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UNE METHODE DE POLARISATION POUR DETERMINER LES PROPRIETES DE LA LUMIERE (MIROITANTE ET DIFFUSEE) REFLETEE PAR UNE FEUILLE OU UNE PLANTE SUR PIED

LIGHT POLARIZATION MEASUREMENTS: A METHOD TO DETERMINE THE SPECULAR AND DIFFUSE LIGHT-SCATTERING PROPERTIES OF BOTH LEAVES AND PLANT CANOPIES

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RESUME

La lumière du soleil miroitée par des plantes sur pied telles que le maïs, le sorgho et le blé est souvent tellement brillante que ces cultures semblent être blanches plutôt que vertes quand nous les observons obliquement. Contrairement à la lumière diffuse de la feuille, la lumiere miroitante n'entre pas dans la feuille. La lumière miroitante semble être blanche parce qu'elle n'entre pas dans la feuille où le pigment cellulaire et le cytoplasme l'absorberaient. La cuticlue de la feuille donne naissance à la lumière miroitante. La cuticule est comme une empreinte digitale qui sert à identifier l'espèce.

L'état de développement et le degré d'humidité de la feuille, ainsi que la température environnante, modifient les propriétés de la cuticule. Tous ces éléments signifient que la partie miroitante du reflet de la plante sur pied est une nouvelle source importante de renseignements pour identifier l'espèce à laquelle la plante appartient et pour analyser sa vigueur.

Cet exposé présente les données des propriétés de la lumière miroitante, diffusée et polarisée de deux plantations de blé evaluées dans les champs. Les résultats montrent que les plantations miroitent et polarisent la lumière dans toutes les directions du regard. (Traduit de l'anglais avec la collaboration de M. Bermondy.)

SUMMARY

The sunlight specularly reflected by such crops as corn, sorghum, and wheat is often so bright that these crops appear white instead of green when viewed obliquely. Unlike the light diffusely reflected by the leaf, the specularly reflected light never enters the leaf. The light appears white because it has not entered the leaf to interact with the cell pigments, walls, or water. The specular reflectance originates at the leaf cuticle, which has been found to be like a "fingerprint" for identifying species. The cuticle properties change with plant development stage, water status, and possibly temperature regime. All of this suggests that the specular portion of the canopy reflectance is an important new source of information about crop species and status. Such information is needed for monitoring crop production on a global basis and potentially can be obtained using remote sensing techniques.

This paper presents the specular, polarized, and diffuse light-scattering properties of wheat at two development stages. The results provide increased understanding of these light scattering properties and offer a testbed for developing models of the radiation transfer process in plant canopies.

1. BACKGROUND

The reflectance factor (R) of a plant canopy is determined in part by the light scattering properties of the constituent foliage, principally leaves for these wheat data (1). As an optical system, the leaf, Figure 1, contains a matrix of cells covered by a protective surface layer, the cuticle (2,3). Light driving the photosynthetic process is absorbed by pigments located in cells in the matrix. Using a ray tracing technique, Kumar and Silva proposed that the unabsorbed light in the central region of the leaf is multiply scattered by refraction by the surfaces of cellular components (4). It seems reasonable to expect that upon leaving the leaf this unabsorbed light from the bulk of the leaf is randomly directed as if the leaf surface were diffuse.

Electron micrographs show that air-cuticle surfaces are never optically smooth but instead exhibit many microscale architectures (3,5,6). The cuticle, is multi-layered and sometimes includes a surface wax layer. On glossy leaves, the wax deposits may form smooth films on the cuticle or platelets which lie flat on the surface. 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 or military tank traps sparsely distributed on the defended tidal flat of an ocean beach (3).

From examination of the electron micrographs, four optical phenomena, Figure 1, appear to be potentially important to understanding light scattering at the air-cuticle surface. First, light will be specularly reflected from optically smooth and similarly oriented portions of the cuticle. Second, specularly reflected light from multilayer cuticles will interfere, although in nature the lack of obvious rainbows of color provided by interference of specular reflections from leaves suggests this type of interference phenomena is unimportant. Third and fourth, the acicular structures on the cuticle surface scatter light according to the criteria in the Rayleigh and Mie theories. The specularly and Rayleigh scattered light is linearly polarized.

The information content of the polarized portion of the light scattered by leaves, canopies, and soils has been examined. Using data obtained in the laboratory and with an aircraft, Egan (7), Egan and Hallock (8), and Egan, et al. (9) found evidence that the degree of linear polarization of the light from a scene measured by an aircraft-borne sensor provides additional discriminatory information with which to classify the scene for purposes of remote sensing. Egan reached a potentially important conclusion that drying of leaves generally increases their depolarizing properties (7). Curran used a photographic measurement technique to relate soil surface moisture to the proportion of polarized light in the scene response (10,11).

2. MATERIALS AND METHODS

Data were acquired on wheat (Triticum aestivum L.) on 19 June and 17 July during 1976 at Williston, North Dakota, USA (Lat. 48 8', Long. 103 44') in support of the Large Area Crop Inventory Experiment (LACIE) (12). On each date agronomic measurements were made to characterize the condition of the wheat canopy (Table I). Meteorologic data (Table I) were acquired at the North Dakota Agricultural Experiment Station at Williston, located near the test sites.

More than 200 spectra (visible wavelength, 0.46 to 0.72 um) were acquired using an Exotech model 20C spectroradiometer (Exotech, Inc., Gaithersburg, Maryland) positioned 6 m above the soil (13). Spectral data and a photograph of the instrument field of view were taken in each of 33 view directions, eight azimuths (the eight points of the compass) at four zenith angles (15, 30, 45 and 60) plus nadir. A polarization analyzer, a sheet of polarizing film (Edmund Scientific) mounted in a rotateable bracket, was attached to the spectroradiometer at the entrance port. In each view direction, two spectra were acquired, one with the polarization analyzer oriented for maximum detector signal amplitude and the other with the analyzer oriented for minimum signal. On 19 June data were acquired from -2h to +2h from solar noon. On 17 July data were acquired from -2h to -0.3h before solar noon and from +1h to +2h after solar noon.

Analysis of the polarizing and specular reflecting properties of the canopy was performed on data at 13 wavelengths selected at 0.02 um intervals from 0.48 to 0.72 um. At a particular wavelength the spectral resolution of the data is better than 1.0% of that wavelength. At each wavelength selected for analysis, the degree of linear polarization was computed as illustrated in Figure 2. For a view direction the two reflectance factors representing the maximum and minimum amount of light transmitted by the polarization analyzer, R_{MAX} and R_{MIN} (Figure 2a), were combined to obtain the following: $R = (R_{MAX} + R_{MIN})/2.0$; $R_Q = (R_{MAX} - R_{MIN})/2.0$; Degree of linear polarization = $100\% \ R_Q/R$. The term R, measured in a particular view direction, equals the reflectance factor of the canopy measured in the same view direction but without the polarization analyzer. The term R_Q, measured in a particular view direction, is the ratio (percent) of the linearly polarized radiance of the canopy divided by the radiance of a perfectly white, perfectly diffuse calibration panel. The degree of linear polarization, measured in a particular view direction, is the ratio (percent) of the linearly polarized radiance of the canopy divided by the radiance of the canopy.

The amount of light specularly reflected by the wheat canopies, Figure 2, was calculated using the Fresnel equations, knowing the angle of incidence of the sunlight on the leaf, and assuming the index of refraction of the leaf cuticle to be 1.5. The angle of incidence, gamma, is given by $\gamma = 0.5 \arccos(\sin\theta_r \cos(\phi_i - \phi_r)\sin\theta_i + \cos\theta_i \cos\theta_r)$ where the angles θ_i, ϕ_i, θ_r, ϕ_r are the zenith and azimuth, sun ($\hat{i}$) and view ($\hat{r}$) directions. The azimuth angles in this equation are measured from north. Gamma is the angle of incidence of a light ray upon a small leaf area correctly oriented to specularly reflect the ray to the spectroradiometer provided the leaf is a specular reflector. Twice gamma is the angle between incident and reflected rays; thus, gamma is derived from the equation $\cos 2\gamma = (\hat{i} \cdot \hat{r})$ Angles of incidence for an illumination zenith angle of 30° are plotted as a function of view direction, Figure 3. For example, the angle of incidence is zero in the antisolar direction, the hot spot, for view angles (zenith, azimuth) = $(30^\circ, 180^\circ)$ and 40° at $(50^\circ, 0^\circ)$. The value $n = 1.5$ is within the range of possible values for the index of refraction of the cuticle of the wheat. The specular portion of the reflectance factor, R_S, is the product of the polarized fraction of the reflectance factor, R_Q, times the ratio of the first and second components of the Stokes Vector, Figure 4.

The diffuse portion of the reflectance factor, Figure 2, is the difference between the canopy reflectance factor, R, and its specular fraction R_S. This again assumes that the amount of specularly reflected skylight is negligible compared to the amount of specularly, reflected sunlight from the canopy. The degree of specularity and the degree of diffuseness, Figure 2, are defined similarly to the degree of polarization, as R_S and R_D normalized by R.

3. RESULTS AND DISCUSSION

A random sample of the total number of spectra of R and R_Q are plotted as a function of wavelength and view direction for June 19, Figures 5 and 6. The results, Figure 5, show that R has a characteristic green vegetation shape with pigment absorption bands in blue ($<0.50\mu$m) and red (0.66μm) wavelength regions. The R is generally largest for data acquired in the 180 ° azimuth view direction, the anti-solar direction and smallest for data 0 ° azimuth view direction. The results, Figure 6, show that unlike R, R_Q does not display the characteristic green vegetation shape--there are no apparent pigment absorption bands (14). Generally, R_Q is largest and smallest in the 0 ° and 180 ° azimuth view directions, respectively.

The angles of the polarization analyzer on the radiometer to measure the minimum and maximum radiances was computed from the view and illumination directions. The minimum radiance is measured when the axis of the analyzer is in the plane of incidence. The angle between the plane of incidence and local vertical $\hat{v}$, both projected on the FOV of the radiometer, is given by the equation

$$\beta = \arccos\left\{\frac{\cos\theta_i\sin\theta_r + \cos(\phi_i - \phi_r)\sin\theta_i\cos\theta_r}{\left[\sin^2(\phi_i - \phi_r)\sin^2\theta_i + (\cos\theta_i\sin\theta_r + \cos(\phi_i - \phi_r)\sin\theta_i\cos\theta_r)^2\right]^{1/2}}\right\}$$

As shown in Figure 7 for an illumination zenith angle of 30 °, the angle β is a function of view direction for example, for a view direction of 50 ° zenith angle and 135 ° aximuth angle from the solar azimuth, the angle β is 40 °. The comparison between the predicted and actual β is presented for both dates, Figure 8. The reason for the one anomously located point on the plot of June 19 is unclear.

The result, Figure 8, that the angle of the polarization analyzer on the radiometer is predicted by the angle β, provides additional, independent evidence that the angle of incidence, defined in the plane of incidence, is a key variable for understanding the optical scattering properties of the canopy. These results, Figure 8, support the polarization model (15) which predicts that the single variable, angle of incidence, explains much of the variation of the amount of linear polarized light with not only view angles but also sun angles.

While Figure 1 shows there are three potential sources of illumination of the wheat canopies, the results, Figure 8, demonstrate that sunlight is the principle one. This is because an angle of incidence is defined for a relatively colimated source such as the sun and is not defined for an uncolimated, extended source such as the blue sky. (While clouds are a potential illumination source, none were present during data acquisition.) If skylight or light from clouds were an important source of illumination for polarization purposes, then β, the predicted angle of the polarization analyzer, would not explain the variation in the data (Figure 8). And the scatter in the data in Figure 8 would be significantly greater.

Of the four scattering processes, Figure 1, only specular reflection and Rayleigh scattering polarize light, yet specular reflection is the primary process polarizing the light reflected by the two wheat canopies, a conclusion supported by several pieces of evidence. First, if the Rayleigh scattered light were a significant fraction of the total reflected light, then the foliage surface would reflect significant amounts of blue light and possibly even have a pronounced bluish appearance; it does not. In fact, measurements of the normal-incidence hemispherical reflectance show that a wheat leaf generally scatters approximately equal amounts of red and blue light and significantly more green than blue (14). Electron micrographs show the epicuticular waxes of species such as apple and cabbage which often do have pronounced blue surface blooms tend to form a jungle of randomly directed rods. Rods are a feature of minor importance of the surface waxes of wheat.

Second, the angular properties of the scattered polarized light support the primacy of specular reflection as the polarizing process. Specular reflections originate at those facets on the rolling topography of the veined wheat leaf which are sufficiently smooth and oriented to redirect incident light to an observer. It is easy to observe that the reflection from a typical, healthy gently curved flag leaf (the topmost leaf on a plant) is polarized. If Rayleigh scattered light were the dominant source of polarized light, then the sunlight reflected by the entire sunlit portion of the leaf would be polarized; it is not. Only the light reflected by a small correctly oriented area, a fraction of the total sunlit leaf, is polarized. As the leaf curve shape is manipulated by hand, the small area moves appropriately about the surface.

All this indicates that specular reflection and not Rayleigh scattering is the dominant polarizing process on the leaf surface. As described in the Materials and Methods section, the Fresnel equations may be used to calculate from the polarization data the specular scattering properties of the canopy.

The results, Figure 2, show that the specular portion of the reflectance factor R_S was 0.9 percent in the blue (0.48 μm) and generally decreased with increasing wavelength. For these results, R_S is a scaled version of R_Q because the ratio 1.18 is independent of wavelength. This is because the index refraction of the cuticle of the leaf is unknown and assumed to be 1.5 at all wavelengths. More typically, the ratio and R_S should be larger in the blue wavelength region than the red. The results, Figure 2, show that the diffuse portion of the reflectance factor R_D was 1.8 percent in the blue (0.48 μm) and has a wavelength dependence typical of green vegetation. The results show that the degree of specularity is slightly more than 30 percent at 0.48 μm and has a curve shape similar to the degree of polarization. Similarly, Figure 2 shows the degree of diffuseness is almost 70 percent at 0.48 μm with a curve shape like R.

The results, Figure 2, demonstrate that, just as for R_Q, R_S represents light reflected at the first surface it encounters. Pigment absorption bands do not dominate the spectra. This light never enters the bulk of the leaf to interact with cellular pigments. Conversely, R_D represents light which has entered the bulk of the leaf to interact with cellular pigments--the pigment absorption bands are more pronounced for R_D than R. The large values of the degree of specularity demonstrate that the specular fraction is a significant part of the total reflected light.

The diffuse and specular fractions of the reflectance factor, Figure 9, of the canopies on June 19 and July 17 are plotted for a wavelength of 0.66 μm and a 60 ° zenith view angle as a function of the azimuth view angle. On both dates the specular fraction was minimum for view directions toward the solar azimuth and maximum for view directions toward the anti-solar azimuth. The decreased specular fraction after heading for view directions toward the sun is particularly striking. For example, the specular portion near zero azimuth view angle is 0.7% on June 19 and 0.3% on July 17. The reflectance factor on June 19, approximately 3.5%, showed little variation with azimuth view angle.

The results, Figure 9, that the specular fraction of the reflectance factor generally decreases with increasing angle of incidence (i.e. for view directions more toward the solar azimuth, Figure 3) are not evident from the visual observation that unheaded wheat canopies appear white instead of green when viewed obliquely toward the solar azimuth. When examining these results, two factors must be considered. First, a zenith view angle of 60 ° is certainly less than the angle (approximately 80 °) where the canopy begins to appear more white than green. This suggests that if additional data had been acquired before heading at larger zenith view angles (80 °) toward the solar azimuth, the values of R_S would tend to increase for increasing angles of incidence and view directions toward the solar azimuth. Presumably, the increase would be greatest for the combination of large zenith view angles and large angles of incidence where the specular reflectance of each facet may approach 1.0. After the wheat heads rise to block the view of the specularly reflecting flag leaves at large zenith view angles, presumably the R_S would not exhibit the same hypothesized increase with increase in the angle of incidence. Instead, these variables presumably would decrease with angle of incidence.

The second and primary factor to consider for understanding the decrease of R_S with increase in angle of incidence, Figure 9 is the amount of sunlit leaf area in the field of view of the radiometer. For an angle of incidence of zero, the hot spot, there is no shaded foliage--it's all sunlit. In contrast in the solar azimuth direction, the shaded back side of the foliage forms a significant fraction of the FOV. For angles of incidence less than the Brewster angle, the R_S should depend to a first approximation upon the proportion of sunlit to shaded leaves in the field of view by the following argument: For the preheaded canopy, the flag leaves are the topmost feature of the canopy and everywhere visible. To a first approximation, the angle distribution of the normals to the specularly reflecting facets on the leaves is as that of the area on a sphere. Like specularly reflecting spherical marbles on a table, specularly reflecting leaves are evident regardless of view direction. From probability, the greater the proportion of sunlit leaf area in the instrument FOV, the larger will be the number of facets specularly reflecting to the instrument. To a first approximation, the specular reflectance of each facet is constant for angles of incidence less than 45 ° . (With $n=1.5$ a smooth dielectric surface specularly reflects 4% at 0 angle of incidence and 5% at 45 ° .) Thus, the decrease in the values of R_S with increasing angle of incidence seems reasonable for both preheaded and headed canopies--considering that the data are limited to angles of incidence less than 51 ° .

Thus, the results, Figure 9, are consistent with the thesis that the specular portion of the reflectance factor of the canopy at angles of incidence less than the Brewster angle depends in large part on the proportion of sunlit to shaded leaves in a particular view direction. A preheaded wheat canopy appears white instead of green in the solar azimuth direction at large zenith view angles due probably less to the large amount of specularly reflected light as to the presumably small proportion of the reflectance factor that represents diffusely reflected light--and is therefore green. Conversely, in the direction of the hot spot, the combination of the lack of shadows and the sunlit, diffusely reflecting foliage may diminish the apparent importance of the specular portion of the reflectance factor. With or without a specular reflection at near normal incidence, the hot-spot, wheat leaves appear green provided the eye is not saturated. This is probably because the diffuse and specular components of the reflectance factor are of a similar order of magnitude near the hot spot, unlike the situation at large zenith view angles toward the solar azimuth where the specular fraction is much much larger than the diffuse.

Of all the spectra measured on June 19, more than half, 58%, had a degree of specularity at 0.66 μm between 20 and 30% -- the specularly reflected light was 20 to 30% of the total reflected light; 24% of the spectra were in the range 10-20%; 8% in the range 0-10%, and 5% were in each of the intervals 30-40% and 40-50%. These results further demonstrate that the specularly reflected light is a significant part of the total light reflected by the wheat canopy.

4. CONCLUSIONS

The polarized portion of the light scattered by the wheat canopies is due to sunlight specularly reflected by the surfaces of the foliage, primarily leaves (rather than stems or heads). This specularly reflected light never enters the leaf to interact with cell pigments. The amount of reflected light polarized by Rayleigh scattering from small particles on the leaf and/or in the sky is insignificant for these canopies. This means that the angle of the polarization analyzer is predictable for measurement of these specularly reflecting wheat canopies under a clear sky. 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. The amount of light specularly reflected and polarized and measured at an oblique view angle toward the solar azimuth direction is strikingly less for the headed canopy compared to the preheaded canopy. This suggests that measurements of the polarization of the canopy reflectance may be used to remotely sense the advent of heading in wheat.

The reflectance factor of the wheat can be partitioned into components due to specularly and diffusely reflected light. For these canopies the magnitude of the specularly reflected light is small compared to that of a glass surface. Yet 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. If they "correctly" predict the canopy reflectance factor, $R(\theta_i,\phi_i;\theta_r,\phi_r)$ then they are incorrect. Such models will inevitably fail for some combination of angles (view/illumination), species, development stage, or other variable, because they do not model the actual cause-effect relationship.

The specular reflection process has been shown to be a key aspect of radiation transfer by two plant canopies. Polarization measurements have been demonstrated as the tool for determining the specular and diffuse portions of the canopy radiance. Additional ground based polarization measurements will aid development of improved models for the transfer of radiation in plant canopies. The feasibility of a satellite borne sensor to obtain the information in the specular portion of the canopy radiance has not been addressed.

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 region is a possibility. Second, because the angle of the polarization analyzer can be set prior to data acquisition and does not depend on the data but solely on view/illumination directions, designs incorporating only two measurements (maximum and minimum radiance) -- rather than three or more -- appear feasible.

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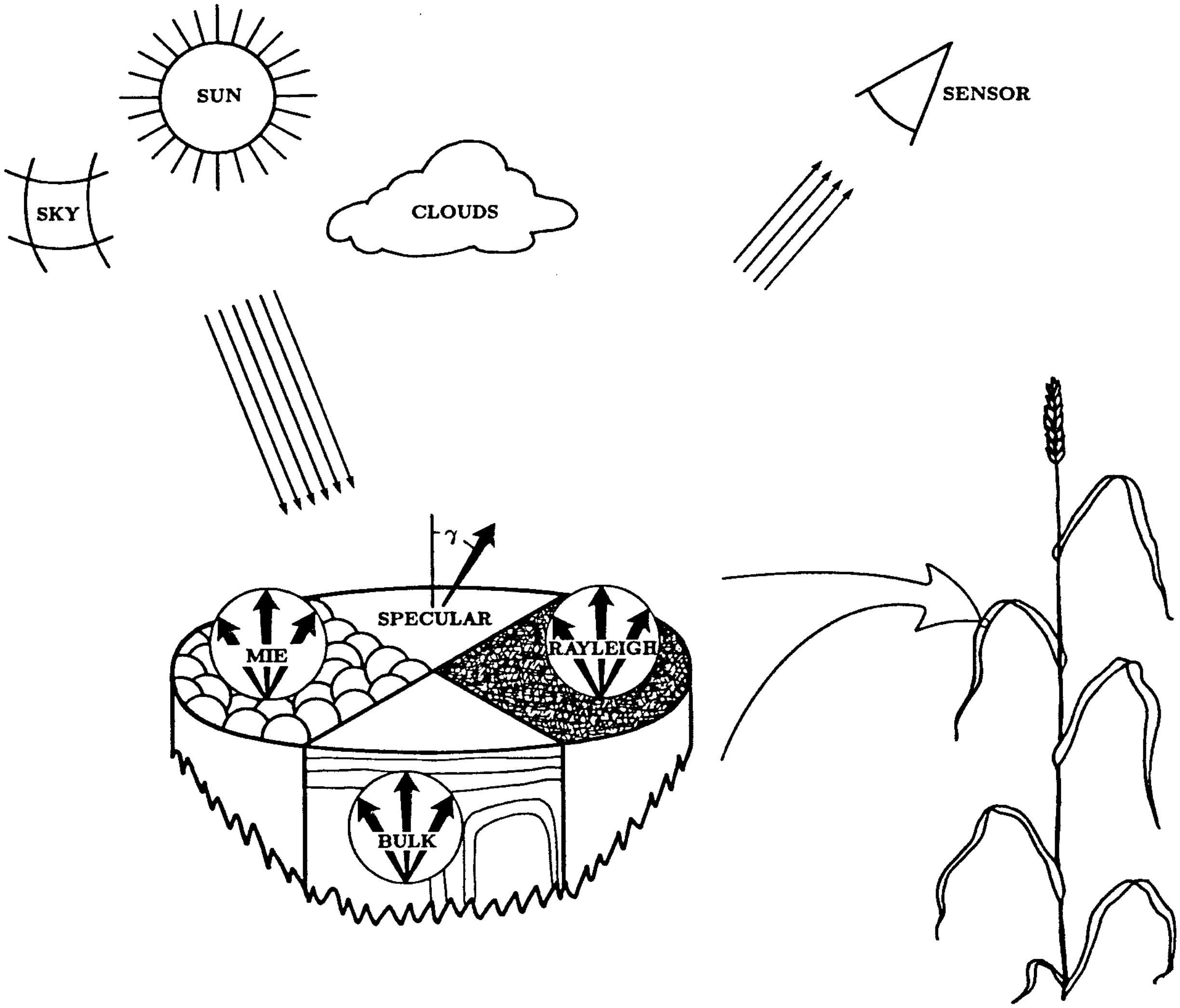


Figure 1. The remotely sensed scene is potentially illuminated by three light sources, sky, sun, and clouds. The light is diffusely scattered from the bulk of the leaf specularly scattered by the surface of the leaf, Mie scattered by large particles on the surface, and Rayleigh scattered by small particles on the surface.

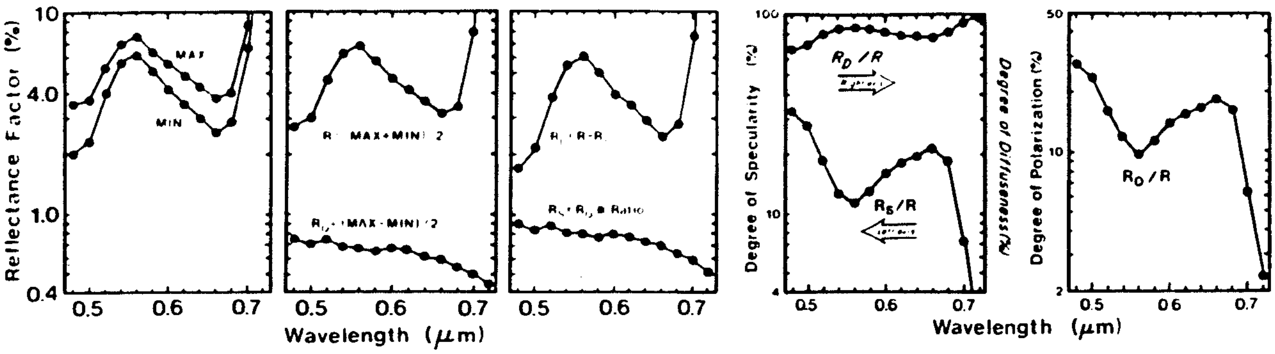


Figure 2. From the data (max, min) measured on the wheat canopy on June 19, 1976 at 60 ° view zenith angle toward the solar azimuth, the polarized (R_Q), specular (R_S), and diffuse (R_D) parts of the reflectance factor (R) and the degrees of specularity, diffuseness, and polarization are determined. The ratio is shown in Figure 4.

Figure 3. Angles of incidence are shown for a solar zenith angle of 30 ° as a function of view direction noting that if an observer sees specularly reflected sunlight, then the direction of the normal to the surface of the specular reflector is unique.

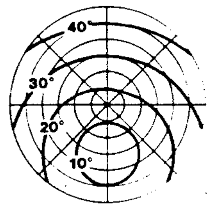
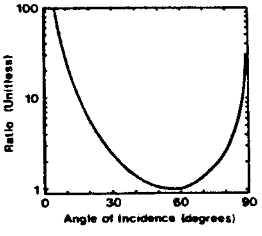
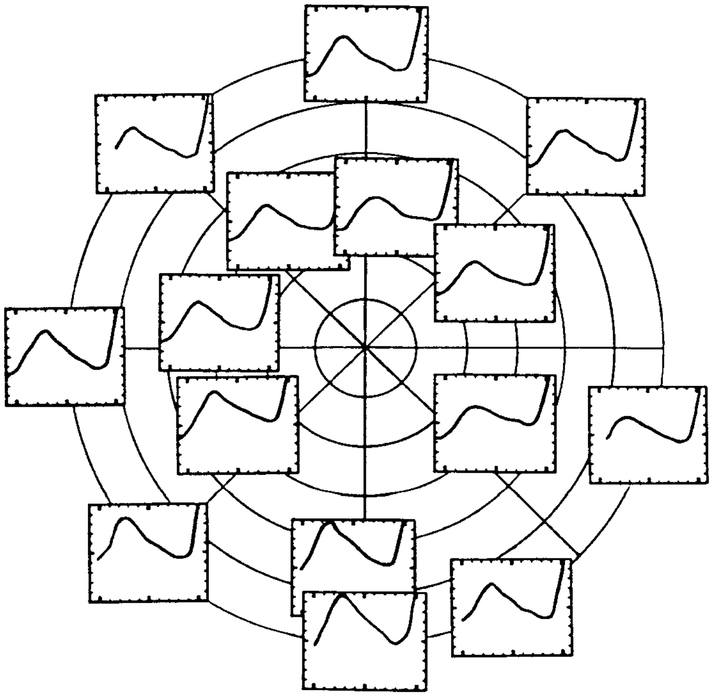


Figure 4. For a specularly reflecting leaf facet, the ratio of the polarized part of the specularly reflected light and the specularly reflected light equals the ratio (shown here) of the first and second components of the Stokes vector of a non-diffuse, purely specular reflector. The ratio depends on the angle of incidence and on the index of refraction of the cuticle of the wheat leaf--assumed here to be 1.5 for purposes of calculating the properties of the canopy.





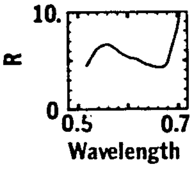
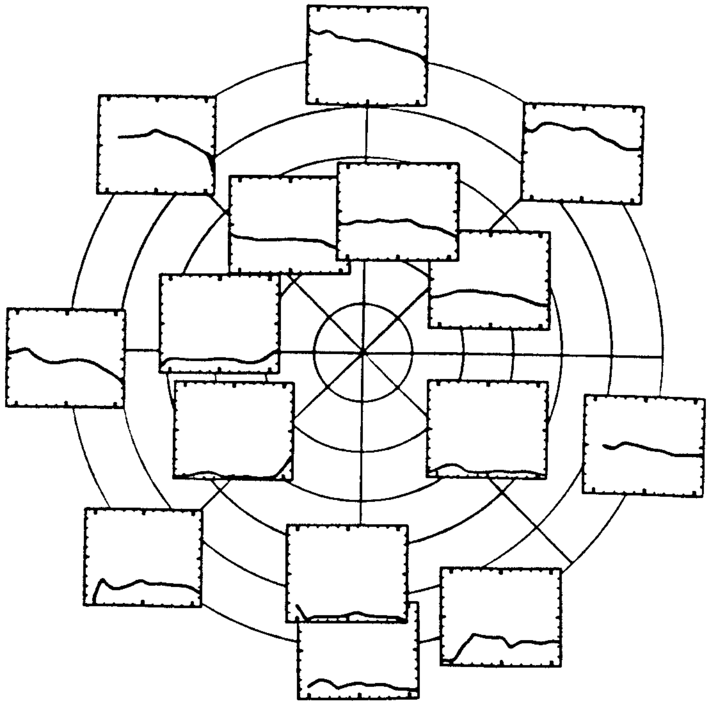


Figure 5. This subset of the spectra acquired June 19, 1976 illustrates the variation of reflectance factor (R) with view direction.



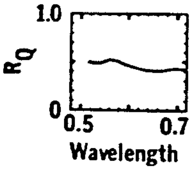
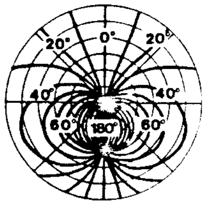


Figure 6. The spectra of the polarized part (R_Q) of the reflectance factor correspond to the spectra of R in Figure 5.

Figure 7. The angle of the axis of the polarization analyzer for measurement of the minimum amount of specularly reflected sunlight is predicted for a solar zenith angle of 30 ° (as a function of).



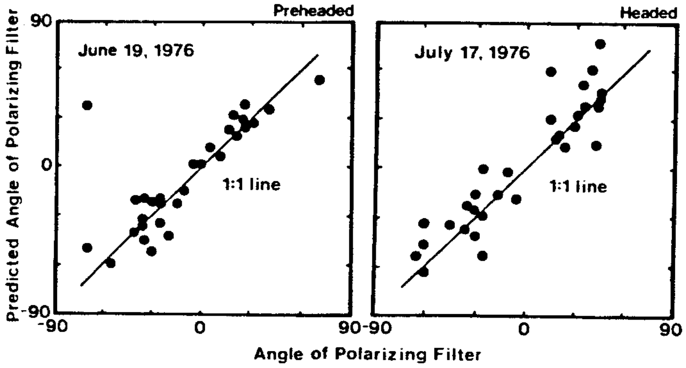


Figure 8. For the wheat canopies measured June 19 and July 17, 1976, comparison of the actual and predicted angles of the axis of the polarization analyzer is made with the adi of a 1:1 line.

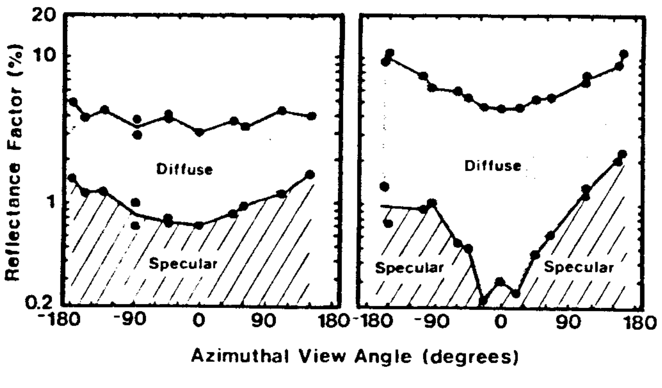


Figure 9. With the aid of the polarization measurements, the reflectance factor of the wheat canopies was split into its specular and diffuse components at 0.66 (μm) wavelength and 60 ° view zenith angle.