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Coupled Surface-Atmosphere Reflectance (CSAR) Model

1. Model Description and Inversion on Synthetic Data

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Absorption and scattering processes in the atmosphere affect the transfer of solar radiation along its double path between the Sun, the Earth's surface, and the satellite sensor. These effects must be taken into account if reliable and accurate information on the surface must be retrieved from satellite remote sensing data. One approach consists in characterizing the state of the atmosphere from independent observations and correcting the data with the help of radiation transfer models. This approach requires a detailed and accurate description of the composition of the atmosphere (e.g., aerosol and water vapor profiles in the case of advanced very high resolution radiometer data) at the time of the satellite overpass and requires significant computer resources. An alternative method is to attempt to simultaneously retrieve surface and atmospheric parameters by inverting a coupled surface-atmosphere model against remote sensing data. This study describes such a coupled model and the results of its inversion against synthetic data, using a nonlinear inversion technique. The results obtained are encouraging in that realistic directional reflectances at the top of the atmosphere can be produced, and the inversion of the model against these synthetic data is capable of estimating surface and atmospheric variables. The accuracy of the retrieval is studied as a function of the amount of noise added to the data. It is shown that some surface or atmospheric parameters are easier to retrieve than others with such a coupled model, and that although it appears to be difficult to accurately and reliably estimate the water vapor amount from channel 2, there is a definite possibility of retrieving the aerosol loading from simulated channel 1 data, if the type of aerosol can be assumed.

1. INTRODUCTION

The scale, intensity, and persistence with which human activities have affected the environment and changed the composition of the atmosphere have raised questions about the sensitivity of the climate system to these perturbations and, in particular, about the likelihood of large-scale and long-term effects [Houghton *et al.*, 1990; Jäger and Ferguson, 1991]. The widespread concern results from the fact that these changes may be unpredictable and largely undesirable. No consensus has been reached yet in the political arena on the need to take action, or even on the extent and severity of the measures that might be adopted, except that there is general agreement on the need for a much better understanding of the processes involved and for a reduction in the uncertainties associated with current predictions.

The most significant worldwide effort in this area is coordinated under aegis of the International Geosphere Biosphere Program (IGBP), also known as the Global Change Research Program [e.g., IGBP, 1988; National Academy of Sciences (NAS), 1988]. This research program

is articulated around a number of priority areas, including the modeling and monitoring of the global environment as well as the investigation of past changes to evaluate how the system has evolved under stress previously. This paper contributes to the overall objectives of these research programs by proposing a new approach to the monitoring of terrestrial surfaces and of the atmosphere, using a coupled surface-atmosphere model to interpret existing satellite remote sensing data.

The development of remote sensing techniques has greatly improved our capability to monitor land surface processes. Specifically, large field of view satellites are able to observe the entire planet on a daily basis (advanced very high resolution radiometer (AVHRR)) or even more frequently (METEOSAT, GOES). Other more specialized satellites offer a greater spatial or spectral resolution but less frequent coverage (SPOT, LANDSAT) and can be used to support detailed studies on smaller areas.

The principal scientific question that must be addressed in this context is the extraction of reliable, quantitative, accurate information on the surface or the atmosphere, or both, from radiation measurements made on board these satellites. For the purpose of this discussion, a remote sensing measurement in the optical spectral region can be considered a parametric function of n physical variables, where each of these variables is itself varying in space, in time, with the

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wavelength of radiation, and with the geometric conditions of illumination and viewing:

$$\rho = \rho(\zeta_1, \zeta_2, \dots, \zeta_n) \quad (1)$$

where $\zeta_i = \zeta_i(x, t, \lambda, \Theta)$, $i = 1, 2, \dots, n$, and where x represents the various spatial coordinates, t stands for time, λ indicates the spectral dependency, and Θ refers to the geometric conditions of illumination and observation [e.g., *Verstraete and Pinty, 1992*]. Typical examples of these variables ζ_i would be the single-scattering albedo or the orientation of the scatterers constituting the observed medium. Since each individual remote sensing observation is a complex function of multiple physical variables, it is not possible, in general, to retrieve the values of these variables from a single measurement through simple analytical procedures. Measurements may be repeated, however, and a numerical inversion method may be used to estimate the most probable value of the physical variables, i.e., the set of variables that best explain the observed variability in the data.

In principle, the variability in any one of the independent variables (spatial, temporal, spectral or angular) can be used to extract information on the medium under observation. Since each observable object (target) is characterized by a particular absorption spectrum, spectral signatures ($\partial\rho/\partial\lambda$) can be used to distinguish different targets. Similarly, the spatial contrast ($\partial\rho/\partial x$) of the signal may be interpreted in terms of the geographical extent and distribution of these objects, and the information contained in the temporal domain ($\partial\rho/\partial t$) can be used to describe the dynamic evolution of the system. So far, the extraction of information on the basis of these variabilities has proceeded on the basis of empirical relations (typically but not exclusively with vegetation indices). Physically based models to describe the angular variations of the signal ($\partial\rho/\partial\Theta$) are much more advanced, in part thanks to the level of understanding that has been acquired in the field of radiation transfer. For this reason, the angular variance of the signal has historically been the principal source of information on the physical processes that must have produced the observed radiation.

Various authors have attempted to retrieve quantitative information on the surface from an analysis of variations in the bidirectional reflectance of this surface [*Goel and Deering, 1985*; *Goel et al., 1984*; *Goel and Strelbel, 1983*; *Goel and Thompson, 1984a, b, c*; *Pinty et al., 1989, 1990*; *Dickinson et al., 1990*; *Verstraete et al., 1990*; *Pinty and Verstraete, 1991a*; *Myneni and Ross, 1991*]. The description and analysis of surface processes is complicated, however, by the presence of the atmosphere, which may significantly contaminate the measurements. Most works concerned with the interpretation of directional effects assume that the data have been taken under conditions where the atmosphere does not significantly contribute to the observed reflectance (laboratory or field measurements), or that they have been corrected to remove such effects.

The latter approach, however, is difficult to implement on an operational basis, because meaningful atmospheric corrections would require a rather detailed knowledge of the state and composition of the atmosphere (in particular the water vapor and aerosol content) at the time of the satellite overpass. While the precipitable water content of the atmosphere can be obtained (albeit at a much coarser spatial resolution than that of AVHRR observations) from general

circulation models or from satellite observations in different spectral bands, aerosol loading is essentially unknown. Atmospheric corrections also imply the manipulation of very large data sets from two different sources and raises significant computing issues.

Since these atmospheric effects are too large to ignore [e.g., *Kaufman, 1989*] and rather difficult to remove on the basis of ancillary data, a logical alternative is to attempt to retrieve simultaneously the relevant information on the atmosphere and the surface from the remote sensing data itself. This implies the design of a coupled surface-atmosphere model, and its inversion against these data to retrieve at once the properties of the atmospheric column and those of the surface. A few authors have carried investigations in this area [e.g., *Lee and Kaufman, 1986*; *Liang and Strahler, 1993*]. This paper also describes a coupled model (where the atmospheric component is simple enough to allow inversions to take place) but focuses on the accuracy and reliability of the results obtained by inversion of this coupled model against synthetic data, as a function of the level of noise in the data.

2. MODELING THE COUPLED SURFACE-ATMOSPHERE SYSTEM

Two specific tools need to be developed in order to exploit the geometric variability in the remote sensing data: a model of the bidirectional reflectance of the surface and a model of the contribution of the atmosphere to the measured reflectance. These topics have been investigated extensively but separately, and existing models will be adopted for the current purpose.

2.1. Atmospheric Radiation Transfer Model

The radiation emitted by the Sun is absorbed and scattered by various atmospheric constituents on its way down to the surface, where it is partially absorbed. The reflected portion is further affected (particularly by scattering) on its second passage through the atmosphere, before reaching the satellite sensor. These radiative processes in the atmosphere are relatively well known and have been extensively documented in the literature [e.g., *Chandrasekhar, 1960*; *Lenoble, 1985*]. They can be taken into account through the use of a radiation transfer model and a description of the atmospheric profiles of the relevant constituents. In this study we used a parameterization [*Rahman and Dedieu, 1993*] of the 5S model [*Tanré et al., 1983*] and standard profiles corresponding to a continental atmosphere.

In practical applications, the total radiation impinging on or emerging from a given medium is decomposed into a direct component (i.e., scattering along the line defined by the source and the target, or the target and the sensor) and a diffuse component (i.e., scattering from or in all directions). As discussed by *Tanré et al. [1983]*, the consideration of the various direct and diffuse contributions on the double optical path defined by the relative location of the Sun, the surface and the satellite leads to the introduction of four different surface reflectances: the reflectance of direct and diffuse incoming solar radiation, both directly into the satellite sensor, and the reflectance of direct and diffuse incoming radiation, both indirectly reaching the instrument, after one or more additional scattering events.

For the purpose of simultaneously retrieving atmospheric and surface information by inversion, it is imperative to keep

the number of model parameters to a minimum (see section 3 below). However, it is well known that natural surfaces (and even the atmosphere itself) exhibit significant anisotropy (i.e., the reflectance of the coupled surface-atmosphere system is intimately dependent on the zenith and azimuth angles of both the illumination and the viewing directions), as a result of their varying optical and structural properties. To satisfy these conflicting objectives (the accurate representation of directional reflectances with a limited number of parameters), we have elected to represent the reflectance of the coupled system as follows:

$$\rho_t(\theta_1, \theta_2, \phi) = t_g \left\{ \rho_a(\theta_1, \theta_2, \phi) + \frac{T(\theta_1)T(\theta_2)}{1 - \mathcal{R}(\theta_1, \theta_2, \phi)S} \left\{ \rho_s(\theta_1, \theta_2, \phi) + [\mathcal{R}(\theta_1, \theta_2, \phi) - \rho_s(\theta_1, \theta_2, \phi)] \left[f_d(\theta_1) + f_d(\theta_2) \frac{T_D(\theta_1)}{T(\theta_1)} \right] \right\} \right\} \quad (2)$$

where t_g is the gaseous transmission on the double path and ρ_s and ρ_a are the bidirectional reflectances of the surface and of the atmosphere, respectively. The effect resulting from diffuse directional illumination is represented through a parameterization of the surface reflectance as suggested by *Tanré et al.* [1983].

In this equation, θ_1 and θ_2 represent the illumination and viewing zenith angles; ϕ is the relative azimuth; $T(\theta_1)$ and $T(\theta_2)$ stand for the transmittance of the atmosphere on the incoming and outgoing directions for the combined direct and diffuse radiation, respectively; S is the spherical albedo of the atmosphere; and the multiplicative factor $1/(1 - \mathcal{R}(\theta_1, \theta_2, \phi)S)$ accounts for multiple reflections between the surface and the atmosphere. \mathcal{R} is computed to represent the contribution of the bidirectional reflectance ρ_s weighted by the angular-dependent diffuse irradiance and T_D is the atmospheric transmittance for direct radiation only. The functions $f_d(\theta_i)$ represent the ratio of the diffuse to the total (direct and diffuse) solar radiation impinging on ($i = 1$) or emerging from ($i = 2$) the surface, at the specified zenith angle of illumination and observation, respectively:

$$f_d(\theta_i) = \frac{I_d(\theta_i)}{I_D(\theta_i) + I_d(\theta_i)} \quad i = 1, 2 \quad (3)$$

where $I_D(\theta_i)$ and $I_d(\theta_i)$ represent the direct and diffuse solar radiation fluxes.

Since the angular dependence of the diffuse irradiance is generally not known, we approximate \mathcal{R} , following *Tanré et al.* [1983], by

$$\mathcal{R}(\theta_1, \theta_2, \phi) \approx A + B\rho_s(\theta_1, \theta_2, \phi) \quad (4)$$

where the coefficients A and B were estimated from radiative transfer calculations using realistic surface properties and atmospheric conditions. In the specific case of the AVHRR sensor and for typical terrestrial surface conditions the authors suggest $A = 0.331$ and $B = 0.032$ for channel 1

(visible red band, 580 to 690 nm, for the NOAA 9 instrument) and $A = 0.328$ and $B = 0.085$ for channel 2 (near-infrared band, 720 to 970 nm, again for the NOAA 9 instrument). These coefficients apply for an average atmosphere, characterized by a typical continental aerosol optical thickness of 0.35. This expression yields a reasonable estimate of the contribution of the diffuse radiation to the total reflectance.

In (2) the direct and diffuse components of the radiation are well separated: the first term corresponds to the atmospheric reflectance, the second term represents the bidirectional properties of the surface, and the third term approximates the contributions due to the diffuse part of the total signals.

Equation (2) clearly illustrates how the atmosphere modifies the anisotropy of the surface. In particular, the third term (which is added to ρ_s) of this equation smoothes the bidirectional contribution of the surface in addition to the first term, by adding a component which couples the diffuse atmospheric and surface properties. Under atmospheric conditions where the scattering effects are limited (i.e., small optical depth), the function f_d tends to a small value and since the atmospheric reflectance is also minimum, the surface angular anisotropy is directly transmitted to the top of the atmosphere without any significant perturbations. Equation (2) also implies that the reflectance taken immediately above the surface is varying with the atmospheric conditions and depends on the scattering properties of the atmosphere with respect to the incoming radiation.

The atmospheric transmissions $T(\theta_1)$ and $T(\theta_2)$ have been estimated with a simple but accurate empirical model fitted to the 5S model of *Tanré et al.* [1986], as explained by *Rahman and Dedieu* [1993]. This model takes into account the gaseous absorptions of ozone, water vapor, oxygen and carbon dioxide, as well as the scattering by molecules and aerosols. A standard continental aerosol profile, as described in 5S, has been assumed. The model accepts as input the zenith and azimuth angles of the illumination and viewing directions as well as the atmospheric contents of the radiatively active constituents (water vapor, ozone, and aerosol).

2.2. Surface Bidirectional Reflectance Model

The bidirectional reflectance of the surface is simulated with the model of *Verstraete et al.* [1990], and *Pinty et al.* [1990]. This model calculates the directional reflectance emerging from an optically thick canopy or soil as a function of the physical and structural properties of the surface and of the angular positions of the Sun and of the observer. The optical and structural properties of the surface include the single-scattering albedo and the phase function of the scatterers, their orientation, and a parameter describing the shape of the holes between the scattering elements. The main advantages of this model are that (1) it is physically based, i.e., the model parameters are precisely defined physical quantities; (2) the description of the hot spot (or opposition) effect derives naturally from the analytical computation of the transmission of radiation along the double path in the porous medium; (3) it uses only four physical parameters and can be inverted against actual or simulated data; and (4) it has been widely used and validated for a variety of soil and vegetation surfaces [*Pinty et al.*, 1989, 1990; *Jacquemoud et al.*, 1991].

Following *Pinty et al.* [1990], the bidirectional reflectance of a deep canopy is given by

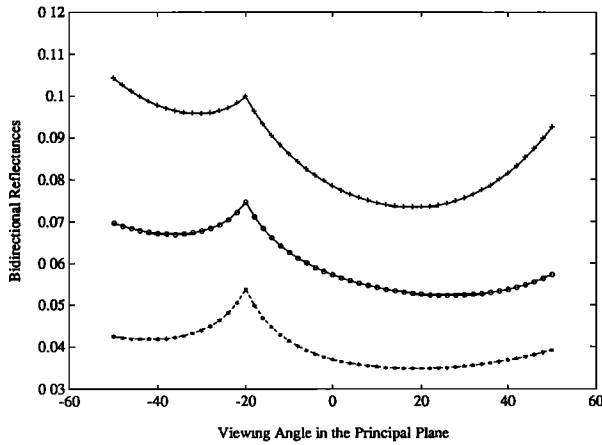


Fig. 1a. Bidirectional reflectances computed in the principal plane for advanced very high resolution radiometer (AVHRR) channel 1: (asterisks) at the surface, (circles) top of the atmosphere with an aerosol optical depth at 550 nm of 0.1, (pluses) top of the atmosphere with an aerosol optical depth of 0.6. The scatterers are assumed to be uniformly distributed in orientation ($\chi_1 = 0$) and the solar zenith angle is set at 20° . The other model parameters are $\omega = 0.2$, $2r\Lambda = 1.0$, $\Theta = 0$, the ozone amount is assumed to be 0.3 cm atm , and the water vapor amount is 2.0 g cm^{-2} .

$$\rho_s(\theta_1, \theta_2, \phi) = \frac{\omega}{4} \frac{\kappa_1}{\kappa_1 \mu_2 + \kappa_2 \mu_1} \cdot [P_v(G)P(g) + H(\mu_1/\kappa_1)H(\mu_2/\kappa_2) - 1] \quad (5)$$

where

$$\mu_1 = \cos \theta_1$$

$$\mu_2 = \cos \theta_2$$

$$\cos g = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\phi)$$

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

$$P_v(G) = \frac{1}{1 + V_p(G)} \quad (6)$$

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

$$P(g) = \frac{1 - \Theta^2}{[1 + \Theta^2 - 2\Theta \cos(\pi - g)]^{1.5}}$$

$$H(x) = \frac{1 + x}{1 + \sqrt{(1 - \omega)x}}$$

In these equations, ω is the average single-scattering albedo of the particles making up the surface; κ_1 and κ_2 are describing the orientation distribution of the scatterers, for the illumination and viewing angles, respectively; $P_v(G)$ is the function that accounts for the joint transmission of the incoming and outgoing radiation, and thereby also for the “hot spot” phenomenon; $P(g)$ is the Henyey-Greenstein phase function of the scatterers; Θ is the phase function parameter; and the expression $H(\mu_1/\kappa_1)H(\mu_2/\kappa_2) - 1$ ap-

proximates the contribution from multiple scattering [see Dickinson *et al.*, 1990].

The functions κ_i represent the average cosine of the angles between the normals to the scatterers and the direction of illumination ($i = 1$) or observation ($i = 2$). These values can be computed exactly if the statistical distribution of scatterer orientation is given [e.g., Verstraete, 1987], or can be estimated with simple empirical expressions, as suggested by Goudriaan [1977, 1988] or by Dickinson *et al.* [1990]. In the special simple case of uniformly distributed scatterers (i.e., all scatterer orientations are equiprobable), κ_i is constant and equal to $\frac{1}{2}$. In the following computations we have used the Henyey-Greenstein formula for the phase function $P(g)$ [Pinty *et al.*, 1990] and the parameterization of Dickinson *et al.* [1990] to estimate the κ_i functions.

The functions P_v and V_p further depend on G , a geometric factor that generally takes on large values, except when the direction of observation is close to the direction of illumination, r , the radius of the Sun flecks on the inclined scatterers, a parameter related to the horizontal distance between the scatterers and Λ , the scatterer area density, expressed as the scatterer surface per unit bulk volume, a parameter related to the vertical spacing of the scatterers. Both r and Λ are relative to the field of view of the instrument and are therefore scale dependent.

2.3. Sensitivity of the Anisotropy of the Coupled Model on Atmospheric Parameters

Absorption and scattering processes are strongly dependent on the wavelength of the radiation, both within the plant canopy and within the atmosphere (although differently so in each medium). As a result, the presence of the atmosphere modifies the anisotropy patterns of the surface insofar as they are observed by satellite instruments. In this section we investigate this question specifically for channels 1 and 2 of the AVHRR instrument. Channel 1 measurements are most sensitive to molecular scattering and to the nature and amount of aerosol. By contrast, channel 2 is mostly affected by water vapor absorption.

Figures 1a and 1b show the effect of changes in atmospheric aerosol optical thickness on the top of atmosphere directional reflectance, over a typical vegetation canopy composed of isotropic scatterers ($\Theta = 0$), as it would be

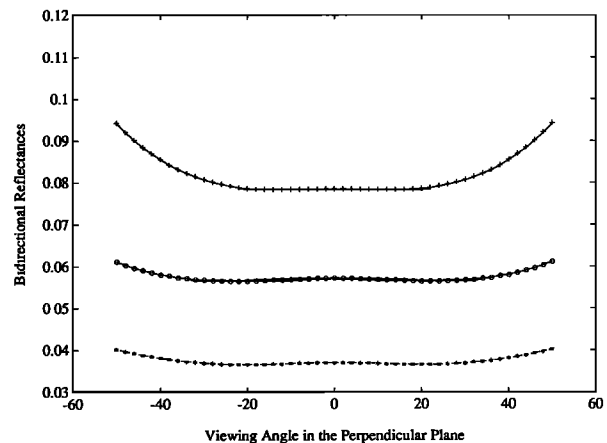


Fig. 1b. Same as Figure 1a except in the perpendicular plane.

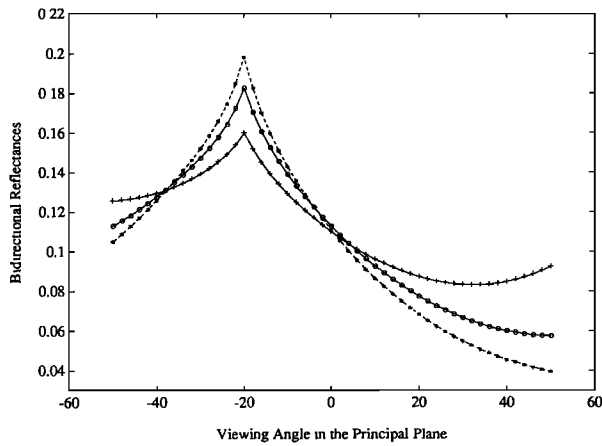


Fig. 2a. Same as Figure 1a except that $\Theta = -0.4$.

sensed by AVHRR in channel 1, as a function of the view angle in the principal and perpendicular planes, respectively. The two different atmospheric conditions we considered are a relatively clear atmosphere with an aerosol optical depth at $0.55 \mu\text{m}$ of 0.1 and a more turbid atmosphere with aerosol optical depth of 0.6; they are shown together with surface values (i.e., in the absence of atmospheric effects) for comparison. It can be seen that although the surface pattern clearly controls the shape of the function at the top of the atmosphere, the net effect of the atmosphere is not only to increase the reflectance (translation of the curves upward), but also to modify the angular distribution of the light (distortion of the curves).

Figures 2a and 2b exhibit the same effect but this time for a scattering medium characterized by a more strongly back-scattering phase function ($\Theta = -0.4$) such as would be observed for bare soils. In this case, a clear atmosphere does not significantly modify the bidirectional signal from the surface, but more turbid conditions appreciably reduce the directional variability of the signal, both in the principal and in the perpendicular planes.

These two sets of figures show that the net effect of the atmosphere can be to increase or decrease the angular variability of the reflected radiation field, depending on the

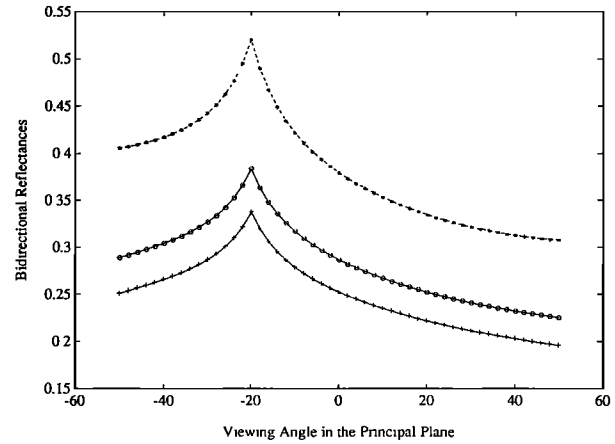


Fig. 3a. Bidirectional reflectances computed in the principal plane for AVHRR channel 2: (asterisks) at the surface, (circles) top of the atmosphere with a water vapor amount of 0.5 g cm^{-2} , (pluses) top of the atmosphere with a water vapor amount of 5.0 g cm^{-2} ; the solar zenith angle is fixed at 20° . The other parameters are as follows: $\omega = 0.8$, $\chi_l = 0$, $2r\Lambda = 1.0$, $\Theta = -0.2$, the aerosol optical depth at 550 nm is 0.3, and the ozone amount is 0.3 cm atm .

optical properties of the underlying surface and the turbidity of the atmosphere.

The effect of atmospheric water vapor amount on the estimated directional reflectance for AVHRR channel 2 is shown in Figures 3a and 3b, again as a function of the viewing angle in the principal and perpendicular planes, respectively. The water vapor contents are 0.5 and 5.0 g cm^{-2} , and the reflectances at the surface (i.e., in the absence of the atmosphere) are shown for comparison. From this figure, it is clear that the atmospheric water vapor mostly decreases the reflectance values for all viewing angles and does not introduce significant changes in the shape of the anisotropy of the surface: Most of the directional variability characterizing the surface is transmitted unaffected at the top of the atmosphere.

Obviously, these figures exhibit only a few of the many possible combinations of surface and atmospheric properties that can be expected in nature, and it remains difficult to draw general conclusions from these specific cases. However, these simulations show that the atmosphere has the

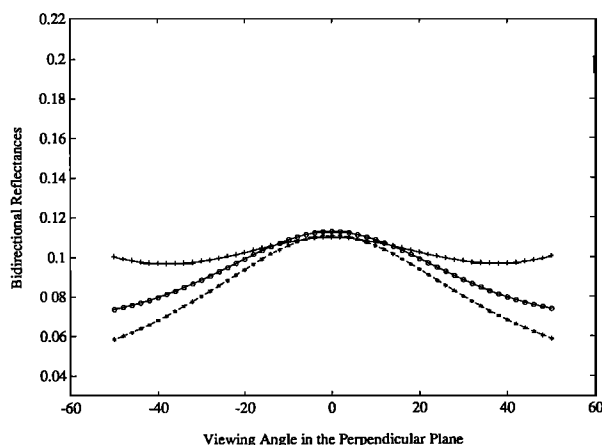


Fig. 2b. Same as Figure 1b except that $\Theta = -0.4$.

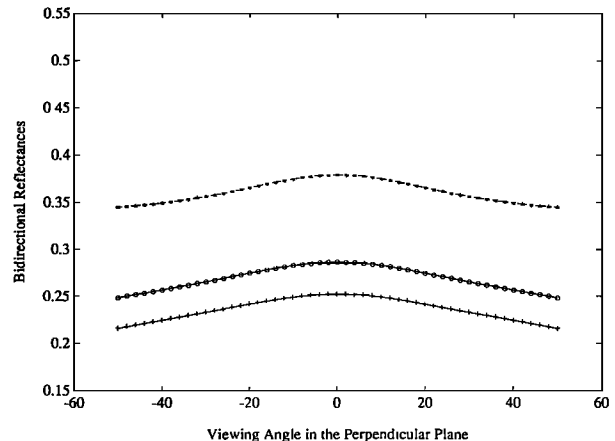


Fig. 3b. Same as Figure 3a except in the perpendicular plane.

potential for modifying both the transmission and the angular distribution of light reflected by the surface:

(1) In the case of channel 1, where chlorophyll absorption leads to small reflectance values over vegetation canopies, atmospheric scattering modifies both the amplitude and the angular distribution of the surface bidirectional reflectance. Since the intrinsic reflectance of the atmosphere can reach values close to that of the surface, increasingly optically deep layers of atmospheric aerosol tend to smooth and mask the surface angular behavior.

(2) In the case of channel 2 the situation is much simpler because the absorption process leads to a uniform reduction in the amplitude of the signal and large zenith angle conditions must be considered before observing a significant change in the angular patterns of reflectance.

It must be pointed out here that it is this asymmetry in the response of the two channels to atmospheric effects which is responsible for the anisotropic contamination of vegetation indices such as the normalized difference vegetation index by the atmosphere.

Although the effect of other absorbing gases such as oxygen, carbon dioxide, and ozone have not been shown here, their relative importance with respect to AVHRR measurements lags behind that of the aerosol and water vapor content [Tanré *et al.*, 1992]. Since AVHRR measurements are strongly affected by these two atmospheric components (which also exhibit a large temporal and geographical variability), it is reasonable to focus on them either when correcting the AVHRR data for the atmospheric masking effects or when inverting a coupled surface-atmosphere model, as is the case in the present study. In the following sections we discuss the invertibility of such a model and examine the accuracy of the retrieved parameters which result from the inversion.

3. DESCRIPTION OF THE INVERSION PROCEDURE

The fundamental issue in remote sensing is the retrieval of reliable accurate information about the target of interest from an analysis of the measurements. Since each observation, in general, reflects the influence of multiple radiative processes (e.g., emission and scattering), the extraction of this information cannot be achieved analytically but relies upon the inversion of mathematical models against multiple observations [e.g., Goel, 1988].

For the purpose of the discussion, let

$$z = f(x_1, x_2, \dots, x_n; y_1, y_2, \dots, y_m) \quad (7)$$

be an analytical representation (e.g., a reflectance model) of the relation between the parameters y_j , ($j = 1, \dots, m$), which describe the physics of the surface, a set of independent variables x_i , ($i = 1, \dots, n$), describing the conditions of observation, and the observable quantity z .

Each individual measurement of the observable quantity z yields a value \hat{z} , which is presumably resulting from a particular set of values of y_j . Since we usually have $m > 1$ unknowns and only one equation, the values of y_j cannot be determined on the basis of this unique measurement and of the single equation. We can make multiple measurements (say M), but then we get, again in principle, a system of M equations in $M \times m$ unknowns:

$$z_1 = f_1(x_{11}, x_{12}, \dots, x_{1n}; y_{11}, y_{12}, \dots, y_{1m})$$

$$z_2 = f_2(x_{21}, x_{22}, \dots, x_{2n}; y_{21}, y_{22}, \dots, y_{2m})$$

$$\vdots$$

$$z_M = f_M(x_{M1}, x_{M2}, \dots, x_{Mn}; y_{M1}, y_{M2}, \dots, y_{Mm})$$

Additional assumptions are needed to solve such a system. Specifically, we will assume (1) that the target does not change significantly between measurements, i.e., that the form of the equation f and values of the parameters y_j are unchanged for all measurements, (2) that different observations, taken for various values of the independent variables x_i , display significant variability, and (3) that more observations are taken for various conditions x_i than there are parameters y_j to retrieve, i.e., $M > m$. Optionally, one or more of the parameters y_j can be specified on the basis of other sources of information, in which case the number of parameters y_j to be retrieved by inversion is decreased.

Following Verstraete and Pinty [1992], the inverse problem can be formulated as follows. Model inversion is a numerical procedure based on the iterative search for the global optimum of a figure of merit function. The sum of the squares of the differences between the observed values and those predicted by the model is often selected, in which case the function to minimize is

$$\delta^2 = \sum_{i=1}^M W_i [\hat{z}_i - f_i(x_{i1}, x_{i2}, \dots, x_{in}; y_{i1}, y_{i2}, \dots, y_{im})]^2 \quad (9)$$

but other criteria could be used as well. The factors W_i are the weights given to the successive measurements. In this study we have set $W_i = 1$ for all observations. In general, the larger the number of free model parameters the more difficult it is to find a unique optimal solution. The models should therefore be as simple as possible.

The mathematical tools to invert models are described in many standard texts [e.g., Press *et al.*, 1992]. We routinely use the routine E04JAF of the Numerical Algorithms Group (NAG) library, which implements a quasi-Newton algorithm to find the minimum of the function δ^2 , subject to upper and lower bounds on the independent variables. This algorithm uses function values only and searches for the optimum solution iteratively from an initial guess provided by the user. As always, when using packaged algorithms, it is up to the user to verify that all conditions required for the applicability of the program are fulfilled and that the results obtained are not sensitive to such things as the choice of initial guesses, the number of iterations, or the criteria used to stop the iteration process.

4. INVERSION OF THE COUPLED SURFACE-ATMOSPHERE MODEL

In this section we demonstrate the feasibility of retrieving both atmospheric and surface parameters from an inversion of a coupled model against simulated satellite remote sensing data.

TABLE 1. Physical Parameter Values Used to Generate the Synthetic Data Sets

Subsystem	Parameter	Channel 1		Channel 2	
		Value	Unit	Value	Unit
Atmosphere	O ₃	0.3	cm atm		
	τ_{550}	0.10, 0.35, 0.70		0.35	
Surface	H ₂ O	2.0	g cm ⁻²	1.0, 2.0, 5.0	g cm ⁻²
	ω	0.2		0.8	
	Θ	0.0		-0.2	
	χ_l	0.2		0.2	
	2r Λ	0.2		0.2	

4.1. Generation of Simulated Satellite Data

The coupled surface-atmosphere model described above was used to generate simulated AVHRR data at the level of the satellite, using the parameter values indicated in Table 1.

Top of atmosphere reflectances were generated for solar and view zenith angles from 0° to 50°, in steps of 10°, and for relative azimuth angles from 0° to 180°, in steps of 45°. The basic data set therefore contain 180 reflectance values.

To investigate the inversion of a coupled model against AVHRR-type data in the solar range, we generated a series of data sets for different types of atmospheres. For AVHRR channel 1, both Rayleigh (molecular) and aerosol scattering are relatively important. The former varies only slowly with surface pressure, but the aerosol optical depth exhibits relatively large temporal and spatial variabilities. We have therefore generated three data sets corresponding to atmospheres of different turbidities to simulate actual data in the “visible” part of the spectrum: a relatively clear atmosphere with an aerosol optical depth τ_{550} of 0.1, a moderate atmosphere with $\tau_{550} = 0.35$, and a more turbid atmosphere for which $\tau_{550} = 0.7$. In each of these three cases, the “true” surface parameters were kept the same, and the other atmospheric parameters were kept at their nominal average values, since they have little or no effect on atmospheric transmission.

To generate data in the near-infrared band, we used a constant value of the aerosol optical thickness, since it is not a major variable in this spectral region. On the other hand, the presence of a water vapor absorption band affects the measured radiance at the top of the atmosphere and must be accounted for. In this case we have also generated three data sets for water vapor contents of 1.0, 2.0, and 5.0 g cm⁻², respectively. Again, the other surface and atmospheric parameters were kept constant. All these data sets will be collectively referred to as the “clean” data sets, to distinguish them from the “noisy” data sets to be described below.

4.2. Method

Since it is difficult to accurately and reliably retrieve a large number of parameters from an inversion scheme, it is advisable to minimize this number in any one inversion. We start by noting that if the aerosol loading affects both channels, the first one is the most sensitive to this atmospheric constituent. At the same time, since the water vapor content modifies the measured radiances in channel 2 only, we take advantage of this decoupling to retrieve the aerosol loading from channel 1 first and impose this value while retrieving the water vapor amount from channel 2. For

analogous reasons we know a priori that the structural properties of the surface (χ_l and 2r Λ) should not be wavelength dependent, assuming that the canopy is vertically homogeneous, and therefore should take on the same values in both channels. We also note that the generally low value of the single-scattering albedo ω of leaves in the visible spectral region results in few multiple-scattering events, and thereby a more sharply defined anisotropy, than in the near infrared. Since the anisotropy of the surface is largely affected by the structure of the medium, we retrieve these parameters from inversion in the visible band and impose their values when performing the inversion in channel 2.

It follows that the inversion should be performed in channel 1 first, to retrieve five parameters: the single scattering albedo ω of the surface, the asymmetry factor of the phase function Θ , the scatterer orientation parameter χ_l , the structural parameter 2r Λ , and the aerosol optical depth at 550 nm τ_{550} . The values of χ_l , 2r Λ , and τ_{550} are then imposed during the inversion of the model against data in channel 2, which yields estimates for the single-scattering albedo ω , the asymmetry factor of the phase function Θ , and the water vapor content of the atmosphere. This approach minimizes the number of parameters to estimate at once and, incidentally, also reduces the computing requirements.

Actual measurements always include a certain amount of noise, and it is important to estimate how sensitive the results of an inversion are to the presence and amount of noise in the data. To this end, we have generated 500 noisy data sets for each type of atmospheric condition and channel, by adding normally distributed random noise with zero mean and standard deviation of 0.1, 2.0, 4.0, 8.0, and 10.0% of the hemispherical reflectance value to the clean data sets described above. The same series of random numbers has been used for each value of the standard deviation. The coupled model was then inverted successively against each of these derived data sets, and these results have allowed the estimation of the mean value and standard deviation of each parameter, as a function of the amount of noise in the data. A coefficient of variability σ_i , also called “error sensitivity” [Goel *et al.*, 1984], has then been estimated as the ratio of these two quantities:

$$\sigma_i = SD_i / X_i \quad (10)$$

where SD_i is the standard deviation of the i th parameter and X_i is the average or true parameter value. This coefficient provides an assessment of the variability of the retrieved canopy parameters when the reflectances are randomly modified, this statistic can be used to characterize the sensitivity of the parameter to noise in the data, and thereby

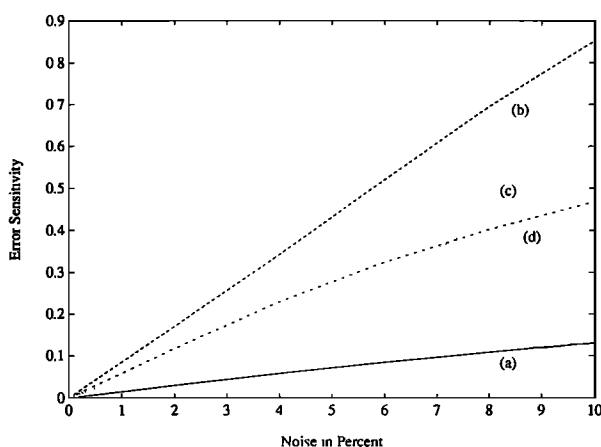


Fig. 4. Error sensitivity of the retrieved parameter values, for AVHRR channel 1, as a function of the amount of noise in the data, for an atmosphere with an aerosol optical depth of 0.1 at 550 nm. The four curves refer to (a) ω , (b) χ_l , (c) $2r\Delta$, and (d) τ_{550} .

the quality of the inversion procedure. The objective of this study on the effect of noise is to document the likely impact of instrumental and other sources of imprecision on the results of the inversion. A different representation of noise would probably affect the results differently. In the next two sections we apply this approach to data sets simulating AVHRR channels 1 and 2.

4.3. Inversion Against Synthetic Data for Channel 1 of Advanced Very High Resolution Radiometer (AVHRR)

The error sensitivity σ_i , defined above, is shown in Figures 4, 5, and 6 for three different atmospheres, differing only by the aerosol optical depth, as a function of the amount of noise in the data.

The estimation of the single-scattering albedo ω turns out to be quite robust with respect to the level of noise in the data. The corresponding error sensitivity increases slightly with increasing noise level and depends somewhat on the type of atmosphere. With a noise level of 10% the error sensitivity is 0.13 for a clear atmosphere, whereas for a moderate or a turbid atmosphere the values are 0.16 and 0.49, respectively. In generating channel 1 data, we have

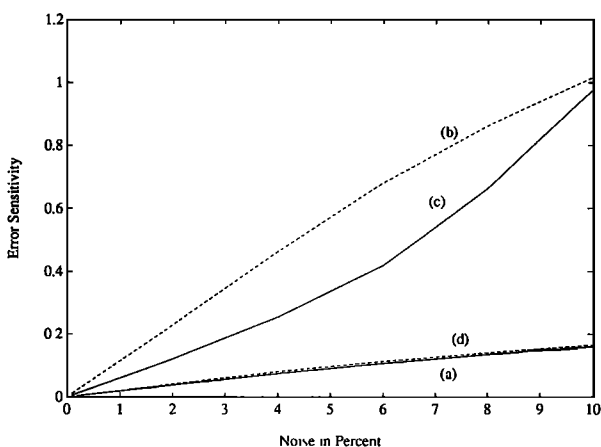


Fig. 5. Same as Figure 4 except for an aerosol optical depth of 0.35 at 550 nm.

assumed isotropic scatterers (i.e., an asymmetry factor $\Theta = 0$), so we cannot calculate the error sensitivity for this parameter. However, independently of atmospheric turbidity the standard deviation of this parameter is about 0.005, which is a very small value. When the noise level is increased to 10%, the standard deviation reaches 0.03. The leaf orientation parameter χ_l is one of the two structural parameters of the surface. The corresponding error sensitivity shows a similar behavior as that of the single-scattering albedo: it increases with increasing noise level for the three types of atmospheres, but much more rapidly than for the former parameter, and increases with the aerosol load. When the noise level in the synthetic data reaches 10%, the error sensitivities are 0.85, 1.01, and 1.4 for a clear, moderate, and turbid atmosphere, respectively.

A relatively unstable behavior is observed for the other structural parameter $2r\Delta$, in which the error sensitivity increases relatively rapidly with the increasing noise level in the data, for the three types of atmospheres. The corresponding error sensitivities are 0.6, 0.98, and 2.5 for a clear, average, and turbid atmosphere, respectively, and for a noise level of 10% in each case. The error sensitivity for the aerosol optical depth seems relatively stable with respect to the noise introduced in the data, with values of 0.46, 0.16, and 0.06 corresponding to a clear, moderate, and turbid atmosphere, again for a noise of 10% in the data. In fact, this result shows that this parameter is almost unaffected by the noise level up to 10% and can be easily retrieved by the inversion technique.

In summary, the optical parameters of the surface and the aerosol loading in the atmosphere appear to be retrievable even from noisy data, while the morphological parameters of the canopy appear to be the more difficult ones to estimate in the presence of noise. Two remarks must be made in this respect, although they are not pursued further in this paper: (1) if the angular sampling scheme to observe the bidirectional reflectance field is flexible, it may be quite useful to increase the density of observations at small phase angles, to improve the accuracy and reliability of the retrieval of the structural parameters, and (2) if this sampling scheme is not flexible (as is usually the case for satellite instruments) or if few or no observations are made at small phase angles, the accuracy of the retrieval of the hot spot parameter may be very low if the data are very noisy.

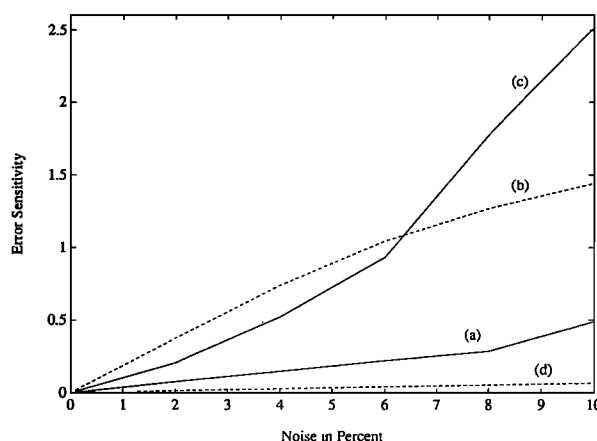


Fig. 6. Same as Figure 4 except for an aerosol optical depth of 0.7 at 550 nm.

4.4 Inversion Against Synthetic Data for Channel 2 of AVHRR

Just as was done above for channel 1, Figures 7, 8, and 9 show the results of repeated inversions of the coupled surface-atmosphere model against 500 instances of synthetic noisy data sets. The three different atmospheric conditions considered here correspond to water vapor contents of 1.0, 2.0, and 5.0 g cm^{-2} . The panels exhibit the error sensitivities of the different parameters, also as a function of the amount of noise.

For all practical purposes the retrieved values of single-scattering albedo ω are not significantly affected by the level of noise introduced in the data, irrespective of the amount of atmospheric water vapor. The error sensitivity for this parameter is also very small for the three values of atmospheric water vapor content, although a slight increase is observed with the increase of noise in the data. With a noise level of 10% the corresponding values of the error sensitivities are 0.043, 0.046, and 0.046 for an atmosphere having a water content 1.0, 2.0, and 5.0 g cm^{-2} , respectively.

The retrieval accuracy of the asymmetry factor Θ is also very encouraging, since it is almost independent of the noise level in the data (up to 10%, for three different water vapor contents in the atmosphere). In fact, for a noise level ranging from 0.1 to 10%, the performance is almost the same. The error sensitivity is also rather small for this parameter in all three cases of atmospheric water vapor content: of the order of 0.06 for a noise of 10%, which indicates that this parameter can reliably be retrieved by inversion, even when the data are noisy.

On the other hand, the retrieved values of water vapor content show a high dependency on the level of noise in the data. The difficulty to retrieve accurate and reliable estimates of this parameter in the presence of noise in the data is confirmed by the error sensitivity statistics, which increases very rapidly with the level of noise. Furthermore, this effect is more pronounced for smaller water vapor content (1.0 g cm^{-2}) than for higher amounts. The corresponding values of error sensitivities are 2.7, 1.7, and 0.75 for a noise level of 10% and for atmospheres having water vapor content 1.0, 2.0, and 5.0 g cm^{-2} , respectively. When

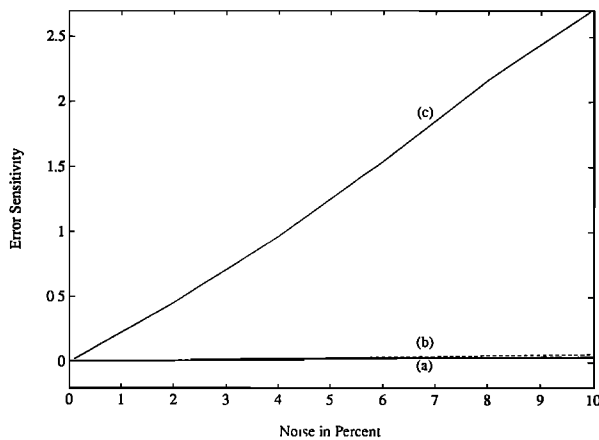


Fig. 7. Error sensitivity of the retrieved parameter values, for AVHRR channel 2, as a function of the amount of noise in the data, for an atmosphere with a water vapor amount of 1.0 g cm^{-2} . The different curves correspond to different parameters, keyed as follows: (a) ω , (b) Θ , and (c) water vapor amount.

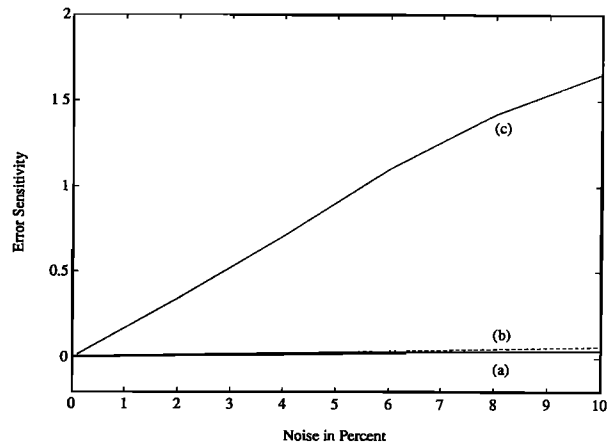


Fig. 8. Same as Figure 7 except for a water vapor content of 2.0 g cm^{-2} .

the noise level drops to 0.1%, the corresponding values of error sensitivity are only 0.02, 0.017, and 0.01, respectively, for the same atmospheres. Clearly, the atmospheric water vapor content is very difficult to retrieve from noisy data with this technique, unless very precise reflectance measurements are made by space instruments.

5. CONCLUSIONS

Various remarks may be made on the series of experiments described in this paper: First, it is possible to design and implement coupled surface-atmosphere models to represent the anisotropy of the total system and yet simple enough to be inverted jointly against simulated satellite data. A parametric model such as this one must be seen as an approximation to the full treatment of the radiation transfer in a medium with two superposed layers. In the specific case envisaged here, the atmospheric medium is well understood and the only unknown optical property is the optical depth of the variable optically active elements. Clearly, in the approach described here and by opposition to the approaches developed earlier, more importance has been given to the proper representation of the surface than to that of the atmosphere.

Second, an analysis of the inversion results has shown that

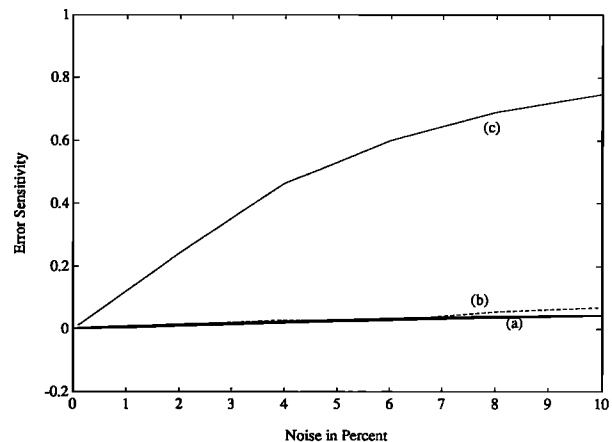


Fig. 9. Same as Figure 7 except for a water vapor content of 5.0 g cm^{-2} .

the variance associated with the noise in the data does not affect the retrieval of all physical parameters equally. Specifically, some of the parameters can be retrieved with good accuracy, even from noisy data, while others are much more difficult to estimate at an acceptable level of accuracy. Since the accuracy of the results depends on the angular sampling of the bidirectional reflectance of the joint surface-atmosphere system as well as the level of noise in the measurements, sampling strategies and the quality of the instruments will have to be designed as a function of the particular scientific objectives being pursued. For instance, AVHRR data may prove to be adequate for retrieving the single-scattering albedo of the surface, in both channels, but not the water vapor amount, unless numerous high-quality data are collected for the particular location and time of interest.

Third, and perhaps most importantly, it has been shown that atmospheric corrections are not, in principle, the only way to account for the masking effect of the atmosphere. Since these corrections always necessitate rather severe hypotheses, such as an average typical atmospheric profile, or rely on large data sets to describe the state of the atmosphere from independent observations, they always represent a rather cumbersome operation. The developments described in this paper show that it may be possible to retrieve atmospheric parameters simultaneously with surface characteristics, provided that sufficient sampling of the bidirectional reflectance distribution and accurate reliable data can be obtained. The multiangle imaging spectroradiometer instrument on board the upcoming AM platform of NASA may significantly improve our data acquisition capability in this respect [Diner *et al.*, 1979].

Specifically, it is suggested that (1) if the surface bidirectional reflectance exhibits a strong hot spot and this angular region is adequately sampled, then the optical and the structural properties of the surface may be retrieved with good accuracy; (2) if the surface does not exhibit such a hot spot, or if it does but the angular sampling is not sufficient in that region, then the optical properties of the surface and possibly the average orientation of the scatterers may be reliably retrieved, but the structure of the canopy cannot be accurately assessed. Furthermore, (3) the estimation of the aerosol loading of the atmosphere appears to be feasible in principle from channel 1 of AVHRR, if the type of aerosol can be assumed (e.g., continental) and if the aerosol loading is large enough, even in the presence of appreciable noise in the data, while (4) the accurate retrieval of the atmospheric water vapor amount from channel 2 data appears difficult, unless the data are of very high quality.

Clearly, the design of the AVHRR instrument and in particular the position of its channels were not selected to retrieve surface and atmospheric properties in the way described above. Rather, the existence of long series of AVHRR observations and the properties of its wide spectral bands have generated a strong interest in the climatological and ecological communities toward the use of these data to document climatic and environmental changes. It is unfortunate that the atmospheric water vapor cannot be easily and simply retrieved from AVHRR channel 2 data, but this parameter is generally rather well known, as it is measured independently by the upper air meteorological stations, or from other remote sensing instruments (such as TOVS, also located on the NOAA satellite).

If new and better atmospheric sounders will be designed and launched in the near future and will provide an adequate description of the distribution of water vapor in the atmosphere, the aerosol loading of the atmosphere has always been and will continue to be a major unknown and a significant perturbing factor for the analysis of data in channel 1 of AVHRR. The prospect of being able to retrieve a useful estimate of this loading from the inversion of a coupled model against these data is therefore most exciting. Of course, this opportunity may materialize only to the extent that accurate data may become available. The new generation of sensors should result in major advances, as noted above.

This paper describes only preliminary results from a simulation study. This work must now be carried over to actual AVHRR data to demonstrate the validity of the approach advocated here. This will require a different model to describe the anisotropy of the surface, because actual ecosystems do not generally satisfy the homogeneity criteria assumed by the surface model used here. These issues will be addressed in a companion paper.

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