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A Physical Model of the Bidirectional Reflectance of Vegetation Canopies

2. Inversion and Validation

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A physically based, analytical model of the bidirectional reflectance of porous media was derived in a companion paper (Verstraete et al., this issue). This model is validated against laboratory and ground-based measurements taken over two vegetation covers, both in the visible and near-infrared spectral regions. An inversion procedure, based on a nonlinear optimization technique, is used to infer the intrinsic optical properties of the leaves, as well as information on the morphology of the canopies, that is, on the geometrical arrangements of these scatterers in space. The model is then used to generate theoretical bidirectional reflectances, using the values of the relevant parameters retrieved from the inversion procedure, and these values compare favorably with the actual observations over the entire range of illumination and observation angles. The values of the parameters retrieved from the inversion procedure are discussed, validated against actual independent measurements, and interpreted in terms of the physical and morphological properties of the vegetation covers.

1. INTRODUCTION

In a companion paper, *Verstraete et al.* [this issue] (hereinafter referred to as part 1) derived a new model of the bidirectional reflectance of a semi-infinite canopy. Based on a physical approach, this analytical model [part 1, equation (51)] expresses the bidirectional reflectance field of a semi-infinite canopy as a combination of functions describing (1) the optical properties of the leaves through their single-scattering albedo and their phase function, (2) the average distribution of leaf orientations, and (3) the architecture of the canopy, which can be interpreted in terms of the average distance between the leaves in the vertical and horizontal directions. If the above functions and the canopy parameters are known a priori, this model predicts the bidirectional reflectances over the upward hemisphere for arbitrary illumination and observation directions, and hence the directional hemispherical reflectance of the surface, also known as its albedo.

In the particular case of a canopy with no "hot spot" component, and where the leaves are uniformly distributed, the single-scattering model fits the three-dimensional ray-tracing model developed by *Kimes* [1984] to better than one percent of the reflectance values, for various distributions of leaf orientations [*Dickinson et al.* 1990].

This paper addresses the inverse problem of retrieving the

model parameters, starting from a sampling of the bidirectional reflectance field. Clearly, what is needed at this step is an economical, efficient, and yet accurate inversion procedure. The achievement of this step allows us to interpret satellite data, and to extract some basic information about the physical and the morphological properties of a vegetation canopy. However, before dealing with actual satellite data, it is appropriate to validate and to test the procedure (that is, the model plus the inversion) against well-processed data gathered at the ground level where the relative contribution of the atmospheric effects is lower and easier to remove. To our knowledge, only a few data sets match the requirements for a rigorous test of the inversion procedure. We selected two of these data sets: The first one is based on laboratory measurements of reflectances over a clover patch [*Woessner and Hapke*, 1987]; the second is based on ground level measurements of a soybean canopy [*Ranson et al.*, 1984]. In both data sets, the bidirectional reflectance exhibits a marked hot spot effect which is of special interest here for reasons discussed in part 1.

2. DEVELOPMENT OF A PARAMETRIC MODEL

According to part 1, the bidirectional reflectance ρ of a canopy illuminated by the Sun from a direction (θ_1, ϕ_1) , observed from a direction (θ_2, ϕ_2) , and normalized with respect to the reflectance of a perfectly reflecting Lambertian surface under the same conditions of illumination and observation, is given by

$$\rho(\theta_1, \phi_1; \theta_2, \phi_2) = \frac{\omega}{4} \frac{\kappa_1}{\kappa_1 \mu_2 + \kappa_2 \mu_1} \cdot [P_v(g)P(g) + H(\mu_1/\kappa_1)H(\mu_2/\kappa_2) - 1] \quad (1)$$

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where

$$\mu_1 = \cos \theta_1 \quad \mu_2 = \cos \theta_2$$

$$\cos g = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\phi_1 - \phi_2)$$

$$H(x) = \frac{1+x}{1+(1-\omega)^{1/2}x}$$

In these equations, θ_1 and ϕ_1 are the zenith and azimuth angles of the Sun, θ_2 and ϕ_2 are the zenith and azimuth angles of the observer, g is the phase angle between the incoming and the outgoing directions, ω is the average single-scattering albedo of the particles making up the surface, $P(g)$ is the average phase function, κ_1 and κ_2 describe the leaf orientation distribution for the illumination and viewing angles, respectively, and the term $H(\mu_1/\kappa_1)H(\mu_2/\kappa_2) - 1$ approximates the contribution from multiple scattering [see Dickinson *et al.*, 1990].

$P_v(g)$ is the function that accounts for the joint transmission of the incoming and outgoing radiation, and thereby also for the hot spot effect arising at low phase angle:

$$P_v(g) = \left\{ \frac{\Lambda}{2} \frac{\kappa_1 \mu_2 + \kappa_2 \mu_1}{\mu_1 \mu_2} \left(\frac{\pi}{a} \right)^{1/2} \exp \left(\frac{b^2}{a} \right) \cdot \left[\operatorname{erf} \left(\sqrt{a} \frac{2r}{G} + \frac{b}{\sqrt{a}} \right) - \operatorname{erf} \left(\frac{b}{\sqrt{a}} \right) \right] + \exp \left(\frac{4}{3\pi} \frac{2r}{G} \frac{\kappa_2 \Lambda}{\mu_2} \right) \left[\exp \left(- \frac{\kappa_1 \mu_2 + \kappa_2 \mu_1}{\mu_1 \mu_2} \Lambda \frac{2r}{G} \right) - \exp \left(- \frac{\kappa_1 \mu_2 + \kappa_2 \mu_1}{\mu_1 \mu_2} \Lambda h \right) \right] \right\} \quad (2)$$

where

$$G = [\tan^2 \theta_1 + \tan^2 \theta_2 - 2 \tan \theta_1 \tan \theta_2 \cos(\phi_1 - \phi_2)]^{1/2}$$

$$a = \left(1 - \frac{4}{3\pi} \right) \frac{G \kappa_2 \Lambda}{2r \mu_2} \quad b = \frac{\kappa_1 \Lambda}{2\mu_1}$$

r is the radius of the sun flecks on the leaves, and Λ is the leaf area density of the canopy, a measure of the density of leaf material.

Bidirectional reflectance data are often reported as values normalized by the reflectance of a Lambertian surface illuminated from the zenith. In this case, the theoretical expression in (1) must be multiplied by μ_1 . Unnormalized reflectance is given by multiplying (1) by μ_1/π .

In order to solve the inverse problem, a parametric version of the physical model must be derived. Consequently, mathematical expressions expressing the phase function for elementary scattering elements and the distribution of scatterer orientation have to be given. For the phase function, the frequently used empirical function introduced by Henyey and Greenstein [1941] was chosen:

$$P(g) = \frac{(1 - \Theta^2)}{(1 + \Theta^2 - 2\Theta \cos \Omega)^{3/2}} \quad (3)$$

where the scattering angle $\Omega = \pi - g$, and Θ is the asymmetry factor ranging from -1 (backward scattering) to $+1$ (forward scattering).

A practical estimate of the average leaf orientation distribution κ can be obtained from the widely used parameterization of Goudriaan [1977]:

$$\kappa_i(\mu_i) = \Psi_1 + \Psi_2 \mu_i \quad \Psi_1 = 0.5 - 0.6333\chi_i - 0.33\chi_i^2 \quad (4)$$

$$\Psi_2 = 0.877(1 - 2\Psi_1)$$

where i stands for 1 or 2, the two directions of illumination and observation, and where $-0.4 < \chi_i < 0.6$. Here, χ_i is more negative (-0.4) for an erectophile canopy (mostly vertical leaves), 0 for a canopy with a uniform leaf orientation distribution (equal probability for all leaf orientations), and more positive (0.6) for a planophile canopy (mostly horizontal leaves). The parameter χ_i is a function of the leaf angle distribution in the canopy:

$$\chi_i = \pm \int_0^{\pi/2} |1 - g_L(\theta_i)| \sin(\theta_i) d\theta_i \quad (5)$$

where θ_i is the leaf zenith angle and $g_L(\theta_i)$ is the leaf angle distribution. Two issues arise from the use of such a model. First, in order to ensure a finite value for the reflectance, very high precision computations must be done to evaluate the error functions in $P_v(g)$. Although this is not a problem on a supercomputer with access to good numerical libraries, it nevertheless reduces the applicability of the model. More serious, however, is the difficulty of inverting such a model; this is not impossible in principle, but the requirements for high accuracy computations, together with the rather complex nature of the model do not seem to encourage the general use of this model.

In order to make the joint transmission function more tractable for inversion purposes, we develop an approximate expression for $P_v(g)$, using some of the significant parameters and variables of (2):

$$\tilde{P}_v(g) \approx 1 + \frac{1}{1 + V_p(g)} \quad (6)$$

$$V_p(g) = 4 \left(1 - \frac{4}{3\pi} \right) \frac{G}{2r\Lambda} \frac{\mu_2}{\kappa_2}$$

where r is the radius of the sun flecks on the inclined leaf. This simple approximate expression has the advantages of being computationally cheap, of being easy to invert on actual data, and of fitting the theoretical model described above with a good accuracy. This approximation was derived for values of χ_i and $2r\Lambda$ varying from -0.4 to 0.6 , and from 0.01 to 2.0 , respectively; for illumination and viewing angles ranging between 0° and 60° ; and for a relative azimuth varying from 0° to 180° . As shown in Figure 1a, (6) fits the exact formula to better than 5% in most cases when χ_i is equal to 0.6 and 0.0 . The worst disagreement, with an error reaching 12%, is observed (Figure 1b) for an erectophile canopy (that is, $\chi_i = -0.4$), when both θ_1 and θ_2 are greater than 50° , for values of $2r\Lambda$ equal to or larger than 2.0 . In practice, the numerical difference between the exact and the approximate formulae is smaller than the typical uncertainties in the observations. Furthermore, it appears that the sharpness of the hot spot phenomenon is controlled by the product $2r\Lambda$ for the range of variations we considered. Therefore, only one parameter (namely $2r\Lambda$) instead of two is required to represent reasonably well the width of the hot spot, and this constitutes a supplementary advantage for

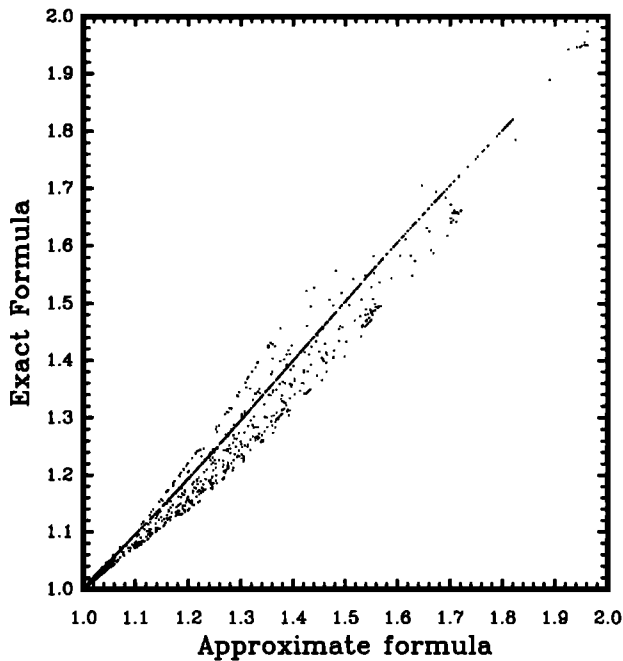


Fig. 1a. Comparison between the exact formulation for the $P_v(g)$ function with its approximate expression as given by (6), for two χ_l values of 0.6 and 0.0.

inversion purposes. Equation (6) has been built in order to preserve most of the physics involved when deriving the joint transmission and the related hot spot phenomenon, and it can be seen that the sharpness of the hot spot is determined by the ratio of the average radius of the sun flecks r to the typical length $1/\Lambda$ which is related to the typical distance between the leaves.

In the end, the proposed parametric model describes the bidirectional reflectance field of a canopy with the help of four unknown parameters: ω , χ_l , Θ , and $2r\Lambda$. The inverse

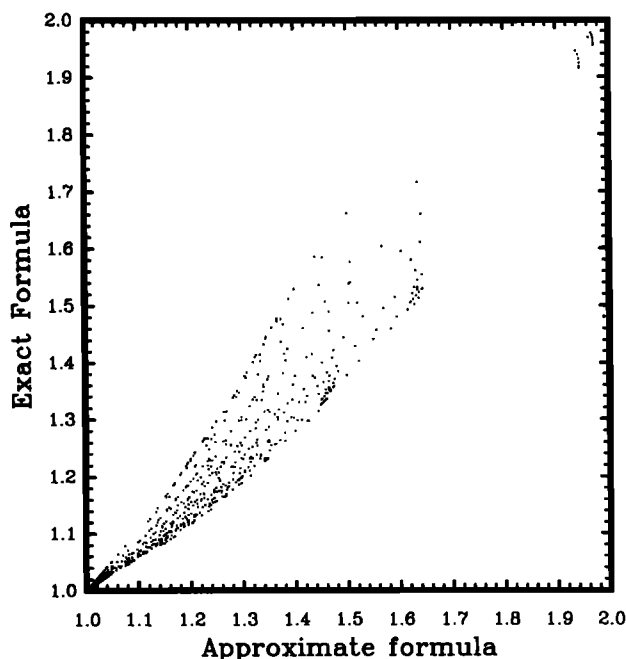


Fig. 1b. Same as Figure 1a, except for χ_l equals -0.4 .

problem consists in retrieving the values of these parameters from a limited sample of bidirectional reflectances, assuming that (1) expresses the functional dependency of the reflected field with respect to these parameters.

3. DESCRIPTION OF THE INVERSION PROCEDURE

Because of the high nonlinearity of (1), the inverse problem must be solved by applying an iterative numerical approach to determine the best values of the four parameters. The procedure adopted in this study is analogous to that chosen by *Pinty et al.* [1989]. The basic requirement is to find the four parameter values which minimize δ^2 , defined as

$$\delta^2 = \sum_{k=1}^n [\rho_k - \rho(\theta_{1,k}, \phi_{1,k}, \theta_{2,k}, \phi_{2,k})]^2 \quad (7)$$

where ρ_k is the measured and ρ the modeled bidirectional reflectance of the surface, for the relative geometry of illumination and observation defined by $\theta_{1,k}$, $\phi_{1,k}$, $\theta_{2,k}$, and $\phi_{2,k}$.

The nonlinear least squares fitting algorithm which is used to solve (7) was selected from the Numerical Algorithms Group (NAG) library. The routine EO4JAF used here implements a quasi-Newton algorithm for finding a minimum of a function, subject to fixed upper and lower bounds on the independent variables, using function values only. An initial guess for each of the desired parameters must be provided to the routine. The root mean square (RMS) of the fits, that is, $(\delta^2/n_f)^{1/2}$, where n_f is the number of degrees of freedom, was calculated to give an indication of the quality of the optimization.

A discussion of the performance of the procedure described above can be found in the work by *Pinty et al.* [1989]. This includes results from a sensitivity study to the initial guess, and a discussion of the impact of the angular sampling frequency of the reflected field on the quality of the retrieval, as well as of the quality of the inversion when data are contaminated by a random noise. According to the results of some new tests done with data generated from (1), it appears that the main conclusions of the sensitivity tests published in this previous study are also valid here.

4. APPLICATION OF THE INVERSION PROCEDURE

Table 1 summarizes the sources, surface types, spectral regions of measurements, and angular sampling frequencies of the two data sets used here. Only part of the entire data set available from these sources was actually utilized. The first data set was chosen both because it contains a fairly well defined hot spot contribution, and because the measured bidirectional reflectances were not contaminated by the contribution from additional atmospheric diffuse sources since the measurements were taken in a laboratory. The second data set tests the model under real atmospheric conditions, and permits the validation of the inversion procedure because the parameters describing the optical properties of individual leaves and their orientation in the canopy were measured independently in addition to the bidirectional reflectances.

The inversion procedure described in section 3 was applied to these two observational data sets. In each case, the values of the four unknown parameters retrieved from the inversion procedure were introduced in (1), in order to

TABLE 1. Data Set Descriptions

Data Set	Source	Cover Type	Spectral Bands of Measurements	θ_1 , deg	θ_2 , deg	$\psi = \phi_2 - \phi_1$, deg
1	Woessner and Hapke [1987]	clover patch	0.448 μm	0, 60	0-80, each 10°	0, 180
2	Ranson et al. [1984]	soybean	0.5-0.6 μm , 0.6-0.7 μm 0.7-0.8 μm , 0.8-1.1 μm	44, 55, 61	0, 7, 15, 22 30, 45, 60	0-360, nonuniform

regenerate the theoretical bidirectional reflectance values under the illumination and observation geometries at the time the data were obtained. This was performed independently for each illumination angle where data were collected, and the direct calculation (that is, modeling the bidirectional reflectances as observed using the retrieved values as input parameters) was applied to estimate the bidirectional reflectances at all illumination angles.

4.1. Laboratory Measurements: Data Set 1

The bidirectional reflectance field of a clover (*Trifolium repens*) patch was measured in the laboratory by Woessner and Hapke [1987]. Detailed information on the apparatus and the design of the experiment can be found in the work by Woessner [1985]. The measurements were taken only in the principal plane (that is, the plane defined by the direction of illumination and the normal to the surface) with the viewing angle varying as indicated in Table 1. Reflectance from a normally illuminated halon sample (polytetrafluoroethylene powder) was used as a standard for the measurements.

The bidirectional reflectance data gathered at 0° of illumination were inverted with (1), using the procedure described in the previous section. The values of the four model parameters retrieved from the optimal fit of this equation, as well as the RMS, are summarized in Table 2. The value of ω , close to 0.1, lies in a range which can be expected from measurements made at 0.448 μm , where strong absorption occurs. A significant backward component is observed in the phase function, which is not generally observed over vegetation. For instance, Dickinson et al. [1990] reported that grass leaves behave more or less like isotropic scatterers. The value of χ_l is indicative of a canopy with a quasi-uniform leaf orientation distribution; however, in the absence of any measurements or observations on the canopy morphology, a detailed discussion of the retrieved χ_l values is not possible. These measurements exhibit a rather sharp hot spot, which is reflected in the small value of the parameter $2r\Lambda$.

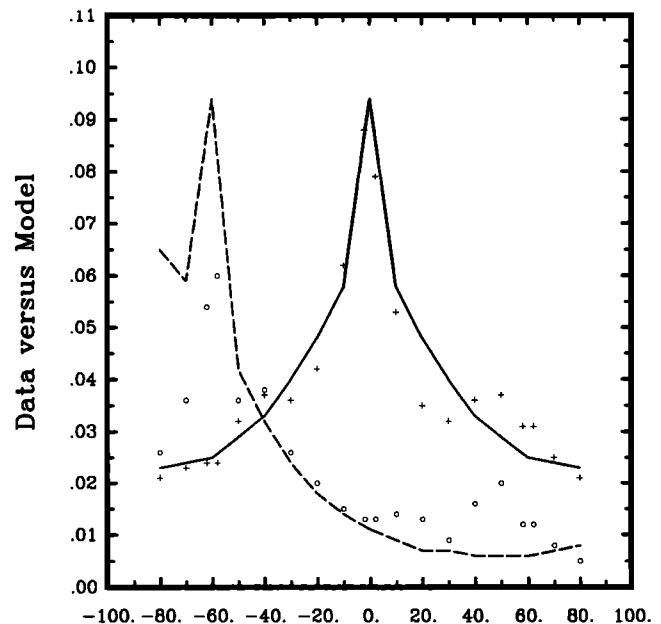
Figure 2 shows the comparison between the bidirectional reflectances modeled with (1), using the optimally fitted parameters, and the whole data set. It must be emphasized

here that the inversion was performed using only data collected at an illumination angle of 0°. The four model parameters retrieved by this procedure were then used to generate the reflected radiances at both 0° and 60°. The patterns present in the data at both angles of illumination are well reproduced by the model. The agreement between the modeled and measured reflectances is, as expected, better at 0° of incidence where the hot spot effect is fairly well reproduced.

For both angles of illumination, disagreement occurs at viewing angles between 40° and 60°, where data display some variations not accounted for by the model. This behavior might be due to the fact that only a few leaves were seen by the sensor, rather than a large ensemble of leaves, and therefore measured reflectance is more sensitive to the detailed structure of the leaves in the patch. The general pattern of the reflectances at 60° of incidence is reasonably well predicted. The value of the parameter $2r\Lambda$, which determines the width of the hot spot phenomenon, has been estimated at 60° from the value retrieved at 0°, using (55) of part 1. The model overestimates the measured reflectance values either in the hot spot region, or when the viewing angle is equal to -80°. Furthermore, when comparing the results of the model inversion on data at 60° to those at 0°, it

TABLE 2. Values of Parameters as Retrieved From Observations Over a Clover Patch

Parameter	Value
Solar zenith angle	0°
ω	0.099
χ_l	0.115
Θ	-0.392
$2r\Lambda$	0.277
RMS of fit	0.0065



Viewing Angle in the principal plane

Fig. 2. Comparison between the bidirectional reflectances measured over a clover patch at 0.448 μm and those modeled with (1), using optimally fitted parameters. Pluses indicate data points for illumination at 0° zenith angle; open circles are for illumination at 60°.

TABLE 3. Values of Parameters as Retrieved From Observations Over a Soybean Canopy

Solar Zenith Angle, deg	ω	χ_l	Θ	$2r\Lambda$	RMS of Fit
<i>Band 1</i>					
44	0.147	0.248	-0.058	2.38	0.0015
55	0.169	0.278	-0.033	1.85	0.0020
61	0.186	0.209	-0.016	1.60	0.0025
<i>Band 2</i>					
44	0.120	0.205	-0.061	2.34	0.0013
55	0.141	0.278	-0.027	1.77	0.0019
61	0.161	0.268	-0.003	1.46	0.0025
<i>Band 3</i>					
44	0.802	0.035	-0.096	0.81	0.011
55	0.809	-0.033	-0.094	0.73	0.014
61	0.815	-0.135	-0.105	0.47	0.016
<i>Band 4</i>					
44	0.915	0.114	-0.119	0.75	0.015
55	0.928	0.094	-0.119	0.61	0.020
61	0.936	0.037	-0.129	0.49	0.023

appears that the parameter $2r\Lambda$ is the one that undergoes the largest relative variation. Since the hot spot is characterized by a strong and sudden increase in reflectance at small phase angles, even a slight error in the measurements can lead to a significantly different values of the parameter controlling the width of this hot spot.

4.2. Ground-Based Measurements: Data Set 2

The measurements of *Ranson et al.* [1984] over a full-covering soybean canopy were also used here because of the quality and extent of agronomical observations made in addition to the reflectances. The percent ground cover, the mean height of the plants and the leaf area index were 99%, 104 cm and 2.9 ± 0.4 , respectively. Although we used the subset of measurements relative to a full and mature soybean canopy, the row planting effects are still detectable at low solar zenith angles. The immediate consequence of this row architecture is a significant azimuthal asymmetry with respect to the principal plane. In order to minimize this alignment effect, we applied our model only to data taken at solar zenith angles greater than 44° . At the remaining three solar angles, the azimuthal asymmetry was small enough to justify the use of data collected on both sides of the principal plane as if they had been acquired on the same side. This procedure allowed us to increase the sampling in azimuth. This latter process was necessary to retrieve the hot spot component which, depending on the leaf sizes and arrangements, occurs on a very narrow range of phase angles.

Since these measurements were taken in situ, the purely bidirectional properties of the surface are smoothed in the data by the contribution of the atmospheric diffuse radiation. Neglecting the contribution due to the multiple interactions between the surface and the atmosphere, the measured bidirectional reflectances R can be expressed following *Pinty et al.* [1989]:

$$R(\theta_1, \theta_2, \psi) = \rho(\theta_1, \theta_2, \psi) + [\bar{\rho}(\theta_1, \theta_2, \psi) - \rho(\theta_1, \theta_2, \psi)]f_d(\theta_1) \quad (8)$$

where

$$f_d(\theta_1) = \frac{E_d(\theta_1)}{E_t(\theta_1)}$$

$$E_d(\theta_1) = \int_0^{\pi/2} \int_0^{2\pi} l_d(\theta_1, \theta', \psi') \sin \theta' \cos \theta' d\theta' d\psi'$$

$$\bar{\rho}(\theta_1, \theta_2, \psi) = \left[\int_0^{\pi/2} \int_0^{2\pi} \rho(\theta', \theta_2, \psi') l_d(\theta_1, \theta', \psi') \cdot \sin \theta' \cos \theta' d\theta' d\psi' \right] [E_d(\theta_1)]^{-1}$$

In these equations, ψ is the relative azimuth between the incidence and observation planes, and θ' and ψ' are dummy integration variables, ρ is the bidirectional reflectance predicted by (1) for the direct beam, f_d is the ratio of diffuse over total irradiance, l_d is the diffuse atmospheric radiance, E_d is the total atmospheric diffuse irradiance, E_t is the total irradiance, and $\bar{\rho}$ is the angular average of the bidirectional reflectance ρ weighted by the diffuse irradiance. Equation (8) can be easily interpreted: the observed bidirectional reflectance R equals the bidirectional reflectance for direct radiation ρ when either there is no diffuse radiation ($f_d = 0$) or when the surface is Lambertian ($\rho = \bar{\rho}$). When neither of these conditions is realized, the uneven illumination from diffuse sky radiation contaminates the measurements, and (8) expresses the correction needed to account for these effects. In this context, *Tanré et al.* [1983] suggested expressing $\bar{\rho}$ as follows:

$$\bar{\rho}(\theta_1, \theta_2, \psi) = a\rho(\theta_1, \theta_2, \psi) + b \quad (9)$$

where the coefficients a and b are estimated from radiative transfer calculations using various realistic surface properties and typical atmospheric conditions. As a first approximation, and according to the results of *Tanré et al.* [1983], we assumed that the published values of a and b derived for savanna at $0.45 \mu\text{m}$ and $0.85 \mu\text{m}$, respectively, were representative of values for a vegetation canopy, on both sides of the $0.7\text{-}\mu\text{m}$ wavelength. The above treatment of the diffuse irradiance differs from the one previously used by *Pinty et al.* [1989] and *Dickinson et al.* [1990] where an isotropic behavior was assumed for this atmospheric diffuse component.

As explained above, the inversion procedure was applied independently for each solar zenith angle and, in each case, the retrieved model parameters were introduced in (1) to regenerate the observed data. Table 3 gives the values of the two optical and of the two geometrical model parameters, leading to a good prediction of the canopy reflectance in the four spectral bands. At a solar zenith angle of 44° , and with bands 3 and 4, some cases of nonconvergence were encountered in trying to invert the data with the optimization procedure. Since the hot spot parameter value was derived independently at the two other solar angles, we provided this information to the inversion procedure which was run again on the observational data in order to retrieve the values of the three remaining model parameters, namely ω , χ_l , and Θ .

The comparison between the data and the modeled reflectances is shown separately in Figures 3a through 3d for the four spectral bands. The agreement is found to be good (most of the points are within $\pm 5\%$ of the reflectance values), even though the bidirectional reflectances vary widely over the hemisphere. The bulk of the discrepancies can be explained in terms of the noise and uncertainty in the data set (including the

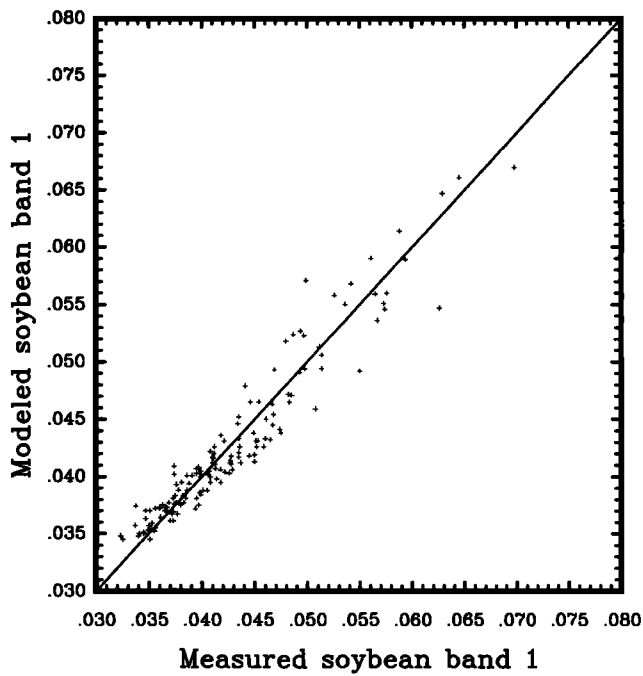


Fig 3a. Comparison between bidirectional reflectances measured over a soybean canopy in band 1 (0.5–0.6 μm) and modeled with (1), using optimally fitted parameters.

assumption of azimuthal symmetry with respect to the principal plane), or as a result of the correction used to remove the contribution of the atmospheric diffuse radiation. In the visible spectral bands, we used the atmospheric data collected by *Ranson et al.* [1984] to specify the value of f_d . In the near infrared bands, because atmospheric data were missing, we selected values of f_d that are consistent both with those in the visible bands, and with the spectral dependency of the predicted f_d by models.

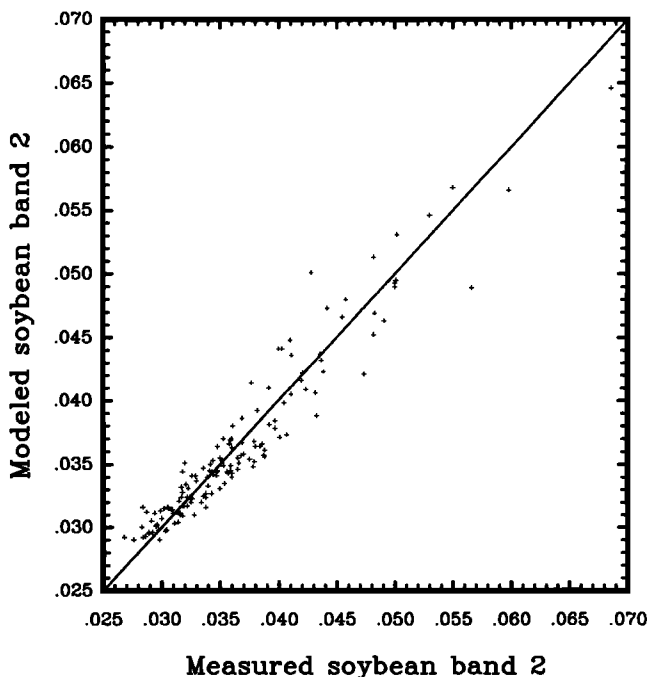


Fig 3b. Same as Figure 3a, except in band 2 (0.6–0.7 μm).

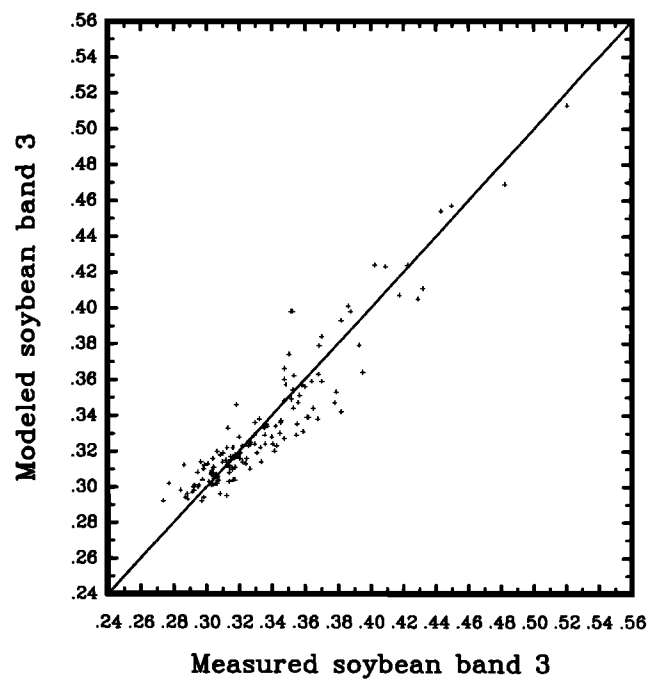


Fig 3c. Same as Figure 3a, except in band 3 (0.7–0.8 μm).

The sensitivity of the results with respect to the parameter f_d was investigated using the data collected in band 1 at 55° of illumination. From the results shown in Table 4, it appears that the best fit to the data is obtained when $f_d = 0$, which implies that there is no diffuse radiation coming from the sky. Since this result is obviously wrong, we conclude that the analytical expression describing the contribution of the atmospheric diffuse radiation to the observed bidirectional reflectances is not good enough. In other words, when the inversion procedure is required to estimate the value of f_d in

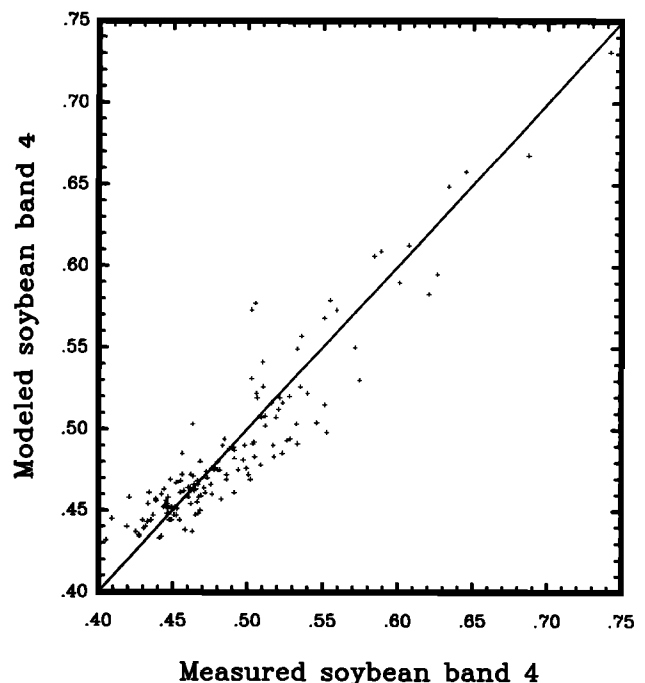


Fig 3d. Same as Figure 3a, except in band 4 (0.8–1.1 μm).

TABLE 4. Sensitivity of Model Parameters With Respect to f_d Value ($\theta_1 = 55^\circ$)

f_d	ω	χ_l	Θ	$2r\Lambda$	RMS of Fit
0.0	0.159	-0.136	-0.013	2.66	0.197×10^{-2}
0.1	0.163	-0.004	-0.018	2.35	0.198×10^{-2}
0.2	0.166	0.129	-0.025	2.09	0.200×10^{-2}
0.3	0.169	0.264	-0.032	1.87	0.203×10^{-2}
0.4	0.172	0.407	-0.041	1.69	0.207×10^{-2}
0.5	0.175	0.563	-0.051	1.55	0.213×10^{-2}

addition to the four canopy parameters, the retrieved value of f_d is zero or very close to zero. Camillo [1987] obtained a similar result. Consequently, the contribution from the diffuse sky radiance must be provided, since its correct value cannot be derived from the inversion of bidirectional reflectances. The parameters relative to the geometry of the canopy appear to be the most sensitive to the values of f_d over the range of values considered here. Significant changes are also likely to occur even with an absolute variation of 0.1 in the f_d value. An interesting feature is that the hemispherical reflectance (that is, the albedo) is increasing with f_d . Although the dependency between the two is not very strong, one could conceivably provide the measured albedo value and thereby constrain the optimization procedure in finding the best f_d value. The inversion procedure might be run simultaneously on the bidirectional and the hemispherical reflectances observed in the field.

4.2.1. *Leaf optical properties.* In each spectral band, the optical parameters of the scattering elements, namely, the single-scattering albedo ω and the phase function parameter Θ , vary within a realistic range. For the visible bands (1 and 2), Θ is very close to zero, indicating quasi-isotropic scatterers, while the values of ω retrieved in the near-infrared bands (3 and 4) exhibit a slight but systematic tendency for a backward scattering component. These two optical parameters can be combined to estimate the hemispherical reflectance ρ_l , transmittance τ_l , and absorptance α_l of individual leaves. The retrieved values are given in Table 5, along with the values reported by Ranson *et al.* [1984], who measured ρ_l and τ_l at the same time as the bidirectional reflectances. For the sake of this comparison, we assumed that the leaves were isotropic, and the ρ_l and τ_l values given by Ranson *et al.* were averaged together. The values predicted as indicated above agree quite well with the independent measurements, the worst case being for band 3 where measured leaf reflectances are about 0.35, while our predicted value is closer to 0.40. These results clearly demonstrate that the inversion procedure is able to retrieve the basic leaf optical properties with a very good accuracy, and therefore validate the model developed in part 1, as well as the parameterization described in section 2. It is imperative to properly account for the hot spot phenomenon. Otherwise the inversion procedure would yield a rather strong and unrealistic backscattering component in order to compensate for the latter effect. This would lead to unrealistic values of the hemispherical optical properties of the leaves. The absorption factors we derived show a systematic decrease with increasing solar zenith angle in Table 5. At this point, and because of a lack of direct measurements of this quantity with a varying illumination angle, it is difficult to know whether the observed variation is genuine or results from a weakness of the inversion procedure we used.

TABLE 5. Comparison Between Retrieved and Measured Optical Parameters on a Soybean Leaf

Solar Zenith Angle, deg	ρ_l or τ_l	α_l
<i>Band 1</i>		
44	0.073	0.854
55	0.085	0.830
61	0.093	0.814
average observed value	0.090	
<i>Band 2</i>		
44	0.060	0.880
55	0.070	0.860
61	0.080	0.840
average observed value	0.068	
<i>Band 3</i>		
44	0.401	0.198
55	0.404	0.192
61	0.407	0.186
average observed value	0.346	
<i>Band 4</i>		
44	0.456	0.088
55	0.463	0.074
61	0.468	0.064
average observed value	0.486	

4.2.2. *Canopy geometry.* As expressed by (5), χ_l describes the average orientation of the leaves in the plant canopy. The values of χ_l retrieved in the visible bands differ significantly from those retrieved in the near-infrared bands: In the former case, the average value of χ_l is equal to 0.248 ± 0.03 indicating predominance of horizontal leaves, while in the latter case, the average value of -0.009 ± 0.08 is typical of a quasi-spherical canopy.

Using (5), the actual χ_l value for the canopy can be estimated from the separate measurements of leaf angle distribution reported by Ranson *et al.* [1984]. The values of χ_l derived from these measurements show slight variations with height in the canopy, but are always greater than zero in each canopy layer, and the estimated χ_l for the entire canopy is equal to 0.245. This global value matches very well the one derived independently from the bidirectional reflectances in bands 1 and 2 and indicates a predominance of horizontal leaves within the soybean canopy. This information appears to be lost or diluted when inferring the value of χ_l from the bidirectional reflectances measured in bands 3 and 4. Various reasons can be invoked to explain this result. Among others, one may emphasize the fact that the functions $H(x)$ which describe the multiple scattering in the canopy assume isotropic scatterers. If there was a significant departure from this case, the inversion procedure might find a value of χ_l optimized to compensate for this weakness of the model. Another potential problem is the assumption of a one scatter-type canopy, whereas some additional scattering may be due to stems and pods. This latter contribution is relatively more important in spectral regions where high-order multiple-scattering events occur.

Table 3 seems to indicate that the parameter $2r\Lambda$ varies spectrally for a given illumination angle. However, since this parameter depends only on the morphology of the canopy, one would not expect such a dependency. As expressed in (1), information about the hot spot is only contained in the singly scattered radiation: adding multiple-scattering effects lowers the contribution of the hot spot function with respect

to the total signal. For example, when the solar zenith angle is 44° , the contribution of the function $P_v(g)$ to the total signal is between 30% and 40% in band 4, and between 80% and 97% in band 1. Thus, for near-infrared bands the hot spot parameter is more difficult to infer from the inversion procedure. In order to examine the relative importance of the value given to the $2r\Lambda$ parameter in the near-infrared bands, we performed an additional inversion where $2r\Lambda$ was fixed at the value derived from the visible bands, so that the inversion procedure was optimizing the values for the three remaining model parameters. The values we retrieved in that way are 0.902, 0.063, and -0.090 for ω , χ_l , and Θ , respectively. These values are very close to those given in Table 3. Consequently, using the value of $2r\Lambda$ inferred from the visible bands as an input parameter to regenerate the bidirectional reflectances observed in band 4 leads to very small differences with the bidirectional reflectances that we generated using Table 3 parameter values. For the particular angular sampling used over the soybean canopy, the mean deviations between the two sets of predicted reflectances are limited to the region where the relative geometry of observation is the most favorable for retrieving the hot spot parameter ($g = 8.5^\circ$), but even for this particular set of angles, the reflectances are changed by less than 2%. Because of the undersampling of the reflectance field at phase angles close to zero, it is clear that an underestimation in the measurement less than 5% at small phase angles is sufficient to explain the spectral variations observed in the $2r\Lambda$.

Assuming that Λ is constant with depth in the canopy, it was shown in part 1 that, at a given illumination angle θ_1 , the parameter $2r\Lambda$ can be related to canopy parameters as follows:

$$2r\Lambda = 2r_0 \left[\frac{\Lambda \mu_1}{y_l \kappa_1} \right]^{1/2} \quad (10)$$

where r is interpreted as an average value of the radius of the sun flecks over a finite depth y_l and r_0 is the radius of the hole between the leaves at the top of the canopy. Equation (10) can be used to examine the dependence of $2r\Lambda$ with respect to θ_1 , and it can be easily shown that

$$(2r\Lambda)_{\theta_1} = (2r\Lambda)_{\theta_0} \left[\frac{\kappa_1}{\mu_1} \right]_{\theta_0}^{1/2} \left[\frac{\mu_1}{\kappa_1} \right]_{\theta_1}^{1/2} \quad (11)$$

where $(2r\Lambda)_{\theta_0}$ expresses the hot spot parameter for a nadir illumination. When applying (11) to each $2r\Lambda$ value given in Table 4, it appears that $(2r\Lambda)_{\theta_0}$ is still varying with θ_1 , questioning the validity of (10) and (11) for the particular canopy we study. A careful analysis of the canopy geometry measurements reported by *Ranson et al.* [1984] reveals that the assumption we made above about a Λ constant with depth in the canopy is not justified. Indeed, although the plants were overlapping, there was still a macrostructure in the uppermost canopy layers due to the approximate spherical shape of the plants. As mentioned earlier in this paper, this causes a slight but detectable azimuthal asymmetry in the principal plane, but also indicates that some volumes at the top of the canopy are scatterer free. For the same reasons invoked in part 1, the macrostructures in the canopy due to the plant stand geometry should lead to a hot spot phenomenon superimposed on that resulting from the canopy microstructures defined by the free spaces between the leaves. Consequently, the leaf area density increases with depth, and the typical surface area of sun flecks a decreases

with depth at a rate larger than that assumed in (10). As a first approximation, it appears from the values in Table 3 that the parameter $2r\Lambda$ can be normalized at a nadir illumination with a simple $\cos \theta_1$ factor, in which case we find $(2r\Lambda)_{\theta_0} = 3.3$ in the visible spectral bands.

Since data were acquired with a ground resolution larger than the nominal distance between the plant rows (the row spacing was 76 cm), the macrostructures described above participate in the hot spot phenomenon. Using simple geometrical considerations, one can verify that the ratio of the typical horizontal distance between the plants to the typical vertical depth free of scatterers between the plants is significantly greater than 1 (in fact the value should be of the order of 3 to 5). Since we showed before that this ratio is related to the value of $2r\Lambda$, the presence of these macroscale structures may explain the large values inferred from the inversion procedure in bands 1 and 2. The immediate consequence of such a large value is a very broad hot spot component in the bidirectional reflectance field. A more detailed discussion of the value of $2r\Lambda$ would require the consideration of a canopy model with a double-peaked distribution in the parameter r , in order to account for the effects of multiple scales in the canopy morphology. However, the validation of the results would also require additional canopy geometry measurements which are difficult to get.

5. GENERAL CONCLUSION

In this work, a model for predicting bidirectional reflectance patterns over a semi-infinite and homogeneous medium has been developed. Although special emphasis was placed on the case of a vegetation canopy, the model has a broader range of application, including bare soil surfaces. To some extent, the present model is a generalization of the previous model proposed by *Hapke* [1981, 1986]. The analytical solution which has been derived depends on the intrinsic optical properties of the scatterers and on parameters describing the canopy geometry. Basically, the solution is established as a combination of four functions, namely, a generalized Lommel-Seeliger law type, a scatterer phase function, a backward scatter function resulting from the non-independency in the transmissions of the incident and the reflected radiation (it is this function that describes the hot spot phenomenon), and a function describing the contribution due to the multiple scattering occurring inside the medium.

The theoretical expression developed in part 1 has been successfully inverted with laboratory and field bidirectional reflectance data. It was shown in this paper that the inversion procedure is able to retrieve the four model parameters describing both the optical properties of the leaves and their geometrical arrangements within the vegetation canopy. Data set 1 was used to show that the model can fairly well predict the bidirectional reflectance patterns, including a well defined hot spot component. The validation of the values of the optical and geometrical parameters retrieved by the inversion procedure was achieved with data set 2. This was made possible because the average leaf orientations, as well as the leaf reflectance and transmittance factors, were measured simultaneously with the bidirectional reflectances of the canopy.

It has been shown that the optical properties of the scatterers conditioning the spectral variations of the bidirectional reflectance of a vegetation canopy can be inferred with good accuracy from remotely sensed data. This conclusion

holds true for the morphological properties of the canopy when using bidirectional reflectances collected at wavelengths shorter than $0.7 \mu\text{m}$. Beyond this wavelength, green leaves exhibit a strong reflection factor which adds a significant multiple-scattering contribution to the measured bidirectional reflectance, making the inverse problem poorly conditioned at such wavelengths. Since the information regarding the canopy morphology can be efficiently extracted from the single-scattering component of the signal, we suggest these canopy properties can be retrieved from data taken at short wavelengths, and then used as an input when performing the inversion with bidirectional reflectances taken at longer wavelengths. In other words, it appears valuable to have some a priori knowledge about the canopy morphology before inverting data at near-infrared wavelengths to retrieve the optical properties of the scatterers.

The simplicity and accuracy of this bidirectional reflectance model makes it a good tool for bidirectional reflectance modeling, but also for the physical interpretation of measured bidirectional reflectance fields. Such a model helps define a common model usable by the remote sensing community, as well as by the modeling community. Its application extends to the definition of a "best observing geometry," as well as to the investigation of the "minimum data set needed," which are both crucial in future in situ experiments and spaceborne missions. This model can be easily coupled with an atmospheric radiative transfer scheme to investigate the consequences of the masking effects of the atmosphere on the bidirectional reflectance pattern measured by satellites. With respect to satellite data, a promising result derived from the theory is that the information regarding the canopy geometry is mainly contained in the backward angular component of the canopy scattering. To the extent that aerosols obey the Mie scattering theory and exhibit a strong forward scattering component, the sensitivity in the retrieval of the geometrical model parameters with respect to the aerosol amount and detailed properties should be minimized over the angular domain where backward reflection occurs.

Because the inversion of remotely sensed data is generally an ill-posed and ill-conditioned problem, in situ measurements providing some a priori knowledge on the observed medium become important. As shown throughout this paper, the field measurements, in addition to the reflectance measurements, can be used both for validation and for interpretation purposes. For instance, on the one hand, the hemispherical reflectance and transmittance leaf factors were used to validate the ω and Θ values retrieved from the inversion procedure, and on the other hand, the detailed measurements of leaf area index were used to interpret physically the hot spot parameter in terms of a typical distance between the plant stands. The amount of a priori knowledge about the ecosystems that is desirable depends on the purpose and extent to which satellite data are going to be interpreted in physical terms. An estimation of the leaf area index (LAI) would be useful, for instance, for surface energy budget calculations, but for this specific objective, the canopy architecture, as expressed through the hot spot parameter might be useless. As discussed in part 1, the LAI cannot be retrieved from measurements in the visible and near-infrared wavelengths, unless the soil reflectance contributes to the signal emerging at the top of the canopy, which in turn means that the canopy is not "semi-infinite"

for that spectral band. More work is needed to address the realistic case of heterogeneous media with small LAI values, and the case of sparse vegetation.

The study we presented in part 1 and in this paper constitutes a significant improvement in the quantitative characterization of surface ecosystems from remotely sensed data, mainly because the physically based expression we derived can be inverted in a rather economical and efficient way. This is particularly significant because the amount of satellite data will continue to increase in the future, and because there is an urgent need for introducing satellite-derived information in general circulation models in order to address various climate change issues.

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