Modeling Spectral and Bidirectional Soil Reflectance

S. Jacquemoud, F. Baret, and J. F. Hanocq

INRA — Bioclimatologie, Montfavet, France

SOILSPECT is a radiative transfer model, derived from Hapke's model, that represents the optical properties of soil from 450 nm to 2450 nm. The spectral and bidirectional reflectance of 26 soils was measured in the laboratory both with a field spectroradiometer (1000 narrow wavebands from 450 nm to 2450 nm) and a radiometer simulating TM channels (the five TM2, TM3, TM4, TM5, and TM7 broad bands). The input parameters of the model [single scattering albedo ω, phase function P(g,g′), and variable characteristic of the soil roughness h] were fitted to these observations. We show that the single scattering albedo is only dependent on wavelength and on soil humidity; the other parameters depend mainly on surface conditions.

INTRODUCTION

Soil optical properties have been studied both in the laboratory with mineral powders and at ground level with field measurements. Baumgardner et al. (1985) and Iron et al. (1989) synthesized the effects of soil constituents on reflectance: the content of minerals, organic matter, iron oxides, or soluble salts make up complex media, the spectral properties of which are also complex. However, Stoner and Baumgardner (1981) defined only five spectral curves characteristic of most of the soils they observed. Another important factor that governs soil reflectance is the moisture content which modifies the optical properties from the visible to the middle infrared (Idso et al., 1975; Bedidi et al., 1991). Most articles in the literature catalogue spectra acquired with a single direction of illumination and a single viewing angle. Such work is necessary for classification purposes. Nevertheless, it contributes little to the understanding of the factors that govern the interaction of solar energy with soils, such as the particle size and the measurement conditions.

Roughness is one of the most important factors influencing the directional reflectance of a bare soil. Several indices (surface-height variations, particle size distribution, etc.) have been defined to describe the soil surface reliefs, but the direct measurement of these variables still presents some difficulties. The understanding and description of light diffusion between the soil particles should give us interesting information on roughness. Many models try to predict the bidirectional reflectance over bare soils: Deering et al. (1990) proposed a geometrical model where forward and backward scattering are separately taken into account. They successfully simulated the directional reflectance of desert surfaces. Cierniewski (1987; 1989) represents the soil surface as equal-sized spheres placed on a freely sloping plane. He assumes that the reflectance is highly correlated with the shadows created by the particles and, therefore, depends on the rough-

Address correspondence to S. Jacquemoud, INRA — Bioclimatologie, BP 91, 84143 Montfavet Cedex, France.

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ness and the measurements conditions (angles of illumination and reflection). This hypothesis is correct, but, as noticed by Escadafal (1989), the reflectance does not decrease as fast as suggested by the model under the assumption of totally dark shadows. This discrepancy is more important when the soil albedo is higher (e.g., with sand). It is consequently necessary to take higher order reflections into account to characterize such cases. There are many models derived from radiative transfer theory to describe the multiple scattering quantitatively (Chandrasekhar, 1960; Irons et al., 1989). They can be inverted in order to retrieve the properties of the Earth surface from remotely sensed data. Hapke (1981; 1984; 1986) and Hapke and Wells (1981) proposed a solution of the radiative transfer equation, which accounts for the opposition effect. This five-parameter model allows simulation of both laboratory measurements and planetary surface observations. Pinty et al. (1989) validated this model on bare soils. However, no study has focused on the spectral dependence of the parameters.

The literature shows a lack of studies that concern the spectral and the directional reflectance properties of bare soil together. These two aspects are often separated, but, for remote sensing applications, they should not be dissociated. This paper will attempt to provide optical constants for a wide range of soil types: for this purpose, we generalize Hapke's model in order to separate the parameters that depend on the wavelength from the ones that are not wavelength-dependent. The first two parts describe the model and the experiment. The following sections concern the actual inversion procedure on directional and then spectral data.

THEORY

Hapke's model (1981) considers a plane surface at $z = 0$ containing irregular and randomly oriented particles that are large compared with the wavelength. This medium is illuminated in the direction (i, ϕ) by collimated light of intensity J and is observed by a detector in the direction $(e, 0)$. The phase angle g is described as the angle between the directions of incident and outgoing light. The radiance I seen by the detector is considered as the sum of a single scattering I_s term and a multiple scattering I_m term:

$$I = I_s + I_m, \tag{1}$$

with

$$I_s = \frac{J\omega}{4\pi} \frac{\cos i}{\cos i + \cos e} P(g), \tag{2}$$

$$I_m = \frac{J\omega}{4\pi} \frac{\cos i}{\cos i + \cos e} [H(\cos i) H(\cos e) - 1], \tag{3}$$

where

$$H(x) = \frac{1 + 2x}{1 + 2\sqrt{1 - \omega x}}, \tag{4}$$

ω is the single scattering albedo (the ratio of the scattered energy to the total energy either scattered or absorbed by the particle) and $P(g)$ the phase function. Chandrasekhar (1960) showed, for a semi-infinite medium, that I_m was less sensitive to the particle phase function than I_s. The singly scattered fraction I_s is therefore calculated exactly for any phase function $P(g)$ whereas the multiply scattered fraction I_m is evaluated under the assumption of isotropic scattering properties, that is, $P(g) = 1$.

The phase function $P(g)$ describes the angular distribution of the light scattered by a terrestrial surface. We have modified it in order to generalize the description of bare soils directional reflectance. It usually corresponds to one kind of diffusion: isotropic scattering, predominantly forward scattering or backscattering (Hapke, 1963; 1981; Pinty and Ramond, 1986) according to the nature of the objects making up the surface. The literature shows that the expression of $P(g)$ often has no theoretical justification: It is chosen because of its simplicity and because it illustrates the kind of scattering observed in a given experiment. Whatever the behavior of the surface, the phase function always depends only on the phase angle g. Nevertheless, such a parameterization cannot accurately represent forward scattering, which is particularly important around the specular direction. We propose a phase function $P(g,g')$ approximated by Legendre polynomials to explain both backscattering and forward scattering (the specular effect) by smooth soils. In this function, the angle g' describes the angle between the specular and the outgoing light directions:

$$P(g,g') = 1 + b\cos g + c\,\frac{3\cos^2 g - 1}{2} + b'\cos g' + c'\,\frac{3\cos^2 g' - 1}{2} \quad (5)$$

with

$$\cos g = \cos i \cos e + \sin i \sin e \cos \phi, \quad (6)$$

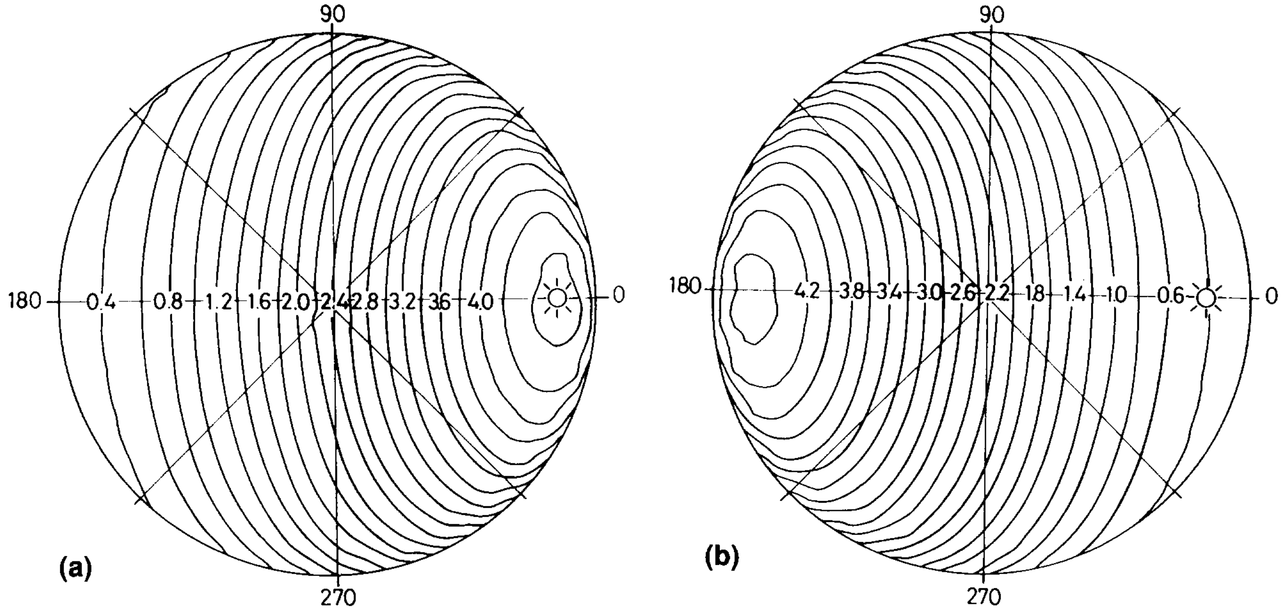
$$\cos g' = \cos i \cos e - \sin i \sin e \cos \phi. \quad (7)$$

As for any phase function, $P(g,g')$ is normalized to unity, that is,

$$\int_{4\pi} P(g,g')\frac{d\Omega}{4\pi} = 1.$$

Figure 1 shows the features of $P(g,g')$ for three different types of reflections: backscattering (Fig. 1a), forward scattering (Fig. 1b), and mixed scattering (Fig. 1c).

However, the phase function is not sufficient to explain the reflectance properties of rough bare soils. Suppose that the soil macrostructure is modeled as a discontinuous system made up of



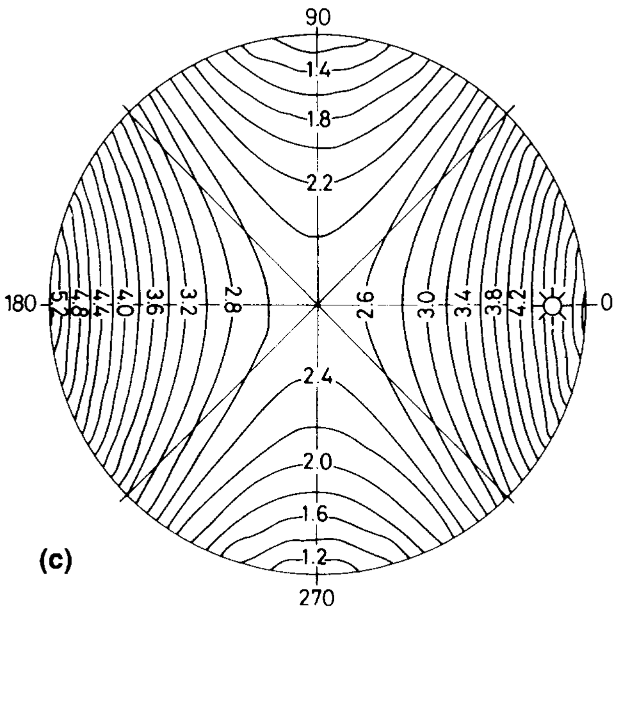


Figure 1. Phase function $P(g,g')$ for three different types of reflection: backscattering [a) $(b,c,b',c') = (2,1,0,0)$], forward scattering [b) $(b,c,b',c') = (0,0,2,1)$], and mixed scattering [c) $(b,c,b',c') = (0,2,0,2)$].

blocks separated by air cavities: The probability of illumination of a particle and the probability of light outgoing towards the detector are not independent; the reflected light escapes preferentially in the "hot spot" direction ($g=0$). When $g=0$, the escape probability of the single scattered fraction I_s is unity. Hapke (1963) introduced a backscattering function $B(g)$, which is a function of the phase angle g, a roughness parameter h related to the porosity of the medium, and an amplitude term for the hot spot, B_o. Similarly, Becker et al. (1985) constructed a cavity correction function CF depending on a cavity parameter p given by $p=R/d$, where R is the radius and d the depth of the cavity. Assuming that the particles making up the surface are not opaque, Hapke (1986) introduced a term $S(0)$ defined as the fraction of the light scattered from close to the surface at $g=0$: $B_o=S(0)/\omega P(0)$. As discussed by Pinty and Verstraete (1990), the parameter B_o is not derived rigorously from the theory. In some cases, the model inversion leads to the physical nonsense $S(0)>1$! In this article, we have reverted to a simplified formulation of B_o setting it to 1 and have rewritten Eq. (1) as follows:

$$I=\frac{J\omega}{4\pi}\frac{\cos i}{\cos i+\cos e}\{[1+B(g)]P(g)+H(\cos i)H(\cos e)-1\}, \tag{8}$$

with

$$B(g)=\frac{1}{1+(1/h)\tan(g/2)}. \tag{9}$$

Hapke (1986) has related the h parameter to the porosity of the medium: Equation (9) clearly shows that, for a given phase angle g, increasing h leads to an increase of the backscattering function. The final formulation of the bidirectional soil reflectance requires the following six parameters: ω, h, b, c, b', and c'. In the next part, we will estimate them from our data set.

THE EXPERIMENT

Measurements were performed in the laboratory to control the irradiance conditions and isolate them from other disruptive external conditions. The spectral and directional reflectances were measured on a sample of 26 very different soils arranged in 50 cm square boxes: fine sand (3 moistures × 2 roughnesses), clay (3 moistures × 3 roughnesses), peat (3 moistures × 3 roughnesses), pozzolana, pebbles. A Laser profilometer (Bertuzzi and Caussignac, 1988) was used to estimate soil roughness in terms of surface height profiles. Five powerful halogen spots (2000 W) alternatively illuminated the samples with quasi collimated light: one at nadir, two in the principal plane ($i=34°$ and $60°$) and two in the perpendicular plane ($i=34°$ and $60°$). We used two kinds of instruments: the Barringer HHRR radiometer with five channels (broad bands respectively centered on $\lambda_1=538$ nm, $\lambda_2=631$ nm, $\lambda_3=851$ nm, $\lambda_4=1768$ nm, and $\lambda_5=2209$ nm) for the bidirectional reflectance measurements, and the Barringer REFSPEC IIA spectroradiometer (1000 narrow wavebands from 450 nm to 2450 nm) for the spectral reflectance. Fields of view were respectively $2.6°\times 15.6°$ (in the perpendicular plane) and $6°\times 7.5°$ so that the two detectors did not see the same area of soil. The directional measurements were acquired from 42 different positions (Table 1). Spectra were measured in the five configurations underlined in Table 1. The reciprocity principle can give us information about the accuracy of the measurements: by permuting the sensor and the source position (changes in lamp illumination are negligible), we have verified, for each broad band of the radiometer, the relationship $V(\theta,\theta')=V(\theta',\theta)$, where V is the radiometer output (in volts). The root mean square of this relationship varies between 0.01 and 0.02 (reflectance). Data were expressed in absolute reflectance, using a reference panel coated with halon (Jackson et al., 1987; Baret and Andrieu, 1989; Marjoram et al., 1990).

RESULTS AND DISCUSSION

To study the spectral reflectance of soils, we first invert the SOILSPECT model on the directional data set acquired in 42 different positions with five broad bands. This should give us some information about the variables of the model which describe the surface features and those which represent the intrinsic soil optical properties. Theoretically, the first ones do not depend on the wavelength: They will help us to invert the model on the spectral data in order to determine the spectral variations of the second ones.

Table 1. Geometries of Measurement for the Bidirectional and the Spectral (Underlined) Data

Source		*Sensor*							
i	ϕ				*e*				
0	0	5	10	15	$\underline{30}$	45	60		
34	0	0	15	20	40	45	50	60	
	90	0	15	$\underline{30}$	45	60			
	180	15	$\underline{30}$	34	40	55	70		
60	0	0	15	30	40	45	50	65	70
	90	0	15	$\underline{30}$	45	60			
	180	15	$\underline{30}$	45	60	70			

Directional Data

In this section, we consider three steps corresponding to soils combinations in order to generalize the inversion procedure.

First step: inversion of the model with the broad band bidirectional data. No hypothesis was made, *a priori*, concerning the spectral dependence of the model parameters. The inversion was carried out on our set of 26 soils: in total, 130 subsamples were available because the five broad bands previously described (λ_1, λ_2, λ_3, λ_4, and λ_5) are considered independently. Due to the nonlinearity of the model, the inverse problem was solved numerically using the Nelder–Mead simplex algorithm. For each subsample, the nonlinear optimization procedure minimizes Δ_λ^2 defined as follows with 42 measured data and six unknown parameters:

$$\Delta_\lambda^2 = \sum_{k=1}^{42} [R_{\text{mes}}(k) - R_{\text{mod}}(k,p)]^2, \tag{10}$$

where $R_{\text{mes}}(k)$ is the measured bidirectional reflectance of the surface for the measurement geometry $k=(i,e,\phi)$ and $R_{\text{mod}}(k,p)$ is the simulated bidirectional reflectance for the same geometry and the parameter set $p=p(\omega_\lambda,h,b,c,b',c')$. The applicability and accuracy of this procedure has been successfully tested, in the same conditions as Pinty et al. (1989), with a clean data set and a noisy data set generated with the model. The model allows the description of the reflectance of both rough, backscattering soils ($0.003<\text{rms}<0.015$) and smooth soils characterized by an important specular effect ($0.008<\text{rms}<0.02$), whatever the waveband. As noticed by Pinty et al. (1989), for each soil, the phase function terms and the h parameter are not very sensitive to the wavelength. This can be explained by the relative independence of the refractive indices (real part) of soil materials (Irons et al., 1989) and the physical characteristics with respect to the wavelength. Therefore, in the second step, we consider the parameters h,b,c,b', and c' to be constant for a given soil.

Second step: We can globally fit the five previous parameters at the same time as the five single scattering albedos ($\omega_1,\omega_2,\omega_3,\omega_4$, and ω_5) corresponding to the five wavebands. For each soil sample, it amounts to minimizing Δ^2 with $42\times5=210$ measured data and $5+5=10$ unknown parameters:

$$\Delta^2 = \sum_{k=1}^{210} [R_{\text{mes}}(k) - R_{\text{mod}}(k,p)]^2, \tag{11}$$

where the p vector can be written $p=p(\omega_1,\ldots,\omega_5,h,b,c,b',c')$. The good results ($0.006<\text{rms}<0.023$) allow a new hypothesis to be tested in the third step: If the soil dries out without any degradation of its mechanical properties, then the parameters h,b,c,b', and c' should remain constant.

Third step: For the same soil taken at three different moisture contents, we can now adjust the h,b,c,b', and c' parameters at the same time as the 15 albedo values ($42\times5\times3=630$ measured data; $5+3\times5=20$ unknown parameters). For rough soils, in which the backscattering properties do not change during the drying, our hypothesis is confirmed (Fig. 2). However, the level of moisture content may affect the behavior of smooth soils. When they are near the saturation point, these soils present a large specular effect not explicitly taken into account in our hypothesis. The drying, which is particularly noticeable for clayey soils, can cause a decrease of the specular effect, an increase of the backscattering effect, and consequently a large variation of the phase function and roughness parameters. In these cases, we must again separate the levels of soil moisture and return to the second step conditions.

These three steps, which correspond to an increase of generalization from step 1 towards 3, are gathered in Table 2 with the example of a clayey rough soil. One can notice that the h,b, and c parameters do not vary a lot with wavelength, whatever the moisture content. On the other hand, the b' and c' parameters are more variable and can take positive or negative values: This instability is probably due to their low weight in expression of the phase function, connected to the main backscattering behavior of this soil. The rms values, while increasing from the first to the

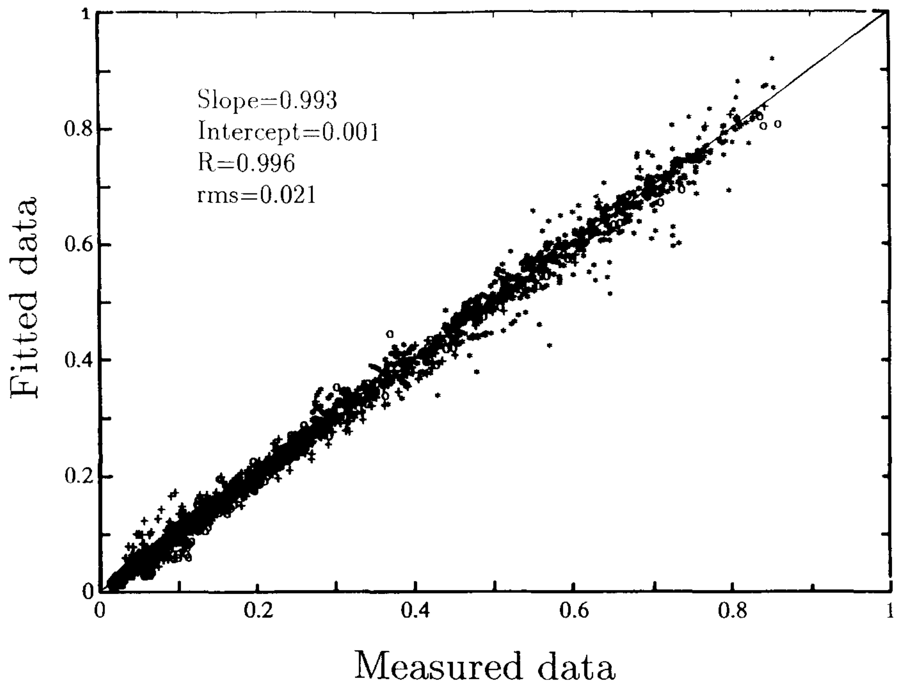


Figure 2. Comparison between simulated and measured bidirectional reflectance (630 data per soil type): (+) clay; (O) peat; (*) fine sand.

third step, remain around 0.01 reflectance and validate our hypotheses. Table 3 summarizes the variability of the different parameters, except ω. At present, we can point out the difficulties that arise from the inversion procedure when separating the roughness parameter h and the phase function parameters b,c,b', and c'. Theoretically, as noticed by Woessner and Hapke (1987), if $g < 20°$, then $B(g) << 1$ and can be ignored. This means that there is no conflict between the phase

Table 2. Model Inversion on a Rough Clayey Soil with Three Different Moisture Contents Using Three Different Hypotheses

	Very Moist Soil					*Slightly Moist Soil*					*Dry Soil*				
	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$	$\lambda 1$	$\lambda 2$	$\lambda 3$	$\lambda 4$	$\lambda 5$
ω	0.165	0.190	0.253	0.304	0.285	0.321	0.361	0.425	0.537	0.422	0.317	0.363	0.404	0.542	0.532
h	0.104	0.122	0.101	0.180	0.107	0.093	0.112	0.111	0.114	0.115	0.101	0.101	0.115	0.107	0.121
b	1.223	1.362	1.452	1.344	1.103	1.359	1.464	1.537	1.492	1.432	1.549	1.665	1.796	1.618	1.582
c	0.410	0.483	0.407	0.295	0.306	0.796	0.779	0.680	0.560	0.535	0.878	0.864	0.775	0.590	0.549
b'	-0.021	0.397	0.239	0.418	0.178	0.052	0.211	0.163	0.238	0.217	0.163	0.357	0.405	0.339	0.322
c'	0.153	-0.085	0.009	-0.065	-0.030	0.007	-0.051	0.001	-0.060	-0.074	0.047	-0.041	-0.016	-0.060	-0.056
rms	0.003	0.004	0.008	0.005	0.007	0.008	0.008	0.009	0.009	0.010	0.007	0.008	0.008	0.010	0.009
ω	0.157	0.201	0.261	0.322	0.259	0.318	0.378	0.443	0.544	0.521	0.322	0.381	0.438	0.539	0.528
h			0.124					0.101					0.101		
b			1.294					1.442					1.606		
c			0.351					0.640					0.686		
b'			0.282					0.186					0.319		
c'			-0.029					-0.050					-0.043		
rms			0.007					0.011					0.011		
ω	0.131	0.165	0.221	0.271	0.216	0.290	0.349	0.405	0.506	0.475	0.311	0.366	0.423	0.526	0.509
h								0.191							
b								1.395							
c								0.744							
b'								0.271							
c'								0.017							
rms								0.013							

Table 3. Variability of the Different Retrieved Parameters for the First Two Cases of Table 2

	Very Moist Soil		*Slightly Moist Soil*		*Dry Soil*		*Together*	
	Mean	*Std*	*Mean*	*Std*	*Mean*	*Std*	*Mean*	*Std*
h	0.123	0.033	0.109	0.009	0.109	0.009	0.114	0.020
b	1.297	0.136	1.457	0.067	1.642	0.096	1.465	0.175
c	0.380	0.079	0.670	0.121	0.731	0.153	0.594	0.194
b'	0.242	0.179	0.176	0.067	0.317	0.092	0.245	0.129
c'	−0.004	0.095	−0.035	0.037	−0.025	0.044	−0.021	0.061
h							0.109	0.013
b							1.447	0.156
c							0.559	0.182
b'							0.262	0.068
c'							−0.041	0.011

function $P(g,g')$ and the backscattering function $B(g)$ when studying forward scattering soils. But, in this case, the significance of h may be greatly affected and its retrieved value unusable for interpretation or comparison with other physical roughness parameters.

In conclusion, the only parameter which varies significantly with wavelength is the single scattering albedo ω. Until now, we have been limited to five broad wavebands. In the next part, we will determine its spectral variations from 450 nm to 2450 nm.

Spectral Data

Before investigating the spectral variations of soil reflectance, we have corrected the spectral data so that they agree with the broad band data acquired at the same measurement position. As described before, the two radiometers do not have the same fields of view, and they were not at the same distance from the target. Thus they did not see the same area of soil, inducing a scale effect. This effect, which is not wavelength-dependent, varies as the measurement position and has been easily removed. The spectrum of the single scattering albedo $\omega(\lambda)$ was fitted from the five reflectance spectra measured in the five illumination geometries previously defined, given the previous set of parameters h,b,c,b', and c' determined on the broad band data. Figure 3 shows the capacity of the model to represent soil reflectances with a good accuracy for very different measurement conditions ($R=0.997$, rms $=0.016$). The discrepancies mainly concern sands, the bidirectional reflectance of which is not described as precisely as for the other soils.

The single scattering albedo spectrum represents the intrinsic optical properties of soil materials: It is independent of the measurement conditions (illumination and viewing angles). The shape of these spectra vary from one soil to another according to the nature of minerals or organic matter and moisture content. Clay, peat, and sand (Fig. 4) present classical absorption features with a decrease of ω from the near infrared to the visible. For example, the peat characterized by a high level of organic matter content (Fig. 4) reflects little radiation in the visible while the reflectance greatly increases in the near infrared (Baumgardner et al., 1985). In the middle infrared, we observe three main peaks due to water absorption at 1450 nm, 1770 nm, and 1950 nm. These bands are explained by overtones and combinations of the three fundamental vibrational frequencies of water molecules in the soil. As soils are drying, we notice an increase of the single scattering albedo across the whole spectrum (Fig. 5): This is the reason why dry soils are usually brighter than wet soils. Modeling soil spectral reflectance as a function of water content is a difficult task. According to Bedidi et al. (1991), spectral signatures of lateritic soils in the visible domain cannot be derived simply from those determined from dry conditions. However, soils, including our examples, present quasihomothetic variations when moisture content varies: These variations affect both the visible and the near and middle infrared bands and are coupled with water absorption phenomena. Therefore, due to the ab-

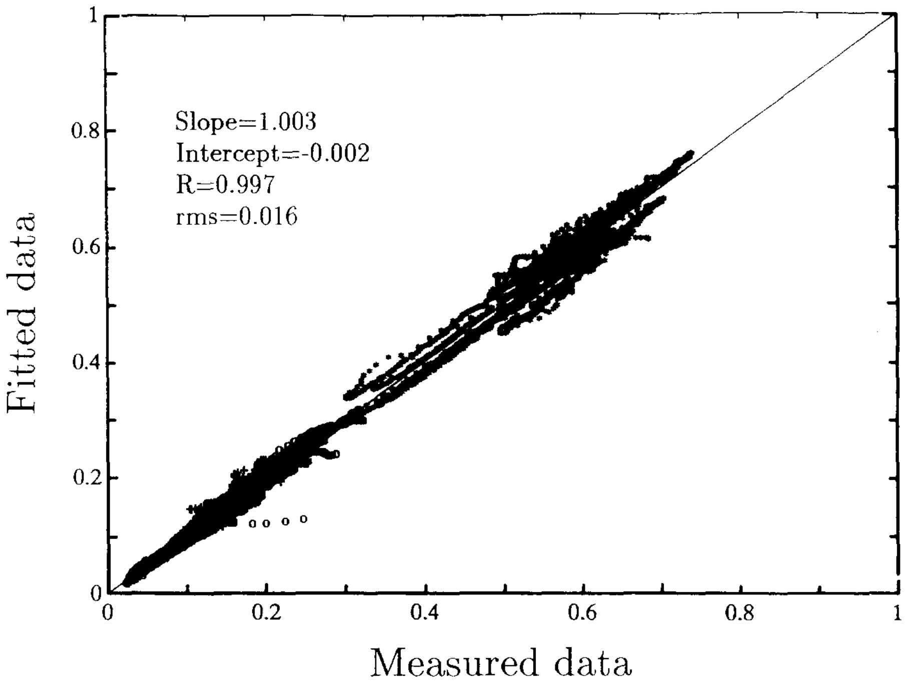


Figure 3. Comparison between simulated and measured spectral reflectance (5000 data per soil type): (+) clay; (O) peat; (*) fine sand.

sence of several intermediate moisture contents between a very wet sample and a very dry sample for each soil, we could not get further in the modelization work.

CONCLUSION

This model allows us to describe, with good accuracy, directional reflectance spectra of soils from 450 nm to 2450 nm. We can distinguish two kinds of input variables: The first varies spectrally (the single scattering albedo ω); the others are wavelength-independent (the roughness parameter h and phase function parameters b,c,b', and c'). The latter are mainly functions of the refractive indices (real part) of the soil components: Their spectral variation is low enough to consider them constant over the optical domain. One advantage of this model is its invertibility. One must remember the

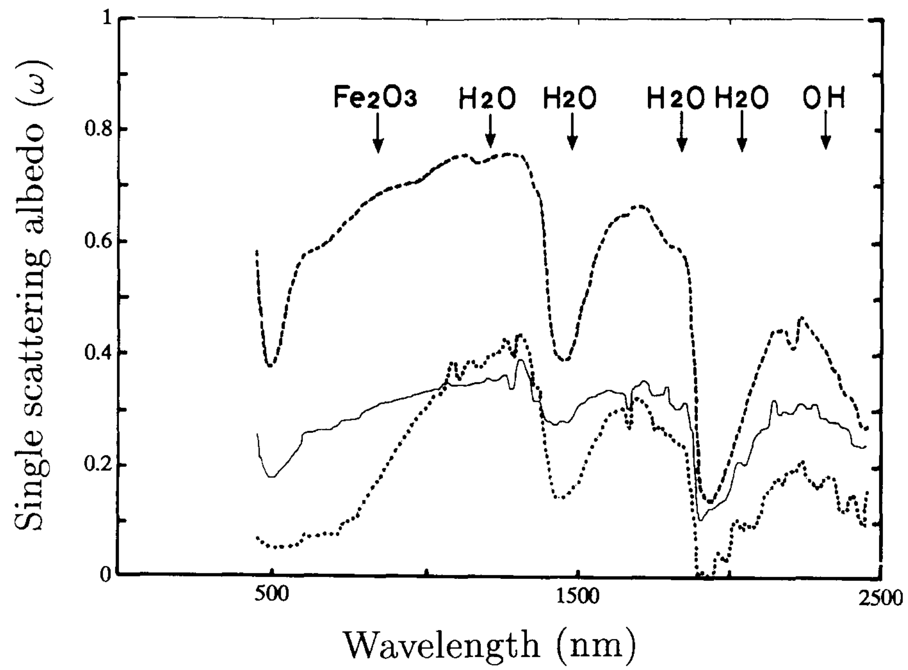


Figure 4. Single scattering albedo spectra of three different soils: (—) clay; (· · ·) peat; (- -) fine sand.

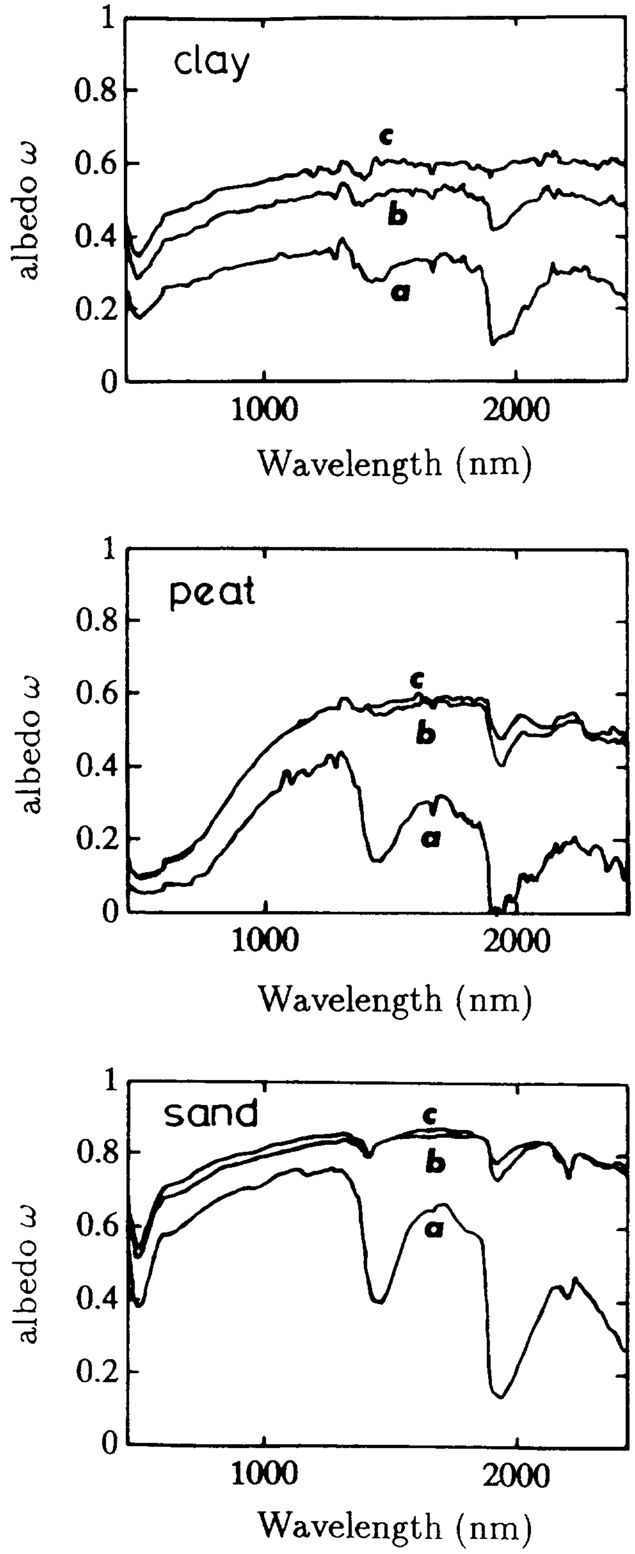


Figure 5. Effects of drying on the single scattering albedo for three different soils: a) wet soil; b) intermediate moisture content; c) dry soil.

difficulty encountered to separate the roughness parameter h and the phase function parameters.

This model allows us to ignore the measurement conditions (illumination and viewing geometry) and to propose variables characteristic of the intrinsic optical properties of soil. This is of great importance if we want to compare soil spectra acquired in different conditions. Finally, we should be able to simulate soil spectral reflectance and use it directly into vegetation canopy reflectance models.

Future studies will consist in relating the h parameter to the measured soil roughness or the ω parameter to the soil moisture content. For the moment, these soil surface characteristics can be retrieved, with good results, from active microwave remote sensing. In the optical domain, there have been few attempts to understand these complex phenomena, which are worthy of more investigation.

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