The Calculation of the Directional Reflectance of a Vegetative Canopy

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The non-Lambertian directional reflectance of a multilayer vegetative canopy is derived. Cause of the reflectance of the canopy is made traceable to the properties of the biological elements of the canopy. A new and possibly useful canopy property leading to the down sun "hot spot" is discussed.

Introduction

The need for the identification of vegetative canopies and the detection of stresses in vegetative canopies by remote sensing techniques has continued to grow in economic importance. The management of natural resources such as forests and wetlands, and the prediction of yields and assessment of pest damage of agricultural crops require both timely and economical survey techniques in order to supply the fundamental information for the formulation and execution of effective management strategies.

One of the most promising remote sensing techniques for rapid and economical mapping of vegetative canopy types is the airborne multispectral optical mechanical scanner using automatic spectral pattern recognition summarized by (Lowe, 1968). This technique is capable of utilizing very subtle but systematic spectral reflectance differences for the mapping of vegetative canopy types.

The major weakness of this technique is the difficulty in relating subtle reflectance differences to the elemental causative factors which could be recognized and classified by botanists on the ground.

Unless some insight is achieved in connecting causative factors with detected effects, there is no foundation for claiming that a specific cause is uniquely coupled with a detected effect. Certain detected effects could be due to spurious causes which may be transient and be fundamentally unconnected with the condition of interest to the remote sensor user even though the occurrence of the detected effect appears to be associated with this condition at one time and location.

A mathematical reflectance model of a canopy, which is based upon the spectral and geometric character of the individual pieces of the canopy, can connect the plant biology causes to the remotely-sensed reflectance effect.

Model Description

The construction of a mathematical model always requires compromises between realism and cogency. There is little doubt that a model which utilizes the exact spectroradiometric character and geometric placement of every individual canopy component will yield the measured spectral reflectance of the ensemble. However, the task of obtaining such data and making the computation is not feasible and does not lead to generalizations concerning the significance of overall canopy properties which are cogent. The canopy reflectance model presented here is a compromise with realism in order to retain some degree of cogency.

This model is an extension of the canopy model of Allen, Gayle, and Richardson (1970) which, in turn, is an extension of the Duntley (1942) equations that are, in turn, extensions of the Kubelka-Munk (1931) equations. The model of Allen, Gayle, and Richardson, hereafter called the AGR model, is a single layer of randomly mixed components. The scattering and absorption coefficients of these components are symbolized in the AGR model but are otherwise not derived from the spectral or geometric properties of specific components. The solar flux is introduced as an angularly dependent relation to account for changes in canopy reflectance during the diurnal cycle. The AGR model does not account for directional reflectance changes as a function of angle of view nor does it permit changes in reflectance of the canopy to be traceable to the specific causative factors of geometric and spectral changes in a particular class of components within the canopy.

The model presented here predicts bidirectional reflectance properties of a canopy traceable to the geometric and spectral properties of identifiable canopy components. This model of the canopy consists of a number of infinitely extended horizontal canopy layers. Within each layer, the components of the canopy are considered to be randomly distributed and homogeneously mixed. Figure 1 illustrates the geometry of the model.

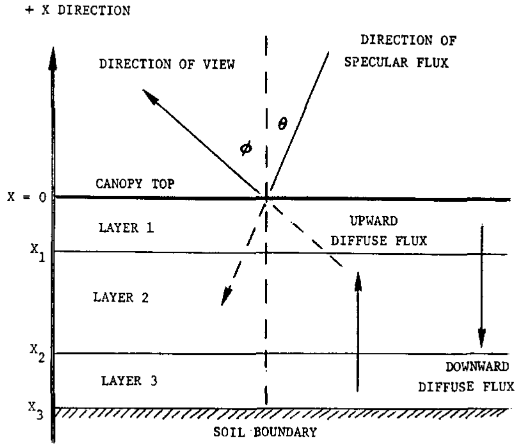

FIG. 1. Schematic of a three layer canopy model. The top of the canopy lies at $x = 0$. The canopy lies in the negative x region. The angle, θ, is the polar angle for specular flux and the angle, ϕ, is the polar angle of view. The canopy is isotropic in azimuth.

Many vegetative canopies have a distinct layer structure. Wheat, for example, produces the grain at the top layer of the canopy, while the stalk and leaves occupy a second layer. In a mature corn field, corn tassels occupy the top layer while leaves and ears occupy a second layer. A leaf slough-off layer may occur as a lower third layer. Forests frequently exhibit a layer structure with the components of different species occupying different layers. The order and content of these layers will effect the canopy directional reflectance. The lowest layer is always bounded by the soil.

Each component of the canopy such as a leaf or stalk is idealized as a combination of vertically oriented and horizontally oriented flat diffusely reflecting and transmitting panels. The size and spectral properties of the panels are obtained from physical measurements of the canopy components. In general, the objective is to determine the size of panels which would intercept the same amount of radiant flux as would the component. The projections of a component on horizontal and vertical planes define panel areas which are fairly close to meeting this criterion while retaining geometric simplicity for the model. Component projections are used to calculate optical cross sections in this model as illustrated in Fig. 2. The laboratory hemispherical spectral transmittance and reflectance of the component are taken to be those of the radiatively equivalent panels of the model.

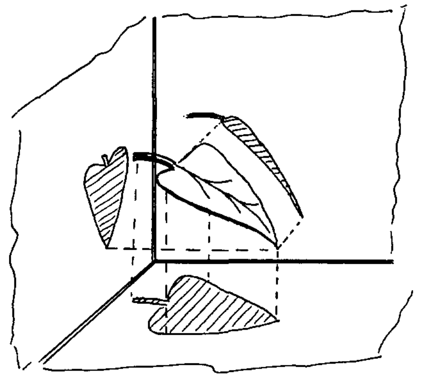

FIG. 2. Optical cross-sections by projections. The horizontal panel area or cross-section, σ_h, of the leaf is shown in the horizontal plane. The vertical cross-section, σ_v, is the sum of the two projections on the vertical planes.

Thus, every physical part of a plant yields two kinds of model components—vertical and horizontal—the sizes and number of which can be found from physical measurements of representative plants. If a plant canopy is stressed by some pathogen, or environmental condition, the changes in plant component geometry due to the stress leads to a corresponding change in the sizes of model panels in a cogent fashion. For instance, moisture stress causes leaves, which are normally horizontal, to droop. The vertical components of the model increase in area at the expense of horizontal components of the model to correspond to the geometric change in orientation of the leaves. If all other factors governing canopy reflectance are considered fixed, the calculated change in canopy reflectance can be attributed to the drooping of the leaves alone.

As in the AGR model, the radiant flux that interacts with the canopy is divided into two kinds, specular and diffuse. The specular flux is that flux which arrives from a part of the sky or the sun and flows into the canopy in a straight line without interception by any canopy component or the soil. The diffuse flux is that flux which has been intercepted at least once. As specular flux enters the canopy and is intercepted by a component, the flux leaves the specular category permanently. It is either absorbed or contributes to the diffuse flux of the canopy.

Calculation of Radiant Flow Field in the Canopy

In the following calculations, the spectral flux density is symbolized by $E_\lambda(s)$ for specular flow and $E_\lambda(d)$ for diffuse flow. The diffuse flux density is again divided into upward and downward flow and is symbolized by $E_\lambda(+d)$ and $E_\lambda(-d)$ respectively. Since the canopy consists of different layers each with its own properties, the specification of the layer must be included in the nomenclature. Thus, for instsnce, $E_\lambda(+d, i, x)$ represents the upward directed flux in the ith layer at level, x.

The calculation to determine $E_\lambda(+d, i, x)$ in each layer is the same as in the AGR single layer model using the equations

$$dE_\lambda(+d,i,x)/dx = -a_i E_\lambda(+d,i,x) + b_i E_\lambda(-d,i,x) + c_i E_\lambda(s,i,x), \quad (1)$$

$$dE_\lambda(-d,i,x)/dx = a_i E_\lambda(-d,i,x) - b_i E_\lambda(+d,i,x) - c'_i E_\lambda(s,i,x), \quad (2)$$

$$dE_\lambda(s,i,x)/dx = k_i E_\lambda(s,i,x). \quad (3)$$

The constants a_i, b_i, c_i, c'_i, and k_i are derived from measurements of canopy components of the ith layer. If only one type of component occupies the ith layer, then

$$a_i = \left[\sigma_h n_h(1-\tau) + \sigma_v n_v\left(1 - \frac{\rho+\tau}{2}\right)\right], \quad (4)$$

$$b_i = [\sigma_h n_h \rho + \sigma_v n_v(\rho/2 + \tau/2)], \quad (5)$$

$$c_i = [\sigma_h n_h \rho + (2/\pi)\sigma_v n_v(\rho/2 + \tau/2)\tan\theta], \quad (6)$$

$$c'_i = [\sigma_h n_h \tau + (2/\pi)\sigma_v n_v(\rho/2 + \tau/2)\tan\theta], \quad (7)$$

and

$$k_i = [\sigma_h n_h + (2/\pi)\sigma_v n_v \tan\theta]. \quad (8)$$

where σ_h is the average area of the projection of the canopy component on a horizontal plane, σ_v is the average area of the projection of the canopy component on two orthogonal vertical planes, n_h is the number of horizontal projections per unit volume, n_v is the number of vertical projections per unit volume, and the angle, θ, is the polar angle for incident specular flux.

The spectral transmittance, τ, and the spectral reflectance, ρ, are the hemispherical reflectance values obtained from measurements of component samples in the laboratory. The factor $(2/\pi)$ associated with the tangent of the specular angle in Relations (6), (7), and (8) is the average value of the cosine of the azimuthal angle. The vertical projection is averaged for random, azimuthal, orientations.

If more than one type of component exists in a canopy layer, then the values of a, b, c, c', and k are obtained for each type separately and added together to obtain the value for the layer. For instance, with three types of components in the ith layer, a_i for that layer is

$$a_i = a_i(\text{type }1) + a_i(\text{type }2) + a_i(\text{type }3).$$

The solutions to equations (1), (2), and (3) are of the form

$$E_\lambda(+d,i,x) = A_i(1-f_i)\exp(g_i x) + B_i(1+f_i)\exp(-g_i x) + C_i \exp(k_i x), \quad (9)$$

$$E_\lambda(-d,i,x) = A_i(1+f_i)\exp(g_i x) + B_i(1-f_i)\exp(-g_i x) + D_i \exp(k_i x), \quad (10)$$

and

$$E_\lambda(s,i,x) = E_\lambda(s,i-1,x_{i1})\exp(k_i x), \quad (11)$$

where A_i and B_i are to be determined by the boundary conditions; C_i, D_i, g_i and f_i are determined by substitution of Relations (9) and (10) into Relations (1) and (2). Substitution yields

$$C_i = \frac{c_i(k_i - a_i) - c'_i b_i}{k_i^2 - a_i^2} E_\lambda(s, i-1, x_{i-1}),$$

$$D_i = -\frac{c'_i(k_i + a_i) + c_i b_i}{k_i^2 - a_i^2} E_\lambda(s, i-1, x_{i-1}),$$

$$g_i = (a_i^2 - b_i^2)^{1/2}, \text{ and}$$

$$f_i = [(a_i - b_i)/(a_i + b_i)]^{1/2}.$$

The quantity $E_\lambda(s, i-1, x_{i-1})$ is the value of the specular irradiance at the bottom of the $(i-1)$th layer, $x = x_{i-1}$.

The boundary conditions require that at the top of the first layer (at $x = 0$) the only downward directed flux is specular flux, $E_\lambda(s, 1, x = 0)$. Thus, downward diffuse flux is zero at that boundary,

$$E_\lambda(-d, 1, x = 0) = 0. \quad (12)$$

The boundary conditions between layers are merely that the upward and downward directed flux is continuous across the layer boundaries. At the soil level, the boundary conditions require that all downward directed flux at the soil level is reflected by the soil to produce upward directed diffuse flux. The specular and diffuse flux within the canopy become fully determined. The boundary conditions for a one layer canopy are simply

$$E_\lambda(-d, 1, 0) = 0, \text{ and}$$

$$E_\lambda(+d, 1, x_1) = \rho(\text{soil})[E_\lambda(-d, 1, x_1) + E_\lambda(s, 1, x_1)].$$

These relations are solved for A_1 and B_1. It is clear that the reflectance of the soil enters into the evaluation of these constants as long as there is any downward flux left at the bottom of the canopy. However, for a very deep and opaque canopy, the characteristics of the soil will be inconsequential to the canopy reflectance. For the infinitely deep canopy, the boundary conditions are

$$E_\lambda(-d, 1, 0) = 0, \text{ and}$$

$$E_\lambda(+d, 1, x_1 \to -\infty) = 0,$$

so that $B_1 \to 0$ and $A_1 = -D_1/(1 + f_1)$.

For the infinitely deep canopy, one can see more easily the influence of the specular flux angle on the diffuse flow. The angular dependence enters through the value of D_1 which is a function of the θ dependent parameters, c, c', and k. In these parameters, $\tan\theta$ multiplies the areas of the vertical canopy components. Therefore, it is the vertical structures in the canopy which are primarily responsible for the variations of flow field with sun angle just as common sense would indicate.

Calculation of Canopy Reflectance

At this point in the calculation of canopy reflectance, only two alterations have been made to extend the AGR model. The first is to introduce scattering terms which are related directly to identifiable component properties that can be physically measured. The second is the introduction of a number of canopy layers. The usual practice at this point is to proceed to calculate the hemispherical reflectance of the canopy by forming the ratio of the upward directed diffuse flux to the downward directed specular flux at the top of the canopy. Since the diffuse flow within the canopy is presumed to be isotropic, the canopy reflectance is presumed to be Lambertian. However, simple visual observation is sufficient to prove that many important canopies are not Lambertian. Moreover, aerial photography and airborne or spaceborne line scanners measure directional reflectance or radiance and not hemispherical reflectance or exitance. The non-Lambertian property of canopies are consequential.

A departure from the Kubelka-Munk and AGR reflectance calculations is made at this point in order to calculate the directional reflectance of a non-Lambertian canopy. In summary, the calculation of canopy radiance employs the first step in the method of the self consistent field. That is, the isotropic diffuse flux as calculated by Relations (9), (10), and (11) is assumed to be only an approximation to the actual non-isotropic flow. This approximate flow field forms the illumination for each infinitesimal layer within the canopy. Using the approximate flow as the illumination and using the spectral and geometric properties of the components within such infinitesimal layer, one calculates the radiance of that infinitesimal layer. Although the components of the infinitesimal layer are assumed to be Lambertian reflectors and transmitters, the vertical components of the infinitesimal layer cause the layer to be a non-Lambertian ensemble. The radiance of every infinitesimal layer may be calculated and using the non-Lambertian contributions of each infinitesimal layer, one can calculate a second and more accurate non-isotropic flow field within the canopy. Now, using the second and more accurate non-isotropic flow field as the illumination, the procedure is iterated until the calculated radiance of each infinitesimal layer for the last iteration is not different from the results of the next to last iteration. The flow field "causing" the radiance and the radiance of the infinitesimal layers "causing" the flow field are then "self consistent." The radiance of the canopy in any given direction of view is then calculated by adding the contributions of each infinitesimal layer to the radiance in that direction.

The calculation by iteration will not be done here principally because the canopy model would rapidly lose cogency. What is done here is to assume that the flow field as calculated by Relations (9), (10), and (11) is already a reasonable approximation and that the radiance contribution of each infinitesimal layer will yield a non-Lambertian canopy radiance which will not be greatly inconsistent with the results of the first iteration if it were to be made. The iteration is assumed to converge rapidly. Indeed, one can expect that this assumption is quite valid for canopies which are not greatly different from Lambertian.

The calculation of the radiance of canopy components in an infinitesimal layer is quite straightforward. The upward flow of diffuse flux illuminates the horizontal components from below producing a contribution to horizontal component radiance by transmission. Thus, the radiance of the infinitesimal layer due to horizontal components becomes

$$\Delta L_\lambda = \sigma_h n_h \Delta x \tau E_\lambda(+d)/\pi.$$

The radiant intensity of a vertical component is increased in part by reflection and in part by transmission so that along the normal to the surface of a vertical component

$$\Delta I_\lambda = \sigma_v(\tau/2 + \rho/2)\, E_\lambda(+d)/\pi.$$

The radiant intensity varies with angle as a Lambertian radiator but the normal to the surface lies in a horizontal plane and in a random azimuthal direction; consequently, the radiant intensity of each vertical component as viewed from polar angle, ϕ, varies as the projected area of the component in the direction of view. The average projected area for such conditions is $\sigma_v(2/\pi)\sin\phi$. Hence, as viewed from polar angle, ϕ, the vertical component produces a radiant intensity of $\Delta I_\lambda = (2/\pi)\sin\phi\sigma_v(\tau/2+\rho/2)\,E_\lambda(+d)/\pi$. The radiance of a layer of vertical components Δx thick as seen from this direction is then

$$\Delta L_\lambda = (2/\pi)\sin\phi\sigma_v \frac{\tau+\rho}{2} E_\lambda(+d)\cdot n_v \Delta x \sec\phi/\pi.$$

The $\sec\phi$ factor is introduced because the radiance of a layer is defined as the radiant intensity per unit projected layer area (not component area).

Similar arguments apply to the contributions of downward directed flux so that the combined radiance of an infinitesimal layer is

$$\Delta L_\lambda = \left[\sigma_h n_h \Delta x \tau + \sigma_v n_v \Delta x \frac{\tau+\rho}{2}(2/\pi)\tan\phi\right] \times E_\lambda(+d,x)/\pi + \left[\sigma_h n_h \Delta x \rho + \sigma_v n_v \Delta x \frac{\tau+\rho}{2}(2/\pi)\tan\phi\right] E_\lambda(-d,x)/\pi + \left[\sigma_h n_h \Delta x \rho + \sigma_v n_v \Delta x \frac{\tau+\rho}{2} \times (2/\pi)^2 \tan\theta\tan\phi\right] E_\lambda(s,x)/\pi. \quad (13)$$

Using a more compact notation, one can write Relation (13) as

$$\Delta L_\lambda = [uE_\lambda(+d,x)/\pi + vE_\lambda(-d,x)/\pi + wE_\lambda(s,x)/\pi]\,\Delta x, \quad (14)$$

where the coefficients u, v, and w are

$$u = \sigma_h n_h \tau + \sigma_v n_v \frac{\tau+\rho}{2}(2/\pi)\tan\phi,$$

$$v = \sigma_h n_h \rho + \sigma_v n_v \frac{\tau+\rho}{2}(2/\pi)\tan\phi,$$

and

$$w = \sigma_h n_h \rho + \sigma_v n_v \frac{\tau+\rho}{2}(2/\pi)^2\tan\phi\tan\theta.$$

Parts of this infinitesimal layer may be seen by line of sight through the rest of the canopy lying above it.

The probability of achieving line of sight through the canopy above from a layer at x is $\exp(Kx)$ where

$$K = [\sigma_h n_h + (2/\pi)\,\sigma_v n_v \tan\phi]. \quad (15)$$

The form of K is the same as that for k governing the flow of specular flux except that the angle of view, ϕ, replaces the specular flux angle, θ.

The radiance contribution of an infinitesimal layer Δx thick at level x in the direction of view ϕ from outside the canopy is

$$\Delta L_\lambda \text{ (from outside)} = e^{Kx}\Delta L_\lambda \text{ (layer)}. \quad (16)$$

Consequently, the radiance of the entire canopy as seen from outside is the integral of all such contributions plus the contribution from the soil boundary.

To simplify the results, a two layer canopy would produce

$$\pi L_\lambda/E_\lambda(s,0) = R(\text{layer }1) + R(\text{layer }2) + R(\text{soil}), \quad (17)$$

where the three terms on the right are the contributions of each layer and the soil boundary given as follows:

$$R(\text{layer }1) = A_1[u_1(1-f_1)+v_1(1+f_1)] \times \{1-\exp[x_1(K_1+g_1)]\}/(K_1+g_1) + B_1[u_1(1+f_1)+v_1(1-f_1)] \times \{1-\exp[x_1(K_1-g_1)]\}/(K_1-g_1) + [u_1 C_1 + v_1 D_1 + w_1] \times \{1-\exp[x_1(K_1+k_1)]\}/(K_1+k_1), \quad (18)$$

$$R(\text{layer }2) = \exp[K_1 x_1]\Big\{A_2[u_2(1-f_2)+v_2(1+f_2)] \times \frac{\{\exp[x_1(K_2+g_2)]-\exp[x_2(K_2+g_2]\}}{(K_2+g_2)} + B_2[u_2(1+f_2)+v_2(1-f_2)] \times \frac{\{\exp[x_1(K_2-g_2)]-\exp[x_2(K_2-g_2)\}}{(K_2-g_2)} + [u_2 C_2 + v_2 D_2 + w_2] \times \frac{[\exp\{x_1(K_2+k_2)]-\exp[x_2(K_2+k_2)\}]}{(K_2+k_2)}\Big\}, \quad (19)$$

$$R(\text{soil}) = \exp[K_1 x_1 + K_2(x_2-x_1)] \times \{A_2(1-f_2)\exp[g_2 x_2] + B_2(1+f_2)\exp[-g_2 x_2] + C_2\exp[k_2 x_2]\}, \quad (20)$$

where $E_\lambda(s,0)$ at the top of the canopy is set equal to unity.

Although the expression is lengthy, the contributions of various kinds are easily identified. All terms multiplied by u are contributions due to upward diffuse flux in the canopy flow field; all terms multiplied by v are contributions due to the downward diffuse flux in the canopy flow field; all terms multiplied by w are contributions due to first surface reflection or transmission of specular flux in the canopy. The contribution due to the soil can be written in another way by virtue of the boundary conditions,

$$R(\text{soil}) = \exp[K_1 x_1 + K_2(x_2-x_1)]\,E_\lambda(+d,2,x_2), \quad (21)$$

which is written in detail above, or

$$R(\text{soil}) = \exp[K_1 x_1 + K_2(x_2-x_1)]\,\rho(\text{soil}) \times [E_\lambda(-d,2,x_2)+E_\lambda(s,2,x_2)]. \quad (22)$$

An important approximation of the canopy reflectance can be made if one assumes that the first surface reflection (and transmission) of specular flux is the dominant effect. For wavelengths in the chlorophyl absorption band, 670 nm, the first surface reflectance and transmission are quite low, i.e., $E_\lambda(+d)$, $E_\lambda(-d) \ll E_\lambda(s)$. Any further reflection and transmission will be negligible so that the observed radiance of the canopy will be due only to first reflection and transmission terms.

Hence, for a single layer canopy

$$\pi L_\lambda/E_\lambda(s,0) \cong w_1(1-\exp[x_1(K_1+k_1)]/(K_1+k_1) + \exp[K_1 x_1 + k_1 x_1]\,\rho(\text{soil}). \quad (23)$$

The expression shows that the reflectance of the canopy due to first surface interaction terms is primarily due to the soil as illuminated by specular flux through the canopy and as seen through the canopy plus a small contribution due to first surface reflection and transmission from the canopy components.

The fundamental geometric qualities of a canopy are layed bare. The angular dependence of K on ϕ [as shown in Relation (15)] and k on θ depends upon the presence of vertical components in the canopy. The reflectance of the canopy in this case can be seen to depend upon two leaf area indices, $\sigma_h n_h x_1$ and $\sigma_v n_v x_1$. The leaf area index for horizontal components corresponds to the leaf area index which is usually defined by agronomists. The leaf area index for vertical components does not correspond to any previously defined quantity. Relation (23) indicates that the geometric structure of a single layer canopy can be determined by remote sensing reflectance measurement at two different angles of view or two different sun angles in a spectral band where first surface reflection is dominant provided that the soil reflectance is known, the canopy component reflectance and transmittance is known for $\lambda = 670$ nm, and the two angles ϕ and θ are known for each of two reflectance measurements.

Calculations were made for a hypothetical one month old corn field over a soil with a reflectance of 10% at all wavelengths and at a sun angle of 45°. The complete directional reflectance model (Fig. 3) yields a higher reflectance than does the first surface approximation (Fig. 4) as would be expected. The two results are essentially the same in the chlorophyl absorption regions of low reflectance and transmittance but differ in magnitude at other wavelengths. Since the soil

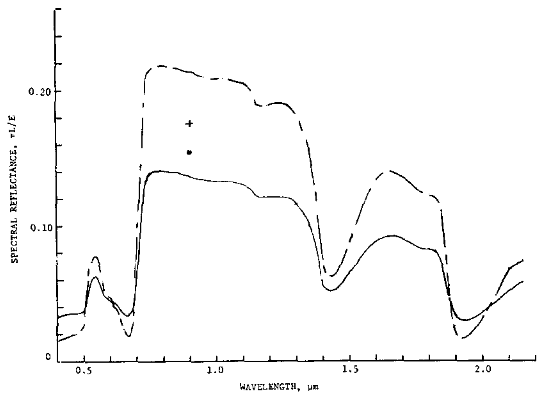

FIG. 3. Directional reflectance of a corn canopy. The solid curve is the spectrum for $\phi = 0°$. The broken curve is the spectrum for $\phi = 75°$. The reflectance at one wavelength for intermediate angles are shown by dot and cross for $\phi = 25°$ and $\phi = 50°$ respectively.

was taken to be without spectral detail, the influence of the soil in this case is merely to moderate the detail of the canopy spectrum for near polar viewing angles. The non-Lambertian character of the canopy is evident in both spectra. Of particular interest is the change in the order of reflectance magnitude as a function of view angle in the 670-nm region as compared to the 1000-nm region. Increasing view angle, ϕ, implies less soil and more canopy contributes to the spectrum. In the 670-nm region, the canopy is much darker than the soil.

Thus, the reflectance goes down with increasing ϕ. In the 1000-nm region, the canopy is lighter than the soil so that the reflectance rises with increasing ϕ. The magnitude of the change with angle depends upon the ratio of vertical to horizontal canopy components. A shift of horizontal components to vertical components would increase the non-Lambertian character. The fact that the non-Lambertian property of this canopy is not extreme is consistent with the assumption that the iteration procedure would converge rapidly.

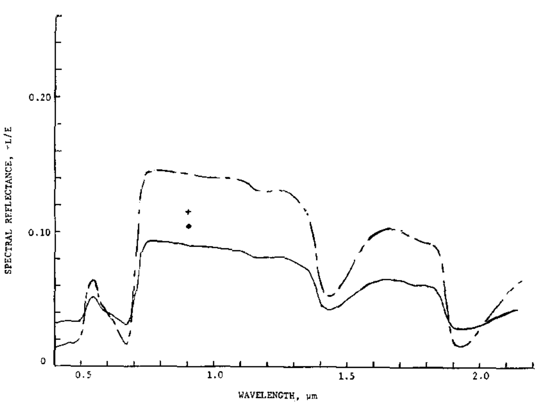

FIG. 4. First surface approximation. The canopy reflectance is reduced if the diffuse flux is neglected under the same conditions as given for Fig. 3. Solid curve, $\phi = 0°$; broken curve, $\phi = 75°$; dot and cross are for 25° and 50°, respectively.

In order to illustrate what reflectance changes would be expected if the leaves of the corn canopy were to droop as might occur under temporary moisture stress, half of the horizontal components of the canopy were transferred to the vertical component category. The results of this change are shown in Fig. 5. The increase in non-Lambertian quality is evident. The reflectance for a view angle of 0° decreases in the 700–900-nm range and increases in the 600–700-nm range. If such a canopy were photographed with infrared Ektachrome film, the image color would show a pronounced shift towards the blue-green. However, the image color for a 75° view angle would produce the familiar magenta with a slightly greater red content. These predicted results for different viewing angles indicate that valuable information concerning canopy geometry is to be found in the non-Lambertian character of vegetative canopies.

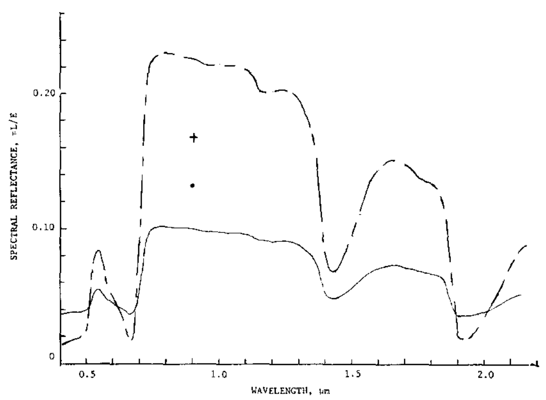

FIG. 5. Reflectance change due to leaf droop. Decrease of horizontal with corresponding increase in vertical components increases the non-Lambertian character of the canopy. Solid curve, $\phi = 0°$; broken curve, $\phi = 75°$; dot and cross are 25° and 50°, respectively.

The complete spectral reflectance of a canopy at different angles of ϕ or θ could yield estimates of the leaf area indices of spectrally distinct canopy components. However, the model clearly predicts that the lower canopy layers will influence the canopy reflectance less because of the exponential factors as shown, for instance, in Relation (19) for the two layer canopy. Unless the upper layers are thin or poorly populated with components, the lower layers influence the canopy reflectance primarily through the multiple reflection diffuse flow factors A and B.

Since the canopy reflectance is effected by the specular flux angle, one can expect that the reflectance for skylight and reflectance for direct sunlight will be significantly different. In this way, the reflectance of a canopy can be different from day to day even at the same sun angle and view angle. A field measurement of directional reflectance should show a variation on a partly cloudy day as more or less direct sunlight is incident upon the canopy.

The Canopy "Hot Spot"

The hot spot in an aerial photograph is a well known phenomenon. When an aerial photograph is taken so as to include a region of terrain directly opposite the sun from the aircraft, an anomalously bright region surrounds the aircraft shadow. The bright region is called the "hot spot". This canopy model offers a natural means of incorporating this effect as it applies to vegetative canopies.

In the calculation of canopy radiance, it was tacitly assumed that the probability of achieving line of sight to at least level x for specular flux, e^{kx}, was independent of the probability of achieving line of sight from level x to the region outside of the canopy, e^{Kx}. It is quite obvious that, when the direction of view coincides with the direction of specular flux, these two probabilities are not independent. If specular flux can penetrate to level x, along a given direction, it is certain that line of sight is achieved outward from level, x, in the same direction. The identical part of the canopy is being used. The calculation of canopy radiance [Relation (16)] involves the multiplication of these two probabilities to form the joint probability which is logically incorrect if these two probabilities become dependent. The functional form which expresses this dependency is a property of the canopy structure which could be a significant new identifying canopy attribute. The general qualitative properties can be expressed by a relation such as,

$$\exp[\{k + K[1 - \exp(-\beta(\theta - \phi)^2 - \gamma(\psi - \xi)^2)]\}x], \tag{24}$$

wherever the joint probability is to be used in Relation (16). In Relation (24), ψ is the specular flux azimuth, ξ is the viewing azimuth, and β and γ are constants characteristic of the coarseness or fineness of the canopy structure.

This expression has the property of reducing the joint probability to $\exp[kx]$ when $\theta = \phi$ and $\psi = \xi$ and smoothly changes to $\exp[(k + K)x]$ for large values of $(\theta - \phi)^2$ or $(\psi - \xi)^2$ when independent parts of the canopy are involved for specular flux and viewing directions.

The impact of dependence upon canopy reflectance is easily illustrated using the first surface interaction approximation given by Relation (23). Wherever the factor $(K_1 + k_1)$ appears, replace it with the factor

$$(k_1 + K_1\{1 - \exp[-\beta(\theta - \phi)^2 - \gamma(\psi - \xi)^2]\})$$

to account for the dependency of the two probabilities. The reflectance at the center of the hot spot is then

$$\pi L_\lambda / E_\lambda(s, 0) = w_1(1 - \exp[x_1 k_1])/k_1 + \exp[x_1 k_1]\rho(\text{soil}). \tag{25}$$

At the same polar angle but at different azimuthal angles from the specular flux direction the radiance is given by relation (23). Due to the fact that K disappears from the Relation (25), the effect of soil reflectance is likely to be increased considerably at the center of the hot spot. The azimuthal angular subtense of the hot spot is a measure of γ. The polar angular subtense is a measure of β.

An interesting possibility is suggested when one considers the hot spot of a two layer canopy. Each layer has its own characteristic degree of coarseness. Thus, it should be possible to find a small hot spot from a fine grained canopy layer superposed upon a large hot spot from a coarse grained layer.

The hot spot effect is frequently several degrees in diameter and would require a uniform canopy large enough to contain the hot spot as viewed from the remote sensing platform. The existence of uniform canopies of sufficient size becomes unlikely when spacecraft altitudes are considered. For a hot spot subtending an angle of 0.1 radian, the canopy would have to extend over a square 10 miles by 10 miles for a 100-mile-altitude platform.

Summary

A means for calculating the directional reflectance of a multi-layer vegetative canopy has been developed to connect the plant biology causes with the remotely sensed reflectance effect. The model is an extension of the AGR model but differs in four ways: (1) The model has been extended to include canopy layers having different biological components; (2) the absorption and scattering coefficients are derived from laboratory measurements of the components; (3) the calculation of the canopy radiance follows the method of the self consistent field to yield a non-Lambertian canopy radiance; and (4) the model is extended to incorporate the qualitative features of the hot spot for uniform canopies with the suggestion that hot spot analysis could yield characteristic canopy attributes useful for identification.

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