response should decrease with decreasing leaf water content in the canopy and therefore serve as an indicator of canopy moisture stress. Visual evidence supports this hypothesis. Leaves under moisture stress often appear less shiny than fully turgid leaves. Dry, senescent leaves often have a matte surface finish.

Detection of the date of heading of a wheat canopy (Fig. 2), information which is needed for use with phenologically based models to predict the ultimate grain yield of the crop, might be feasible using satellite polarization measurements (Fig. 7). The eventual weight of grain produced by each wheat plant is largely determined by the condition of the flag leaf, its size and vigor, and by the weather regime endured by the plant following heading when the grain head begins to fill[30]. Knowledge of the date of heading permits a better estimate of the post-heading weather for the crop. Prior to heading the topmost foliage on the wheat plant is the flag leaf, easily the most visible and illuminated canopy component (Fig. 2). Following heading, wheat heads are the topmost foliage and partially obscure the flag leaves to both sunlight and observation, changing the values of both P_s and P_v. Figures 5 and 6 show that the magnitude of the polarized light, which depends directly upon the specular reflections from flag leaves, will decrease by a factor of 60 for θ_s=30 and θ_v=0 for the two hypothetical canopies during heading as the leaves are increasingly obscured to both illumination and observation. The obscuration of the flag leaves is enhanced at off nadir observation angles directed toward the solar azimuth (Fig. 6). Potentially both the condition of the flag leaves and the date of heading of a crop might be monitored using polarization measurements obtained from a satellite sensor with both on and off nadir viewing capability. Such a view capability has been proposed for the MRS sensor.

Applicability of the polarization model should extend to many species because shiny leaves which specularly reflect sunlight are ubiquitous, unconfined by geography or climate. Other plants besides wheat, sorghum, and corn with specularly reflecting leaves include coffee, sudan grass, banana, orange, sugarcane, and many forest species. Schieferstein and Loomis found epicuticular wax deposits on about half of the plant species they tested[19]. However, the mere presence of a cuticle wax layer does not guarantee that a leaf will specularly reflect and polarize a significant portion of the incident light; the leaf must also appear shiny. Fibrillar light scattering significantly diminishes the polarization response of pubescent soybean leaves. And the surface of the wax layer of some species is insufficiently smooth to specularly reflect light[18].

V. CONCLUSIONS

This paper discusses a model for the amount of linearly polarized light reflected by the shiny leaves of such crops as wheat, corn, and sorghum, each a grain of major economic importance to the world. 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 the smooth boundary separating two dielectrics.

The theory demonstrates that, potentially, measurements of the linearly polarized light from a crop canopy may be used as an additional feature to discriminate between crops such as wheat and barley, two crops so spectrally similar that they are misclassified with unacceptable frequency. Examination of the model suggests that, potentially, satellite polarization measurements may be used to monitor crop development stage, leaf water content, leaf area index, hail damage, and certain plant diseases. Such information is needed for use with models which predict crop grain yield.

The model adds to our understanding of the potential information content of scene polarization measurements. The information content of these measurements has not been extensively investigated and needs to be understood to evaluate the potential usefulness of the proposed polarization sensor for the satellite borne Multispectral Resource Sampler. The efficacy of a satellite sensor measuring the linear polarization of a scene through the atmosphere remains to be determined.

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