REMOTE SENS. ENVIRON. 27: 251-260 (1989)

The Influence of Leaf Orientation and the Specular Component of Leaf Reflectance on the Canopy Bidirectional Reflectance

Juhan Ross
*Aleksandr Marshak**
Institute of Astrophysics and Atmospheric Physics, Estonian Academy of Sciences, Tôravere, Estonia, USSR 202444

To calculate the plant canopy bidirectional reflectance distribution function (BDRF), the Monte Carlo method is used. The Ross–Marshak canopy model (Ross and Marshak, 1985; 1987a, b; 1988) is generalized to the case of the arbitrary leaf angle distribution (LAD). The contribution of the specular component of leaf reflectance given by the Fresnel law, resulting from the presence of the wax layer of a leaf, is taken into account. The influence of the LAD on the BRDF is estimated in the principal plane. The differences of the BRDF are shown between the canopies with equal first moments of the LAD and unequal second ones. The mathematical technique of the Monte Carlo method which allows estimation of the contribution of the specular component of the BRDF is derived. With the help of this technique a series of numerical experiments, showing the influence of the LAD on the contribution of the specular component of leaf reflectance, has been carried out. These results can be used for the interpretation of the remote sensing data of vegetation and for the inversion of canopy reflectance models, for estimating the LAD, and the size of the leaf wax layer.

*Corresponding author.
Received 31 March 1988; revised 21 October 1988.

0034-4257/89/$3.50

INTRODUCTION

In previous papers (Ross and Marshak, 1985; 1987a, b; 1988) we described the geometrical model of a plant and a canopy structure on the whole, derived the technique of the Monte Carlo method for the calculation of the plant canopy bidirectional reflectance distribution function (BRDF), and carried out a series of numerical experiments to estimate the influence of various parameters of the model on the BRDF. It was proposed that all the leaves were mat and they had a constant inclination angle ϑ_L. However, numerous experimental data show (see, for example, Ross, 1981) that there is a broad distribution of leaf inclination angles and this distribution can be described by the statistical function of the leaf angle distribution (LAD) $g(\vartheta_L, \varphi_L)$, where φ_L is the leaf azimuth. Different distribution functions g have been proposed by Bunnik (1978), Ross (1981), and Goel and Strebel (1984). Some experimental data on the phase function of a leaf (Moldau, 1965; Breece and Holmes, 1971; Woolley, 1971; Gausman et al., 1973; Ross, 1981, p. 180) show that the phase function of a large variety of plants has a strong specular reflection, resulting from the presence of the wax layer on a leaf surface. Some optical models (Moldau, 1967) have qualitatively explained the regularity of reflection and transmission. However, sufficiently simple formulae and algorithms for the calculation of the leaf phase function are absent with the exception of the Nilson–Kuusk model (Nilson and Kuusk, 1984) and SAIL model (Verhoef, 1984; Reyma and Badhwar, 1985), in which the specular component has been added to the leaf reflectance. It is necessary to add a very versatile paper of Vanderbilt and Grant (1985). They discuss a model for the amount of light specularly reflected and polarized by a plant canopy.

The purpose of the present paper is the improvement of our previous model of the plant canopy by the introduction of the LAD function g instead of a constant inclination angle ϑ_L and calculation of the specular component of leaf reflectance. With the help of a series of numerical experiments the influence of these parameters on the BRDF is estimated. The following simple optical model of a leaf is proposed: The transmission is isotropic and characterized by the spectral coefficient T_λ. The reflection consists of two components: the diffuse component defined by the spectral coefficient R_λ and the specular component $R_F(\vartheta', n)$, depending on the angle ϑ' of the incident light ray on the leaf and on the optical index of refraction of the wax n (Gausman et al., 1973; Nilson and Kuusk, 1984), and independent of the wavelength. [In fact, following the results of Vanderbilt and Grant (1985) the index of refraction depends slightly on the wavelength.]

In most models which describe the radiative transfer in the atmosphere and in global models of climate, the reflection from the ground surface is defined by the Lambert law with some albedo. The results of the present paper show in which cases the Lambert surface approximates the plant canopy well and when such approximation gives serious errors. Finally, the conclusions of this paper are applied to agricultural canopies in general.

THE SIMULATION OF THE SPATIAL LEAF ORIENTATION

Let the function $(1/2\pi)g(r_L)$, independent of depth, be the probability density of the distribution of leaf normal orientated to an upper hemisphere (Ross, 1981) and

$$\frac{1}{2\pi}\int_{\Omega_u} g(r_L)\,dr_L = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\pi/2} g(\vartheta_L,\varphi_L)\sin\vartheta_L\,d\vartheta_L\,d\varphi_L = 1.$$

Here Ω_u is an upper hemisphere, $r_L = (\vartheta_L, \varphi_L)$ is the unit vector of the direction of leaf normal, $dr_L = \sin\vartheta_L\,d\vartheta_L\,d\varphi_L$. Let us suppose that the inclination angle ϑ_L and the azimuth φ_L are independent and the distribution along φ is uniform. Then $g(r_L) = g(\vartheta_L)$ and $\int_0^{\pi/2} g(\vartheta_L)\sin\vartheta_L\,d\vartheta_L = 1$. For convenience let us introduce the function

$$g^*(\vartheta_L) = g(\vartheta_L)\sin\vartheta_L \qquad \left[\int_0^{\pi/2} g^*(\vartheta_L)\,d\vartheta_L = 1\right],$$

which defines the fraction of leaves per unit leaf zenith angle ϑ_L.

Such a model allows us to choose the following LADs.

1. All leaves have a constant inclination angle ϑ_0:
$$g(\vartheta_L) = \delta(\vartheta_L - \vartheta_0),$$
where δ is a Dirac delta function.
2. Trigonometrical orientation (Bunnik, 1978):
$$g^*(\vartheta_L) = a + b\cdot\cos 2\vartheta_L + c\cdot\cos 4\vartheta_L.$$
3. Beta distribution (Goel and Strebel, 1984)
$$g(\vartheta_L) \sim \beta(\mu,\nu) = \frac{\pi}{2}\,\frac{x^{\mu-1}(1-x)^{\nu-1}}{B(\mu,\nu)}, \qquad x \in (0,1),$$
where $B(\mu,\nu) = \Gamma(\mu)\Gamma(\nu)/\Gamma(\mu+\nu)$ is the beta function (Γ is the gamma function).

With the help of distributions 2 and 3, one can simulate the following orientations:

(a) Uniform ($a = 2/\pi$, $b = c = 0$ or $\mu = \nu = 1$):
$$g(\vartheta_L) = (2/\pi)(\sin\vartheta_L)^{-1},$$
$$g^*(\vartheta_L) = 2/\pi.$$
(b) Spherical ($a = \sin\vartheta_L$, $b = c = 0$ or $\mu = 1.930$, $\nu = 1.101$):
$$g(\vartheta_L) = 1, \qquad g^*(\vartheta_L) = \sin\vartheta_L.$$
(c) Planophile ($a = b = 2/\pi$, $c = 0$ or $\mu = 1.172$, $\nu = 2.770$):
$$g(\vartheta_L) = (4/\pi)\cos^2\vartheta_L(\sin\vartheta_L)^{-1},$$
$$g^*(\vartheta_L) = (4/\pi)\cos^2\vartheta_L.$$

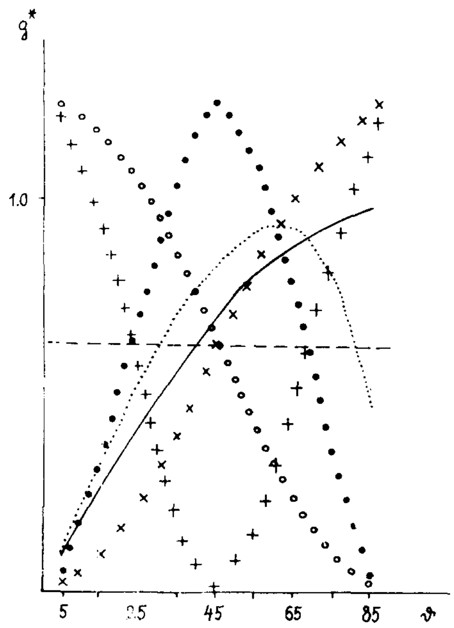

Figure 1. Various LAD: 1) (○) planophile; 2) (---) uniform; 3) (—) spherical; 4) (×) erectophile; 5) (●) plagiophile; 6) (+) extremophile; 7) (···) soybean.

(d) Erectophile ($a = 2/\pi$, $b = -2/\pi$, $c = 0$ or $\mu = 2.770$, $\nu = 1.172$):

$$g(\vartheta_L) = (4/\pi)\sin\vartheta_L,$$
$$g^*(\vartheta_L) = (4/\pi)\sin^2\vartheta_L.$$

(e) Plagiophile ($a = 2/\pi$, $b = 0$, $c = -2/\pi$ or $\mu = \nu = 3.326$):

$$g(\vartheta_L) = (4/\pi)\sin^2 2\vartheta_L(\sin\vartheta_L)^{-1},$$
$$g^*(\vartheta_L) = (4/\pi)\sin^2 2\vartheta_L.$$

(f) Extremophile ($a = 2/\pi$, $b = 0$, $c = 2/\pi$ or $\mu = \nu = 0.433$):

$$g(\vartheta_L) = (4/\pi)\cos^2 2\vartheta_L(\sin\vartheta_L)^{-1},$$
$$g^*(\vartheta_L) = (4/\pi)\cos^2 2\vartheta_L.$$

In practice, the extremophile distribution is not realized in the actual canopies and it is interesting only for model calculations. The graphs of various functions g^* are represented in Fig. 1 together with the data for the soybean canopy, which have been taken from the paper of Goel and Strebel (1984).

For the case of trigonometrical distribution the angle ϑ_L is constructed as a solution of the equation

$$\int_0^{\vartheta_L} g^*(\vartheta)\,d\vartheta = \alpha,$$

where $\alpha \in (0,1)$ is uniformly distributed. The solution of the last equation can be easily found according to Newton's method, where the initial value is $\pi/2$.

One can simulate the beta distribution with the parameters μ and ν in the following way (Hastings and Peacock, 1975). Let α_1, $\alpha_2 \in (0,1)$ be uniformly distributed. One calculates $S_1 = \alpha_1^{1/\mu}$ and $S_2 = \alpha_2^{1/\nu}$ and if $S_1 + S_2 \leqslant 1$; then $\beta(\mu,\nu) \sim S_1/(S_1 + S_2)$. If $S_1 + S_2 > 1$, one must take the next two uniformly distributed values, calculate S_1 and S_2 for them, and check the last inequality again.

Table 1. Relative Computer Time for the Construction of a Canopy Model

Canopy Type	*Beta Distribution*	*Trigonometrical Distribution*
Uniform	4.9	2.0
Planophile	9.0	14.4
Erectophile	9.0	5.4
Plagiophile	63.1	13.6
Extremophile	3.6	10.2
Spherical	6.7	1.5
Constant	1.0	1.0

Now, the question arises: which distribution must be used to simulate, for instance, the planophile leaves? Since both distributions have statistically similar results (Goel and Strebel, 1984), then a convenient criterion for such a choice may be the computer time spent on the construction of a canopy model. In Table 1 the times for the construction of the canopy model relative to the most simple case of a constant inclination angle are shown. It is evident from the table that for some orientation (uniform, erectophile, plagiophile, and spherical) the trigonometrical LADs have an advantage, except in the cases of planophile and extremophile. The very long simulation time for plagiophile canopy type according to the beta distribution is a result of the great values for parameters μ and ν.

CONTRIBUTION OF THE SPECULAR COMPONENT OF LEAF REFLECTANCE

The specular component of the reflection results from the presence of the wax layer on the leaf surface (Vanderbilt and Grant, 1985). Intensity of the specular component R_F is defined by the formula of Fresnel:

$$R_F(\vartheta', n) = \frac{1}{2}\left[\frac{\sin^2(\vartheta' - i)}{\sin^2(\vartheta' + i)} + \frac{\tan(\vartheta' - i)}{\tan(\vartheta' + i)}\right], \quad (1)$$

where $i = \sin^{-1}(\sin\vartheta'/n)$. Reflection takes place in the plane defined by the leaf normal r_L and the incident ray r', and the reflection angle ϑ is equal to the angle ϑ' between r_L and r'. Note that in the limiting case $\vartheta' = 0$ (the incident ray goes along the normal) the formula (1) does not work and in that case

$$R_F(0, n) = [(n-1)/(n+1)]^2.$$

Evidently, with the help of direct imitation or the so-called method of straightforward simulation it is impossible to estimate the contribution of the specular component, since the probability that after the interaction the photon reflects in the direction of a receiver at a solid angle $\Delta\Omega$ is too small. Below we suggest the following algorithm:

After the interaction with the upper surface of a leaf, i.e., $\cos(r_L, r') > 0$ (in the opposite case the specular component is neglected because the reflected photon goes down), we artificially twine the normal of the leaf along the azimuth to the vertical plane with the receivers and begin "to fluctuate" the leaf orientation according to the normal law with the mathematical expectation equal to the difference between the leaf normal and incident angle with some dispersion. For economy of computer time, first, we do not simulate the normal distribution itself but approximate it by two normalized hyperbolas. Secondly, we use only trigonometrical functions of the angles of the incident and reflected rays and not the angles themselves. However, the values of the angles themselves are needed for the construction of the hyperbola since a hyperbola is described by $f(x) = 1/x$. Therefore, in this case, the trajectory goes only along the net of directions defined before and the hyperbolas themselves are approximated by the piecewise functions.

Then the contribution of the specular component of the leaf reflectance is given by the equality

$$F = \frac{\int_{\Delta\Omega_L} R_F g(r_L)\, dr_L}{\Delta\Omega}. \quad (2)$$

Let us describe the above process more precisely. Let a parameter $\delta \in [0,1]$ characterize the dispersion of our approximation ("a spread" of the specular component). If $\delta = 0$, then the contribution occurs in all directions and, if $\delta = 1$, the contribution is only to the receiver in the direction of the reflected ray. Further, we introduce the coefficients a_i, $i = 1, \ldots, L$ (L is the number of receivers). Let $\delta_{ii} = \delta$, then

$$a_i = \begin{cases} \delta_{ij}, & r \in \Delta\Omega_j, \\ j = 1, \ldots, L, & \cos(r_L, r') > 0, \\ 0, & \cos(r_L, r') < 0. \end{cases}$$

Here r is the specularly reflected ray and

$$\delta_{ij} = \gamma_j \Delta\vartheta_i$$

$$\cdot \begin{cases} |\vartheta_i - \vartheta_j|^{-1}, & i \neq j, \quad \varphi_i = \varphi_j, \\ |\vartheta_i + \vartheta_j|^{-1}, & i \neq j, \quad \varphi_i = \varphi_j + 180°, \end{cases}$$

where the parameters γ_j are chosen as normalization factors in such a way that $\sum_{i=1}^{L} \delta_{ij} = 1$, $j = 1, \ldots, L$.

So, for every act of interaction with leaf for the calculation of the specular component contribution to the ith receiver, we summarize the values of $R_F(r_L, r', n) \cdot a_i(x_k) \cdot (\sin\vartheta_L)^{-1} \cdot B_j(x_k)$. Here x_k is the point of Markov's trajectory, and $B_j(x_k)$ is the "weight" of photon for k-order scattering for jth trajectory, $B_j(x_1) = 1$, $B_j(x_k) = (1-\kappa)B_j(x_{k-1})$, $k = 2, 3, \ldots$, and κ is the coefficient of leaf absorption. The presence of $(\sin\vartheta_L)^{-1}$ results from the fact that in the above model the LAD has been constructed according to the function $g^*(\vartheta_L)$ but not $g(\vartheta_L)$, which is summarized in Eq. (2).

If N trials are carried out, then we obtain an estimation of the contribution of the leaf specular component for the ith receiver, namely,

$$F_i \approx \frac{1}{N} \sum_{j=1}^{N} \sum_{k=1}^{\infty} R_F(r_L, r', n) \cdot a_i(x_k) \cdot (\sin\vartheta_L)^{-1} \cdot B_j(x_k), \qquad i = 1, \ldots, L. \quad (3)$$

Note, that in the case of interaction with the soil or stem, $R_F = 0$.

CALCULATION OF THE BRDF

Let us introduce the coefficients Q according to

$$Q^{i,j}(x_k) = P_i(x_k) B_j(x_k), \qquad i = 1, \ldots, L,$$

where

$$P_i(x_k) = \begin{cases} K\int_{\Delta\Omega_i} \rho\, dr & \text{if a photon from the point } x_k \text{ flies to the direction of a solid angle } \Delta\Omega_i, \\ 0, & \text{in the opposite case,} \end{cases}$$

and $\rho(r, r_L) = 2\cos(r, r_L)$ is the phase function of the Lambertian surface of a leaf. Here $K = T_\lambda$ or $K = R_\lambda$, and it depends on whether reflectance or transmittance takes place. Thus, $Q^{i,j}(x_k)$ is a contribution of the jth photon at the point x_k to the estimation of the ith functional. Then one can calculate the estimate of the contribution to the ith receiver as an average of N realizations, namely,

$$I_i \approx \frac{1}{N} \sum_{j=1}^{N} \sum_{k=1}^{\infty} Q^{i,j}(x_k). \tag{4}$$

In order not to add the "small weight" $B_j(x_k)$ into the inner sum in (3) and (4) but to obtain the unbiased estimations, we undertake a random cutoff of the trajectory (Ross and Marshak, 1985; 1988).

Taking into account (3) and (4), the BRDF is calculated according to

$$b_i = \frac{I_i + F_i}{\cos\vartheta_i \cdot \Delta\Omega_i}, \qquad i = 1, \ldots, L.$$

RESULTS OF NUMERICAL EXPERIMENTS

The results of numerical experiments, carried out for the standard set (Ross and Marshak, 1987b) of parameters of the canopy model, are demonstrated below. They show the influence of the LAD and the specular reflectance component on the crop BRDF.

So, the plant architecture is described as follows: The height of the plant $H = 60$ cm; each plant has four round leaves with a diameter of 7.6 cm; the azimuth angle between the successive leaves on the genetic spiral $\alpha_\Gamma = 120°$; the stems are absent. The canopy architecture is a check rows crop with leaf area index LAI = 3. The optical parameters are: The leaf reflection coefficient $R_\lambda = 0.04$; the leaf transmission coefficient $T_\lambda = 0.04$; the index of refraction is varied from $n = 1.0$ to $n = 1.4$; the soil is black ($R_{\text{soil}} = 0$). The conditions of illumination are: The solar azimuth related to the row is $\varphi_0 = 30°$; the solar zenith angle is $\vartheta_0 = 30°$ or $\vartheta_0 = 60°$; the diffuse radiation is absent.

All calculations are carried out in the principal plane.

INFLUENCE OF THE LAD

In this section we suppose that the specular component of leaf reflectance is absent, i.e., $n = 1.0$. In Fig. 2 the crop BRDF for different LADs is presented. The average leaf inclination angle is varied from the horizontal ($E\vartheta_L = 0°$) to the vertical ($E\vartheta_L = 90°$) (here E is the mathematical expectation). By decreasing the average leaf inclination angle the BRDF increases for all view directions. Hence, the effect of the hot spot also increases and it is the cause of asymmetry of the BRDF in relation to the nadir view direction. Some increases of the BRDF in the nadir view directions for the horizontal and planophile leaves can be explained by the concrete angle in the genetic spiral $\alpha_\Gamma = 120°$. For example, if $\alpha_\Gamma \leqslant 60°$ (Ross and Marshak, 1987b), this increase disappears.

The picture of reflectance changes sharply with the increase of the solar zenith angle. In Fig. 3 the vertical cut of the BRDF in the case of $\vartheta_0 = 60°$ is presented. In comparison with $\vartheta_0 = 30°$ (see Fig. 2), the dependence of the BRDF on the view angle increases strongly to both sides in relation to the nadir direction (towards the antisolar azimuth directions) and $b(\vartheta)$ is described by the parabola

$$b(\vartheta) = a_2\vartheta^2 + a_0 \tag{5}$$

sufficiently well, especially for the crops with more erectophile leaves. By increasing the number of planophile leaves, the value a_0 increases: from $a_0 = 0$ for vertical leaves to $a_0 = R_\lambda/2$ for planophile leaves. [In the case of horizontal leaves and even planophile leaves the approximation of the BRDF by a parabola (5) is not quite correct, since in the case of horizontal leaves in the opposite side of the sun ($\varphi = \varphi_0 + 180°$) it is seen from Fig. 3 that the reflection is practically constant for all view directions.] As is seen from Fig. 3, the coefficient a_2 in (5) decreases from erectophile to the planophile LAD and the "extension" of the parabola takes place. An essential distinction of parabola arises only in the direction of the hot spot, where a sharp and slim peak is observed.

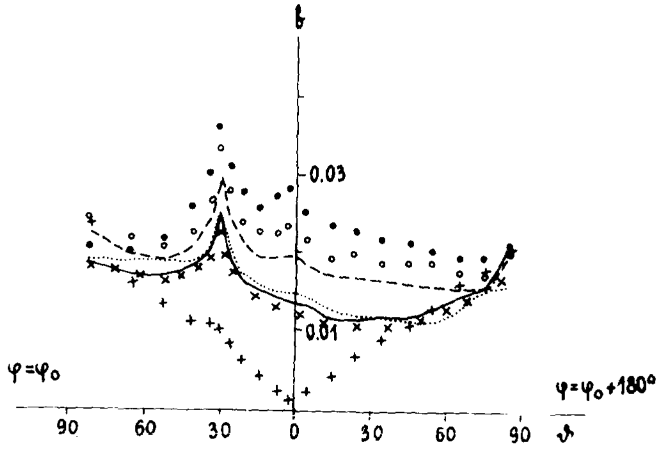

Figure 2. Polar diagram of the canopy BRDF on the principal plane at different LADs, $\vartheta_0 = 30°$, $n = 1.0$.

N of curve	*LAD*	*Mathematical Expectation*
1 (●)	horizontal	0.0
2 (○)	planophile	26.8
3 (---)	uniform	45.0
4 (—)	spherical	57.3
5 (×)	erectophile	63.2
6 (+)	vertical	90.0
7 (---)	soybean	51.8

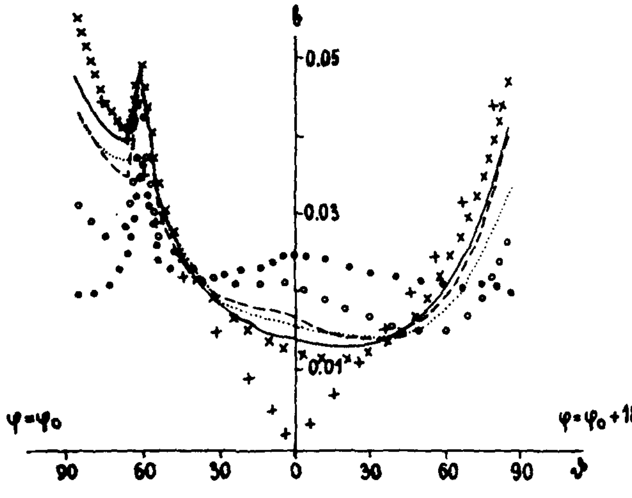

Figure 3. Polar diagram of the canopy BRDF at different LADs, $\vartheta_0 = 60°$, $n = 1.0$ (the definitions are the same as in Fig. 2)

The comparison of the BRDF for the orientations having equal first moment ($E\vartheta_L = 45°$) and unequal dispersion (see Fig. 4) is of interest. If in the sun's side ($\varphi = \varphi_0$), the BRDFs practically coincide, but if in the opposite side of the sun ($\varphi = \varphi_0 + 180°$) for $10° < \vartheta < 70°$ strong distinctions are evident. Note that by increasing the dispersion the BRDF increases correspondingly. The minimum of the BRDF occurs in the case of $D\vartheta_L = 0$ since the leaves whose normals are directed near the sun's opposite side $\varphi_L \approx \varphi_0 + 180°$ are slightly illuminated by the direct solar radiation (Ross and Marshak, 1987b; 1988). Thus the BRDF around the region of $\vartheta \approx 90° - E\vartheta_L$ is very sensitive to the dispersion of the LAD.

INFLUENCE OF THE SPECULAR COMPONENT OF LEAF REFLECTANCE ON THE BRDF

It is obvious that considering only first-order scattering, the contribution of the specular component of leaf reflectance is independent of the diffuse coefficient of reflection and transmission but it is defined by LAD and by the refraction coefficient n. Since this contribution is the same for all spectral regions, it is most interesting to investigate the influence of the specular component contribution on the LAD in the red spectral region.

Additional numerical experiments for the canopy with spherical LAD indicate that in the case of $\vartheta_0 = 30°$ and $n = 1.4$ the contribution of the specular component makes up the values of the BRDF from 0.01 to 0.02 and the maximal value is achieved in the region of the hot spot. By increasing the solar zenith angle the contribution of the specular component increases correspondingly and for $\vartheta_0 = 60°$ and view directions $\vartheta \geqslant 60°$ (in the sun's side) it reaches 0.04. The presence of nearly vertical leaves, the specular component from which is directed to these directions, is a cause of such an increase. By increasing n from 1.0 to 1.4 the sharp increase of the BRDF is clearly seen (especially in the hot spot region). Such an increasing BRDF has an exponential character.

Figures 5 and 6 demonstrate the influence of the LAD on the contribution of the specular component in the cases of $\vartheta_0 = 30°$ and $\vartheta_0 = 60°$. If $\vartheta_0 = 30°$ for the orientations that have a large number of planophile leaves in the BRDF, the specular shine is clearly seen and the more horizontal leaves give the strong peak. (For the crop with horizontal leaves in the region of the specular reflection the δ function appears.) The extremophile leaves have the largest value (up to 0.20) of the contribution of the specular component, since they have nearly horizontal leaves, then planophile leaves (up to 0.16), and uniformly oriented leaves (up to 0.12). For the spherical, plagiophile and especially erectophile oriented leaves, the peak in the specular region is generally absent since the number of horizontal leaves in these orientations is small. By increasing the view directions in the opposite side of the sun the BRDF decreases for extremophile leaves and, on the contrary, it increases for the plagiophile leaves since for these view directions the essential role is played by the plagiophile leaves. The contribution to the near nadir directions $\vartheta < 20°$ is given by the

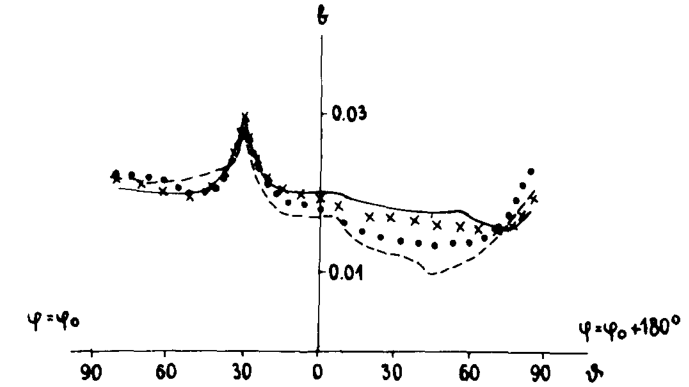

Figure 4. Polar diagram of the canopy BRDF at equal average inclination angle $E\vartheta_L = 45°$ and unequal dispersion $D\vartheta_L$, $\vartheta_0 = 30°$, $n = 1.0$.

N of curve	*LAD*	*Disperson*
1 (---)	constant ($\vartheta_L = 45°$)	0 °
2 (●)	plagiophile	4.6°
3 (×)	uniform	11.8°
4 (—)	extremophile	18.9°

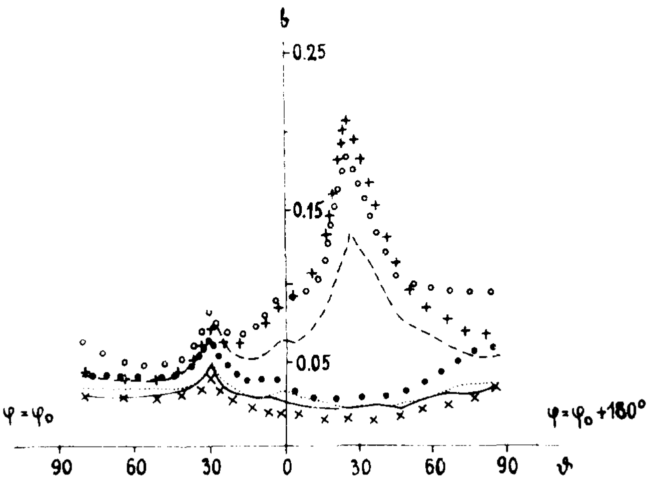

Figure 5. Polar diagram of the canopy BRDF taking into account the specular component of the leaf reflectance, $\vartheta_0 = 30°$, $n = 1.4$ (the definitions are the same as in Fig. 1).

leaves whose normals are oriented to the near vertical directions $\vartheta_L < 30°$. That is why in this region the BRDF is ordered according to the existence of such leaves: planophile and extremophile, then uniform, plagiophile, spherical, and finally erectophile. An analogous picture is observed in the region of the hot spot.

The same leaf orientations, except for the solar zenith angle $\vartheta_0 = 60°$ are presented in Fig. 6. Note that in comparison with $\vartheta_0 = 30°$ the peak in the specular region is absent and the continuous increasing of the BRDF takes place by increasing the view directions in the opposite side of the sun. The cause of this effect is the fact that in spite of the decrease of the number of photons, reflected in the directions $\vartheta > 60°$, the "weight" of them, i.e., the value of R_F [see Eq. (1)] increases. This is due to the fact that in this case the reflection occurs at a large angle relative to the leaf normal and by increasing the angle between the normal and the incident ray the sharp increase of the specular component takes place. This is the result of the composition of these factors. By this fact one can explain that the BRDF for the plagiophile leaves does not surpass the BRDF for the spherical leaves in the case of large view directions in the opposite side of the sun. In the sun's side for the same view directions (the region of hot spot inclusive) the sharp increase of the BRDF for erectophile, extremophile, and spherical orientations is observed. The cause of that is the presence of the large number of the vertical leaves.

In Figs. 2, 3, 5, and 6 we have shown the BRDF of the real canopy of soybean, the LAD of which is simulated by the beta distribution. The parameters μ and ν were calculated by Goel and Strebel (1984), namely, $\mu = 2.177$ and $\nu = 1.607$. Such a canopy, as compared with the spherical orientation, has more planophile and fewer erectophile leaves (see Fig. 1). This fact is reflected by their BRDFs. In Figs. 2 and 5 ($\vartheta_0 = 30°$) the BRDF of the soybean surpasses slightly that of the

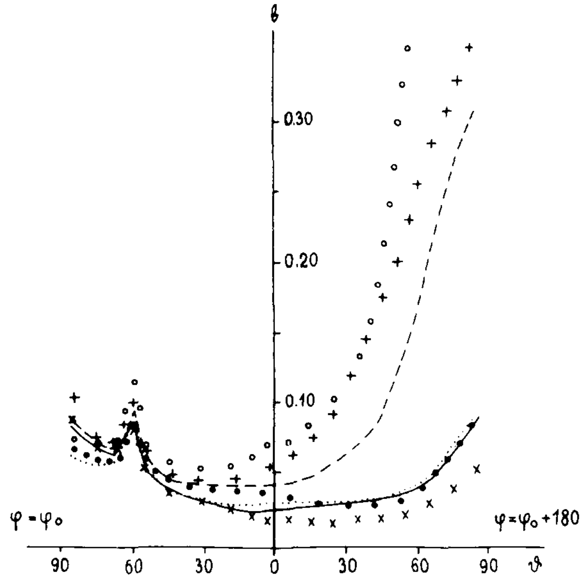

Figure 6. Polar diagram of the canopy BRDF taking into account the specular component of the leaf reflectance, $\vartheta_0 = 60°$, $n = 1.4$ (the definitions are the same as in Fig. 1).

spherically oriented canopy but it is significantly less than that for a uniform LAD. The peak in the region of the specular reflection is absent, which is a result of the small number of horizontal leaves (see Fig. 1). In the opposite case in Figs. 3 and 6, for the large view directions, the BRDF of the soybean canopy is less than that for the spherical canopy since in this region the photon reflected from erectophile leaves gives the significant contribution to the BRDF. In the near nadir region for both specular reflected photons (Fig. 6) and photons reflected by the Lambertian law (Fig. 3), the role of plagiophile leaves is essential and the BRDF of soybean crop in this region is a little greater than that for the spherically oriented leaves.

Remark. The sharp increase of the specular component for the more horizontal leaves in the case of $\vartheta > 60°$ is not realized in the actual canopies and it is necessary to modify the formula of Fresnel (1) by the attenuation factor k, depending on the angle between ϑ' and ϑ_L (see Vanderbilt and Grant, 1985).

CONCLUSION

The results represented in the present paper show that the method of Monte Carlo is a useful tool for the estimation of the influence of the LAD and the specular component of leaf reflectance on the BRDF. This method allows us to simulate an arbitrary theoretical LAD as the LAD measured experimentally. The presence of only two independent parameters of beta distribution gives it an advantage in comparison with the trigonometrical distribution, especially for those orientations for which the computer time spent for their realization does not surpass significantly the time spent on the construction of the realization of the trigonometrical distribution (see Table 1).

The analysis of numerical experiments shows that for high sun (Fig. 2) the BRDF is larger if the fraction of planophile-oriented leaves is larger. The increase of the dispersion of the LAD in the case of equal mathematical expectation leads to an increase in the BRDF in the region near the view direction $\vartheta = 90° - E\vartheta_L$ in the opposite side of the sun (Fig. 4).

For low positions of the sun the dependence of the BRDF on the LAD is quite different (Fig. 3). For the canopy with more erectophile leaves, the BRDF is sufficiently well described by the parabola with inclusion of the peak in the region of the hot spot. For such crops the greatest distinction from the Lambertian surface arises, but for horizontal and near horizontal orientations, the approximation of the canopy by the Lambertian surface gives fewer mistakes with the exception of the region around the hot spot.

The consideration of the specular component of leaf reflectance significantly changes the BRDF. In the region of specular shining for high sun the large increase of the BRDF is observed in the case of nearly horizontal leaves and the height of the peak increases as the leaves become more horizontal (Fig. 5).

For low sun (Fig. 6) the peak in the specular region is absent and the BRDF increases continuously for the view directions $\vartheta \geqslant \vartheta_0$, especially for crops with planophile orientation. This effect can be explained by the significant increase in the contribution of the specular component in these view directions.

So, for the red spectral region the consideration of the contribution of the specular component is necessary for the construction of a canopy reflection model. In the near infrared spectral region for the crops with the spherical and more erectophile LAD, the contribution of the specular component may be neglected. Hence, for the planophile leaves (especially in the case of low sun) even for the near infrared spectral region neglecting of the specular component may give a serious error in the results.

The authors acknowledge the discussions with Dr. T. Herbert of the University of Miami. He kindly agreed to read the manuscript of the present paper; he made many useful remarks and rendered linguistic help as well. We are thankful also to our colleagues Drs. T. Nilson and A. Kuusk for fruitful discussions.

REFERENCES

Breece, H. T., III, and Holmes, R. A. (1971), Bidirectional scattering characteristics of healthy green soybean and corn leaves in vivo, *Appl. Opt.* 10:119–127.

Bunnik, N. J. J. (1978), *The Multispectral Reflectance of Shortwave Radiation by Agricultural Crops in Relation with Their Morphological and Optical Properties*, Mededelingen Landbouwhogeschool, Wageningen, The Netherlands, 78-1.

Gausman, H. W., Allen, W. A., Wiegand, C. L., Escobar, D. E., Rodriguez, R. R., and Richardson, A. J. (1973), The leaf mesophylls of twenty crops, their light spectra, and optical and geometrical parameters, Technical Bulletin 1465, Agricult. Res. Service, U.S. Dept. of Agric., Texas Agric. Experiment Station, 59 pp.

Goel, N., and Strebel, D. E. (1984), Simple beta distribution representation of leaf orientation in vegetation canopies, *Agron. J.* 76:800–802.

Goel, N. S., and Thompson, R. L. (1984), Inversion of vegetation canopy reflectance models for estimating agronomic variables. IV. Total inversion of the SAIL model, *Remote Sens. Environ.* 15:237–253.

Hastings, N. A. J., and Peacock, J. B. (1975), *Statistical Distributions*, Butterworths, London.

Moldau, H. (1965), Vegetative course of the luminance factor of leaves of some plants, in *Questions on Radiation Regime of Plant Stand*, Acad. Sci. ESSR, Inst. of Phys. and Astronomy, Tartu, pp. 89–95 (Russian).

Moldau, H. (1967), Optical model of plant leaf, In *Phytoactinometric Investigations of Plant Canopy*, Valgus Publishers, Tallinn, pp. 89–109 (Russian).

Nilson, T., and Kuusk, A. (1984), Approximate analytical formulas for calculating the spectral brightness coefficients of agricultural vegetation, *Earth Res. Space* 5:76–83 (Russian).

Reyna, E., and Badhwar, G. D. (1985), Inclusion of specular reflectance in vegetative canopy models, *IEEE Trans. Geosci. Remote Sens.* 4:731–736.

Ross, J. (1981), The radiation regime and architecture of plant stands, Dr. W. Junk Publishers, The Hague, Boston, London, 391 pp.

Ross, J. K., and Marshak, A. L. (1985), A Monte Carlo procedure for calculating the scattering of solar radiation by plant canopies, *Sov. J. Remote Sens.* 4:783–801.

Ross, J. K., and Marshak, A. L. (1987a), A Monte Carlo determination of spectral radiance of the vegetative cover as a function of illumination conditions, *Earth Res. Space* 2:96–105 (Russian).

Ross, J. K., and Marshak, A. L. (1987b), A Monte Carlo estimation of the canopy architecture effect on canopy reflectance, *Earth Res. Space* 4:86–93 (Russian).

Ross, J. K., and Marshak, A. L. (1988), Calculation of the canopy bidirectional reflectance using the Monte Carlo method, *Remote Sens. Environ.* 24:213–225.

Tucker, C. J., and Garrat, M. W. (1977), Leaf optical system modeled as a stochastic process, *Appl. Opt.* 16:635–642.

Vanderbilt, V. C., and Grant, L. (1985), Plant canopy specular reflectance model, *IEEE Trans Geosci. Remote Sens.* 4:722–730.

Verhoef, W. (1984), Light scattering by leaf layers with application to canopy reflectance modelling. The SAIL model, *Remote Sens. Environ.* 16:125–141.

Woolley, J. T. (1971), Reflectance and transmittance of light by leaves, *Plant Physiol.* 47:656–662.