Modeling the Scattering of Light by Homogeneous Vegetation in Optical Remote Sensing

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ABSTRACT

This paper discusses the problem of radiation transfer in geophysical media, in particular, within homogeneous plant canopies over terrestrial surfaces. The emphasis is placed on the specificities of this problem when it is addressed with the radiation transfer equation classically used in atmospheric sciences. The discussion takes place in the context of remote sensing applications, where the main constraint is to be able to invert the photon transport model against observations to retrieve the properties of the observed media. To facilitate the solution of the radiative coupling between the vegetation and atmospheric layers, the same formal approach is used in both media, and the extinction and differential scattering coefficients are specified in a similar way. The accurate description of the radiation transfer within a vegetation layer is complicated by the fact that both of these coefficients depend on the position of the external sources of radiation, and by the lack of precise knowledge about the radiative boundary conditions at the top and bottom of this layer. Effective solutions to the radiation transfer problem in plant canopies require the introduction of specific hypotheses, for instance, in the treatment of the multiple scattering contribution.

1. Introduction

Instruments onboard earth-orbiting satellite platforms measure the radiance field exiting from the planet. These measurements can, in principle, be interpreted to describe the radiative properties of the observed media (soil, vegetation, and atmosphere), provided these media actually affect the measured radiance field. However, an accurate understanding of the processes governing the scattering of light by atmospheric and terrestrial objects is required to properly interpret these measurements. Observations of light scattering in space therefore appear to be an important potential source of information to document the radiative state of the earth system.

In the optical domain, each measurement acquired by a satellite sensor is a function of the particular geometry of illumination and observation at the time of observation, and includes the contributions of all media interacting with the incoming solar light. These media exert their influence on the transfer of radiation through their specific radiative properties, which control how light is scattered and absorbed.

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The primary objective of remote sensing scientists is therefore to acquire a fundamental understanding of these radiative processes and to exploit this knowledge by implementing algorithms and operational procedures to effectively extract the information of interest from the measured signals. This is known as an inverse problem, and its solution involves the development of two distinct tools, namely, a model capable of accurately simulating how the radiance field is affected by the media in which it propagates and an efficient and reliable numerical algorithm capable of estimating the values of the model parameters that best describe the observed variability in the data. In practice, the numerical inversion of a model against a dataset raises many technical issues (e.g., see Pinty and Verstraete 1992). Specifically, the choice of initial guesses, the range of allowed parameter variability, the nature and implementation of the numerical algorithm, and the precision of the computer used all directly affect the values of the retrieved parameters, and consequently the reliability of the results. One of the most difficult issues that needs to be addressed is the number of independent parameters the radiation transfer model may use. Indeed, the larger this number, the easier it becomes for the model to fit a particular dataset, and the less likely a unique solution can be identified. In this case, the accuracy and reliability of the results may be seriously compromised, as the numerical procedure may settle on a locally but not globally optimal solution.

The development of radiation transfer models for the

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purpose of retrieving useful information from remote sensing data must clearly take these constraints into account and pay particular attention to 1) the selection of the minimal set of independent variables required to represent the physics of the problem and 2) the quantification of the likely errors unavoidably associated with the specific assumptions and simplifications made. Clearly, the objective is to strike a suitable compromise between the drive to develop detailed and accurate representations of all the relevant radiative processes and the need to ensure the efficient selection of a reliable numerical solution with a given inversion procedure.

Physically, the radiance field emerging above any vertically homogeneous layer composed of a large number of scatterers (such as an atmospheric or vegetation layer) can be described by a photon transport equation expressing the conservation of energy in that layer and the specification of the external sources of radiation. Such a transport equation is an integro–differential equation that expresses the simple fact that the change in intensity along a given direction Ω_i may be due to the absorption or scattering of light in other directions ($\Omega_i \rightarrow \Omega_j$: extinction or sink term) or from other directions into the direction of interest ($\Omega_j \rightarrow \Omega_i$: multiple scattering or source term). The contribution of external sources of radiation is handled through appropriate boundary conditions. The internal processes of absorption and scattering fully depend on the optical properties of the scatterers and their geometrical distribution in the medium. In the transport equation that describes the radiation intensity vector at point z in the direction Ω, the radiative properties of the medium are specified by an extinction coefficient $\sigma(z, \Omega, \Omega_0^{1,2})$ for the sink term, and a differential scattering coefficient $\sigma_s(z, \Omega, \Omega_*)$ for the internal source term; both coefficients depend explicitly on the original directions of photons, namely, the direction of incoming external source of radiation at the top (Ω_0^1) and bottom (Ω_0^2) of the canopy, or the previous directions (Ω_*) of the multiply scattered photons reradiated in direction Ω after the interaction has happened. These coefficients may represent the properties of individual scatterers or the statistical characteristics of the medium, depending on the spatial scale of investigation.

Mathematically, this transport equation can be solved for the intensity at any level in the medium provided the analytical expressions for the two coefficients σ and σ_s, as well as the upper and lower boundary conditions, are given. This radiation transfer problem can also be solved for more complex systems of two or more media if this system can effectively be represented as a stack of homogeneous layers for which all conditions above are individually verified. The physical coupling between these layers and the corresponding media is then accounted for through the appropriate boundary conditions. Hence, the fundamental problem of remote sensing can be formally solved in many terrestrial situations, for a wide variety of coupling conditions between the intervening layers.

From a technical point of view, however, the generation of an accurate solution to the general photon transport problem involving a set of coupled integro–differential equations requires significant computer resources and is hindered by many numerical issues. It is therefore often necessary to solve the radiation transport problem for each major medium of geophysical interest separately (e.g., the soil, vegetation, atmosphere, and cloud layers) and to enforce the coupling in a second stage since the outputs from any one of the models produces the directional intensities of the external sources (boundary conditions) interacting with the surrounding media. Such an approach also affords more flexibility in the development and validation of the components of the fully coupled model.

The classical theory of radiation transfer describes the scattering of light by a large ensemble of scatterers, under a number of assumptions, including the far-field approximation. This theory provides the conceptual and mathematical framework to solve the remote sensing problem, although the constraint of the far-field approximation should be removed if it is to be applied to the transport of radiation in media composed of a limited number of relatively large scatterers. Indeed, in optically dense media such as soils and canopy layers, the occurrence of mutual shadowing between elements of the medium constitutes physical evidence that the scattering events in the medium are not independent from each other but depend on the shape, size, orientation, and relative position of the individual scatterers.

The transfer of radiation in the atmosphere is adequately represented by the classical theory, which applies to elementary volumes containing a large number of infinitely small scattering elements. In this case, the formulation of the physical problem is simplified since the extinction and scattering coefficients do not depend on the absolute directions of the radiation produced by external sources. From a mathematical point of view, this implies 1) that the differential scattering coefficient can be made a function only of the scattering or phase angle (the angle between the incoming and scattered radiation), and can be expressed with orthogonal functions (e.g., Legendre polynomials), and 2) that the radiation transport equation can be formulated without specifying these external sources of radiation a priori.

However, in the case of plant canopies, the size of the scatterers is much larger than the wavelength in the solar spectral domain. When the scatterers are located sufficiently close to each other, the scattered radiation field may not have reached its asymptotic limit before being scattered again. It is thus not clear that the transfer of radiation in such a discrete set of finite-size objects may be treated as if it was a continuous problem, especially when there are few but large absorbing or scattering elements. In principle, the description of the transport of photons in plant canopies would therefore re-

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quire detailed three-dimensional models describing explicitly the position, orientation, and optical properties of the leaves. This approach has been pursued with explicit Monte Carlo ray tracing or radiosity models (e.g., see Ross and Marshak 1988, 1991; Borel et al. 1991; Govaerts and Verstraete 1995; Govaerts et al. 1996), but these models are not operationally invertible against actual remote sensing data because there are too many model parameters and because of their large computing resources requirements.

In the absence of a general theory of radiation transfer applicable to both continuous and discrete media, it appears reasonable to extend the usefulness of the classical theory by deriving more sophisticated and general expressions for the two extinction coefficients σ and σ_s. These modified expressions should capitalize on the findings of the theory of photon transport in turbid media, but also incorporate the effect of the discrete nature of the medium on the radiation field. Although this approach does not yield a universally applicable solution, it has the advantage of resulting in a uniform and coherent formulation of the scattering problem in a number of common geophysical media, thus rendering the treatment of the remote sensing problem in actual applications more consistent.

Significant advances to address some of these issues have recently been achieved in the context of remote sensing of vegetated areas in the optical domain. Remarkable work initiated by Ross (1981) and then pursued by other teams [Shultis and Myneni (1988), Marshak (1989), Simmer and Gerstl (1985), Knyazikhin et al. (1992), Liang and Strahler (1993)] has stressed the complexity of radiation transfer in vegetation canopies. Ross initially introduced the concept of oriented point-like scatterers, which permits taking into account the particular orientation distribution of plant leaves. Later, Shultis and Myneni (1988) based their approach on the theory of photon transport under steady-state conditions and proposed a rather rigourous approach for developing advanced expressions for the extinction and the differential scattering coefficients, in addition to providing a numerical solution for solving the resulting transport equation. These works provide an excellent basis to discuss the specificities of the radiation transfer through a vegetation layer and how this problem differs from the atmospheric problem.

Other studies, based on a more heuristic approach (e.g., see Nilson and Kuusk 1989; Gerstl and Borel 1992) have shown the importance of the holes or voids between scatterers in a vegetation canopy, which lead to a specific angular signature in the radiance field known as the hot-spot effect. Verstraete et al. (1990) developed a full model for the single scattering of a horizontally homogeneous canopy made of leaves of finite size and proposed an analytical physically based expression to represent the hot-spot phenomenon. Typically, this effect arises from the relative arrangement of the individual scatterers, which allows some space free of scatterers through which the radiation can escape the canopy without any further extinction. In the context of the radiation transfer theory, the description of this effect implies that the extinction coefficients depend on a set of structural parameters of the canopy as well as the directions of incoming and outgoing radiation.

The further extension of this theory to correctly estimate the source term (multiple scattering inside the canopy) raises, however, considerable difficulties since this would imply keeping track of the previous directions followed by the incoming radiation on a particular scatterer. This problem does not seem tractable today (Myneni et al. 1991; Knyazikhin et al. 1992), unless simplifications are made (Myneni and Ganapol 1991). The underlying issue and principal stumbling block is the three-dimensional nature of the canopy, which cannot be adequately rendered by theories applicable to stacks of horizontally homogeneous turbid layers. Fortunately, the hot-spot effect is largely due to the single-scattering component of the scattered solar radiation field, which is both largely understood and which can be adequately described by the classical radiation transfer theory even as a one-dimensional problem. Indeed, the more radiation transfer depends on multiple scattering, the more the photons loose the memory of their initial direction, and the less the effect of the canopy structure on the anisotropy observed outside this layer is noticeable.

The objective of this paper is to discuss the problem of modeling light scattering within a vegetation canopy in the context of the many physical, mathematical, and technical constraints expressed above. The investigation is limited to horizontally homogeneous and plane-parallel media. The discussion is based on the physical principles outlined above, and the limits of the solution provided by an extension of the classical radiation transfer theory are examined. The paper provides an overview of the problem of light scattering in complex media composed of a discrete number of finite size scatterers and proposes a solution compatible with the treatment of radiation transfer in the atmosphere.

2. Statement of the radiation transport problem in plant canopies

As stated earlier, the context of applied remote sensing implies the use of inverse techniques, which imposes constraints on the representation of the transport problem in order to make it solvable as accurately as possible from the physical point of view and as fast as possible from a computational point of view. In practice, this implies that appropriate but reasonable assumptions must be made on the formulation of the extinction and differential scattering coefficients.

The first such simplification, implied by the use of a radiation transport equation, is that the canopy is assumed to be made up exclusively of leaves and that the radiative effects of trunks and branches or other bio-

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physical components can be neglected. The canopy medium is thus treated as a "cloud of leaves," where the leaves are idealized as plates of finite size, with inclinations given by a probability density distribution of leaf normals. Consequently, the efficiency with which radiation is intercepted by the medium is controlled both by the leaf normal distribution function and by the distribution of voids between these leaves in the canopy. Formally, this implies that the differential scattering coefficient depends on the absolute direction of photon travel in any and all possible interactions. Although this is numerically tractable (with the help of some approximations) for the first couple of interactions, the problem becomes unsolvable when the complete history of photon travels has to be accounted for since the precise location of leaves must then be known. This particular question has been investigated by Myneni et al. (1991), who introduced the concept of photon memory. Clearly, this memory effect, which depends on the structural properties of the canopy (i.e., the distributions of the size and orientation of the leaves and their position relative to each other), requires an explicit representation of the canopy, as well as a Monte Carlo ray tracing (or other such advanced) method to compute the solution. To simplify the problem, the differential scattering coefficient controlling the source term can be rewritten by changing the cumulative history of directions noted by Ω_*, with the particular direction of the impinging radiation Ω' determined only by the last scattering event. Physically, this modification implies that the source term is now treated using an oriented pointlike scattering approximation and σ_s represents the probability of scattering into the direction Ω for radiation coming from any direction Ω', which itself depends only on the scattering phase function of the "oriented points."

For standard applications in remote sensing, the sink term is much easier to represent since the direction of the principal source of illumination (generally the sun) is always precisely known. Consequently, if an average distribution of the shape of the empty spaces in the canopy is given, the extinction coefficient σ can be expressed as a function of the direction Ω_0 of the sun and the distribution of the leaf normals. Additionally, by limiting the structural effects to the top of the canopy, $\sigma(z, \Omega, \Omega_0^{1,2})$ simplifies to $\sigma(z, \Omega, \Omega_0)$. It is important to note that the representation of the vegetation canopy is not the same for the single, and the multiple scattering components, since the latter assumes a conventional turbid medium while the former takes into account the finite size of the scatterers with respect to the primary source of directional light.

The radiation transfer equation (under steady-state conditions and neglecting polarization) can therefore be expressed as follows along a direction z perpendicular to the layered medium (which for remote sensing problems of earth observation, is often naturally the local downward vertical):

$$-\mu\frac{\partial I(z, \Omega)}{\partial z} + \tilde{\sigma}(z, \Omega, \Omega_0)I(z, \Omega) = \int_{4\pi} \tilde{\sigma}_s(z, \Omega' \to \Omega)I(z, \Omega')\, d\Omega', \qquad (1)$$

where I represents the intensity (W m^{-2} sr^{-1}) at point z in the exiting direction Ω, and $\tilde{\sigma}$ (m^{-1}) and $\tilde{\sigma}_s$ (m^{-1} sr^{-1}) are the extinction and differential scattering coefficients, respectively, taken at the same point z and along the direction Ω. Clearly, the three terms of the equation above correspond to volumetric quantities and their mathematical dependencies with respect to the location z, and the direction Ω of the incoming external sources are conditioned by the physical properties of the medium under study (i.e., homogeneity, density, size, and orientation of the particles).

Since plant canopies grow leaves whose typical sizes are much larger than the wavelengths of the radiation, the transport problem should be expressed as a three-dimensional problem in order to describe explicitly the extinction and scattering coefficients. However, when considering a horizontally infinite homogeneous medium bounded by a spatially uniform and flat surface, the transport equation can be written and solved along a single vertical axis specified by the z coordinate. The bulk of the radiation transport in plant canopies relies on the ability of the medium to intercept radiation "before" either absorbing or scattering this energy; therefore, the density of the medium is a crucial variable, which, in the particular case of homogeneous plant canopies is expressed by the leaf area density, $\Lambda(z)$ (m^2 m^{-3}). Since this variable is common to both the extinction and scattering coefficients, it can be used to normalize Eq. (1) and to introduce a biophysical coordinate, L, namely, the leaf area index:

$$-\mu\frac{\partial I(L, \Omega)}{\partial L} + \sigma(L, \Omega, \Omega_0)I(L, \Omega) = \int_{4\pi} \sigma_s(L, \Omega' \to \Omega)I(L, \Omega')\, d\Omega', \qquad (2)$$

where

$$dL = \Lambda(z)\, dz \qquad (3)$$

and

$$\sigma(L, \Omega, \Omega_0) = \tilde{\sigma}(z, \Omega, \Omega_0)\Lambda^{-1}(z) \qquad (4)$$

$$\sigma_s(L, \Omega' \to \Omega) = \tilde{\sigma}_s(z, \Omega' \to \Omega)\Lambda^{-1}(z). \qquad (5)$$

The total leaf area index of a homogeneous vegetation canopy (LAI) is accordingly defined as the integral of the function describing the vertical distribution of the leaf area density, $\Lambda(z)$ (m^2 m^{-3}) between the upper boundary of the canopy medium ($L = 0$ at $z = 0$) and the lower boundary ($L = L_H$ at $z = H$), where H is the total height (in m) of the canopy medium:

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$$\mathrm{LAI} = \int_0^H \Lambda(z')\, dz'. \quad (6)$$

It must be noted here that the coordinate L provides a convenient way of expressing the radiation transport equation in a vegetation canopy, provided all the relevant functions can be expressed formally in this new scheme of reference. Since L does not carry any information about a spectrally dependent property similar to a mass absorption coefficient, the coordinate L cannot be straightforwardly assimilated to an optical depth coordinate of common use in atmospheric sciences.

Formally, Eq. (2) can be solved numerically if at least one external source of solar radiation and the values or expressions for the extinction and differential scattering coefficients are provided. Therefore, Eq. (2) can be solved for given boundary conditions for any layer of the canopy. However, in practical applications, it is usual to simplify the problem further by assuming a vertically homogeneous plant canopy over its full height, in which case the extinction and scattering coefficients, as well as the leaf area density, do not change along the L coordinate. With this additional assumption, the transport equation becomes applicable over the entire canopy, which is then considered as a single absorbing and scattering layer. Clearly, this assumption is not often verified in actual canopies, but the solution of the radiation transfer equation and, in particular, the treatment of the structural effects in vertically inhomogeneous canopies would be very complex.

In the context of remote sensing applications, these simplifications are practical since they allow an analytical description of the single-scattering contribution, which constitutes the bulk of the information at wavelengths where the plants use solar radiation for the photosynthesis. Simultaneously, the multiple-scattering contribution can be solved following classical methods like the discrete ordinates method (DOM) after a convenient separation of the uncollided, first collided, and multiply collided intensities, as suggested already by Marshak (1989), Iaquinta and Pinty (1994), and Iaquinta (1995). The radiation transport problem then reduces to the derivation of analytical expressions for the extinction and differential scattering coefficients, as well as to the definition of a set of boundary conditions at the top and bottom of the vegetation canopy.

3. Radiation transfer equation in a plant canopy of infinitely small dispersed particles

From the previous discussion, it follows that the use of a turbid medium concept for solving the radiation transfer problem in a plant canopy is, strictly speaking, questionable (see, e.g., Ross 1981). However, since the theory of radiation transfer in turbid media has been extensively used in the past for climate modeling studies (see, e.g., Dickinson 1983; Sellers 1985), as well as for satellite data interpretation (see, e.g., Myneni et al. 1995), we will discuss the radiation transfer first in that particular context. In the next section, we will show the modifications and adaptations to the turbid medium theory needed to address the specific issues raised by the discrete properties of a plant canopy when measured at optical wavelengths.

a. *Specification of the extinction coefficient for the sink term*

The interception of radiation by plant leaves crucially depends on the distribution of leaf normal orientations and their projection in the view direction Ω. Such a function was first introduced by Ross (1981) as the function $G(\Omega_x)$, which is expressed as

$$G(\Omega_x) = \frac{1}{2\pi}\int_{2\pi+} g_L(\Omega_L)|\Omega_L\cdot\Omega_x|\, d\Omega_L. \quad (7)$$

Physically, $G(\Omega_x)$ is the mean projection of a unit foliage area, in the direction Ω_x, per unit volume of canopy. In Eq. (7), $g_L(\Omega_L)$ is the probability density function for the leaf normal distribution (Ω_L), which satisfies

$$\frac{1}{2\pi}\int_{2\pi+} g_L(\Omega_L)\, d\Omega_L = 1, \quad (8)$$

where $2\pi+$ represents the upper hemisphere.

Clearly, calculation of the value of the $G(\Omega_x)$ function requires a model for the probability density function $g_L(\Omega_L)$, a function of the polar and azimuthal angles of the leaves. Since actual canopies offer a great deal of diversity and complexity with respect to these angles, it is generally desirable to simplify the representations and summarize them using typical probability density functions (see, e.g., Verstraete 1987). Explicit functions are provided to describe a uniform, planophile, or erectophile distribution, as well as more complex cases such as those involving paraheliotropism and diaheliotropism. For practical purposes, the assumption of a random leaf distribution in azimuth significantly reduces the mathematical complexity of the function $g_L(\Omega_L)$. The three major models to consider for the $g_L(\Omega_L)$ function are 1) the geometrical distribution from Bunnik (1978), 2) the elliptical distribution of Nilson and Kuusk (1989), and 3) the beta distribution from Goel and Strebel (1984). These models all aim at representing the same typical types of probability density functions from the simple but explicit behavior of the polar angle of leaves for various canopies. Bunnik's model results from an analysis of experimental data and gives a discrete representation of the $g_L(\Omega_L)$ function, while the elliptical and beta distributions, both requiring two parameters to be defined, allow a continuous representation of this function. Any one of these models for leaf normal distribution can then be used to compute the $G(\Omega_L)$ function. As shown by Ross (1981) and (Knyazikhin and Marshak 1991), the first function controlling the extinction coefficient to enter the radiation transport equation in L coordinate is given by

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$$\sigma(L, \Omega) = G(L, \Omega). \quad (9)$$

It must be noted here that Eq. (9) neglects the effects of diffraction and describes the extinction due to ''oriented'' points in the immediate neighborhood of the particle, hence not in conditions described by the far-field approximation. As a matter of fact, the extinction process described above corresponds to the treatment adopted for a standard turbid medium of low density.

b. Specification of the scattering coefficient for the source term

As pointed out in the introduction, only explicit three-dimensional models such as radiosity or Monte Carlo ray tracing models can fully account for the finite size of the leaves in a plant canopy. In the context of the discussion in section 2, the differential scattering coefficient $\sigma_s(L, \Omega, \Omega')$ then represents the probability for the radiation coming from an arbitrary direction Ω' to be scattered toward the particular direction Ω. Clearly, the radiative transfer problem is to describe the effects of flat oriented plates whose size tends to zero, and then to adopt a scattering model for both sides of the individual leaves. Therefore, the scattering coefficient should functionally depend on the probability density function for the leaf normal distribution $g_L(\Omega_L)$ in order to describe the interception of radiation and the scattering function of the elements in order to redistribute part of this radiation in the three-dimensional space. Technically, the scattering function for the elements can be approximated by a bi-Lambertian model as proposed by Ross and Nilson (1968) and Shultis and Myneni (1988). In this model, a fraction of the intercepted energy, r_l, is reradiated as a cosine distribution around the leaf normal, and the remaining part, noted t_l, is transmitted on the other side of the plate following the same cosine dependency. The ''plate point'' scattering model is expressed through a reflection and a transmission coefficient and

$$f(\Omega' \rightarrow \Omega, \Omega_L) = f(r_l(\Omega' \cdot \Omega_L, \Omega \cdot \Omega_L);\ t_l(\Omega' \cdot \Omega_L, \Omega \cdot \Omega_L)), \quad (10)$$

where the photon hits the lower (upper) surface of the leaf if $(\Omega' \cdot \Omega_L) > 0$ $((\Omega' \cdot \Omega_L) < 0)$, and the photon exits from the lower (upper) surface of the leaf when $(\Omega \cdot \Omega_L) > 0$ $((\Omega \cdot \Omega_L) < 0)$, respectively.

In the plant canopy problem, the functions r_l and t_l represent the leaf reflection and transmission functions, respectively, and the bi-Lambertian model simplifies these functions into two constant state variables noted r_l and t_l. These two parameters have to satisfy the energy conservation principle, which implies that

$$\omega_l = r_l + t_l \quad (11)$$

and

$$\int_{4\pi} \sigma_s(\Omega' \rightarrow \Omega)\, d\Omega = \omega_l G(\Omega'), \quad (12)$$

where ω_l corresponds to the albedo of the element l and, in the context of plant canopies, is identical to the single-scattering albedo of the differential volume of scattering used in a turbid medium theory. If this bi-Lambertian assumption cannot be made, the albedo of element l should be written as $\omega_l(\Omega', \Omega_L)$. According to our formalism and as already demonstrated in previous studies (Shultis and Myneni 1988; Myneni et al. 1989), $\sigma_s(L, \Omega' \rightarrow \Omega)$ is given by

$$\sigma_s(L, \Omega' \rightarrow \Omega) = \frac{1}{2\pi} \int_{2\pi+} g_L(L, \Omega_L) |\Omega' \cdot \Omega_L| f(L, \Omega' \rightarrow \Omega, \Omega_L)\, d\Omega_L. \quad (13)$$

Equation (13) illustrates the assumption made earlier for the treatment of the source term, namely, that the multiply scattered radiation is not affected by the presence of spaces free of scatterers in the plant canopy medium. Therefore, Eqs. (12) and (13) are strictly valid for anisotropic oriented pointlike scatterers. In practice, the typical values of the leaf reflectance and transmittance are very close to each other (see, e.g., Jacquemoud and Baret 1990), which supports the approximation of an isotropic scattering by the leaves for high (greater than 1) orders of scattering. Accordingly, the differential scattering coefficient in the source term is approximated by the following expression:

$$\sigma_s(L, \Omega' \rightarrow \Omega) = \frac{\omega_l(L)}{4\pi} G(L, \Omega'). \quad (14)$$

Iaquinta (1995) made extensive tests to examine the consequences of this isotropic assumption for a vertically homogeneous canopy. He found that the difference in emerging radiance at the top of the layer resulting from this assumption is negligible in the visible region and does not exceed 4% in the near-infrared region. However, when this assumption is used in the equation of radiation transfer with an assumption of no azimuthal dependency, the error may be as high as 5% in the visible and 50% in the near-infrared, for a planophile canopy. Therefore, the assumption of isotropy, which significantly simplifies the formulation of the differential scattering coefficient, must be used with caution in the context of remote sensing applications.

c. Specification of the boundary conditions

To derive a transport equation that does not depend explicitly on the source of radiation, it is convenient to specify all external sources of radiation as boundary conditions. In the plant canopy problem, multiple oriented sources of radiation are available at the top and the bottom of the canopy. Physically, the upper boundary ($z = 0$) receives direct solar radiation but also the angularly distributed radiation that results from the scattering by the atmosphere, and the lower boundary ($z =$

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z_H) receives the radiation emerging from the underlying soil. The precise specification of the external sources of radiation, as well as the definition of the scattered intensities, requires a three-dimensional coordinate system as described below.

The vertical axis z is directed downward (i.e., toward the lower boundary of the medium) and the direction of the photon's travel is specified by an azimuth angle ϕ with respect to an absolute direction (for instance the north) and a zenith angle θ with respect to the outward normal oriented in the opposite direction of the z axis. The radiation impinging on the upper boundary is then oriented downward and the direct solar radiation is similarly defined by an azimuth angle ϕ_0 and a zenith angle θ_0. With the above definitions, the cosines of the downward and upward radiation are, respectively, negative and positive.

The upper boundary of the canopy receives monodirectional radiation from the sun in the direction Ω_0, in addition to the radiation that has been scattered by the atmosphere of optical depth τ_a. The latter source will be considered as multidirectional but carries much less energy than the former under typical clear-sky situations, where remote sensing of terrestrial surfaces is used. Formally, such a standard external boundary condition at level $z = 0$ is expressed by

$$I(0, \Omega) = I_0\delta(\Omega - \Omega_0) \exp\left[-\frac{\tau_a}{|\mu_0|}\right] + I_d(\tau_a, \Omega) \quad (\mu < 0;\ \mu_0 < 0). \tag{15}$$

Equation (15) allows the description of the external sources of radiation for the general canopy problem. However, for most applications, the most standard boundary condition uses only a monodirectional source of radiation and the multidirectional source aspect is ignored. As a consequence, this simplification limits the coupling of the canopy problem with the atmosphere problem through the atmospheric optical depth only.

At the bottom of the canopy layer ($z = z_H$), a fraction of the impinging solar radiation is scattered back into the canopy according to the radiative properties of the underlying soil. This external source of radiation specifies the lower boundary condition in the canopy problem and can be expressed as follows:

$$I(z_H, \Omega) = \frac{1}{\pi}\int_{2\pi-} \gamma_s(z_H, \Omega, \Omega')I(z_H, \Omega')|\mu'|\, d\Omega' \quad (\mu > 0;\ \mu' < 0), \tag{16}$$

where $\gamma_s(z_H, \Omega, \Omega')$ is the bidirectional reflectance distribution function of the soil, which is in fact approximated by its bidirectional reflectance factor. In practice, for numerical reasons, when solving the radiation transport equation, it is quite appropriate to adopt a simpler boundary condition and assume that the underlying soil behaves as a Lambertian surface. In that case, Eq. (16) is modified to obtain

$$I(z_H, \Omega) = \frac{R_s(z_H)}{\pi}\int_{2\pi-} I(z_H, \Omega')|\mu'|\, d\Omega' \quad (\mu > 0;\ \mu' < 0), \tag{17}$$

where $R_s(z_H)$ is the soil's directional hemispherical reflectance (albedo).

Physically, the assumption of a Lambertian soil is appropriate under conditions where the source term is large and tends to be isotropic; clearly, such conditions are more easily reached with isotropic scattering conditions and for relatively optically deep canopies, which implies that the radiation has ''partly forgotten'' its largely monodirectional origin, as is generally the case for clear-sky conditions. Conversely, this assumption becomes questionable when the leaf area density and the leaf area index of the canopy are low and when the leaves behave as strong forward scatterers. A somewhat simpler condition prevails when the canopy can be considered as a semi-infinite absorbing and scattering layer. Indeed, for such conditions, the upward radiation $I(z, \Omega)$ is not controlled by the external source at the lower boundary $z = z_\infty$, which, therefore, can be specified by

$$I(z_\infty, \Omega') = 0 \qquad (\mu' < 0). \tag{18}$$

It must be emphasized here that the level $z = z_\infty$ can only be defined when the downward radiation $I(z, \Omega')$ is equal to zero for all points of the field. These conditions can sometimes be fullfilled in plant canopies at the visible wavelengths since the extinction process is generally very efficient and the ''point leaves'' do not exhibit a well-marked forward scattering property.

Clearly, depending on the problem to be solved, the above sets of upper and lower boundary conditions can be mixed. However, the simplest couple of conditions consists in considering a monodirectional source at the top of the canopy and a Lambertian soil surface at the bottom.

At this point, the radiation transfer problem in a plant canopy with negligible size is fully specified since 1) the desired integro–differential transport equation is established, 2) the extinction and differential scattering coefficients are both expressed, and 3) the upper and lower boundary conditions are given. The required properties for the plant canopy system per se are the leaf reflectance and transmittance, the probability density function for the leaf normal distribution, and the leaf area density. This particular radiation transfer problem can be seen as a ''standard problem'' for a plant canopy.

4. The radiation transfer equation in a plant canopy with closely packed particles of finite size

When sensing a vegetation canopy at optical wavelengths, the most striking observational evidence comes from the presence of shadows due to the leaves themselves. It is speculated that these effects may be partly accounted for by the specification of the extinction co-

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efficient, Eq. (9), which describes a global attenuation of the radiation due to the interception by the particles; this coefficient was derived in the context of a standard transport equation using the concept of a leaf area density for representing the density of particles, which are, implicitly, very numerous and infinitely small in order to satisfy the far-field approximation. However, the basic phenomenon of leaf intershadowing is not described explicitly, as can be seen from Eq. (9), which does not depend on the size distribution of the leaves itself.

Moreover, a second observational evidence is that the proportion of the shaded area is changing with the directions Ω_0 and Ω. In particular, little or no shadows are observable when looking at the medium from any direction Ω close to that from which it is illuminated (Ω_0). As far as the radiance field is concerned, it implies that a relative increase in the radiance values is observed for such conditions and that a local relative maximum is reached when the two directions are exactly coincident.

This increase in the radiance (or reflectance) values in the antisolar direction is commonly observed over closely packed porous media (e.g., soils, vegetation canopies) and is intimately linked to the structure of the medium through the sizes and shapes of the voids between the scattering particles. It is known as the ''hotspot'' effect by the terrestrial community and is analogous to the opposition or Heiligenschein effect discussed in planetology. Basically, the occurrence of voids in a discrete medium allows radiation to escape with a higher probability at angles close to the illumination angle. Furthermore, the shape of the voids free of scatterers is a crucial parameter to describe the angular domain in the three-dimensional space where the extinction of the radiation differs from the standard exponential attenuation law.

Describing the plant canopy as a set of finite-size plates statistically distributed in space, Nilson and Kuusk (1989) derived a ''hotspot factor'' that depends on the probability for a given point to be seen along the direction Ω when the canopy is illuminated from the direction Ω_0. They also found that the correlation function that represents this probability is a function itself of the size of the leaf and the height of the canopy. The physical mechanism generating the hotspot effect was studied in detail by Verstraete et al. (1990), who provided a precise geometric formulation to modify the classical expression for the total optical path along the direction Ω. Indeed, it was demonstrated that the joint transmission (i.e., a function of the total optical path for the photon stream) along the incoming and outgoing directions can be parameterized by idealizing the structure of the canopy, as shown in Fig. 1 of Verstraete et al. (1990), except that the coordinate z is increasing downward in the present paper.

The theory behind this figure expresses the fact that a leaf at level z_l can be illuminated from the external source of radiation only if its surface is not in the shade of a different leaf, located at a level above z_l, along the direction of illumination. Therefore, and with the assumption of circular sun flecks on the leaves, the geometry of illumination can be idealized by a tube or a volume of parallel radiation noted $\mathcal{V}_1$. Similarly, the geometry of observation is approximated by a second volume of exiting radiation $\mathcal{V}_2$. These two volumes share a common part noted $\mathcal{V}_\circ$ whose shape and size is totally controlled by the structure of the canopy (i.e., by the typical distance between the leaves in three-dimensional space). Denoting $\mathcal{V}_\bullet$ the complement of $\mathcal{V}_\circ$, that is, the fraction of $\mathcal{V}_2$ not in common with $\mathcal{V}_1$, Verstraete et al. (1990) have then shown that the actual optical path of the scattered radiation can be estimated by the following expression:

$$\tau_\Omega(z, \Omega_0, \Omega) = \frac{\|\mathcal{V}_\bullet\|}{\|\mathcal{V}_2\|} \int_z^0 \tilde{\sigma}(z'\Omega)\, dz', \qquad (19)$$

where $\|\mathcal{V}\|$ stands for the actual volume occupied by $\mathcal{V}$. Verstraete et al. (1990) introduced the nondimensional variable ζ_*, which takes values between 0 and 1 over the vertical interval in which the two cylindrical volumes intersect. After some mathematical developments, they demonstrated that the term correcting the optical path of the system was given by

$$1 - \frac{2}{\pi\zeta_T}\Bigg[\zeta_* \cos^{-1}\zeta_* - (1 - \zeta_*^2)^{1/2} + \frac{1}{3}\sin^3(\cos^{-1}\zeta_*) + \frac{2}{3}\Bigg], \qquad (20)$$

with $\zeta_* = \min(1, \zeta_T)$ and $\zeta_T = zG_f/2r$. In the special case where $\zeta_T > 1$, $\zeta_* = 1$, this equation reduces to

$$1 - \frac{4}{3\pi\zeta_T}. \qquad (21)$$

It can be seen that the correction term becomes negligible when ζ_T tends to large values, that is, when the two directions are far from each other ($G_f \to \infty$) or for deeper layers ($z \to \infty$).

In Eqs. (20) and (21), r denotes the radius of the circular illuminated area on the leaf and G_f is a geometric factor defined by

$$G_f = [\tan^2\theta_1 + \tan^2\theta_2 - 2\tan\theta_1 \tan\theta_2 \cos(\phi_1 - \phi_2)]^{1/2}. \qquad (22)$$

Now, with the assumptions that the leaf area density Λ and the function $G(\Omega_x)$ are constant along the coordinate z, the correction function for the extinction coefficient $\tilde{O}(z, \Omega_0, \Omega)$ is given by $\partial(\|\mathcal{V}_\bullet\|/\|\mathcal{V}_2\|)/\partial z$, which is equal to

$$\tilde{O}(z, \Omega_0, \Omega) = 1 - \frac{2}{\pi}\{\cos^{-1}\zeta_* - \zeta_*[1 - \zeta_*^2]^{1/2}\} \qquad (23)$$

with $\zeta_* = \min(1, \zeta_T)$ and is constant and equal to 1 when $\zeta_T > 1$, $\zeta_* = 1$.

This expression provides a physically sound mech-

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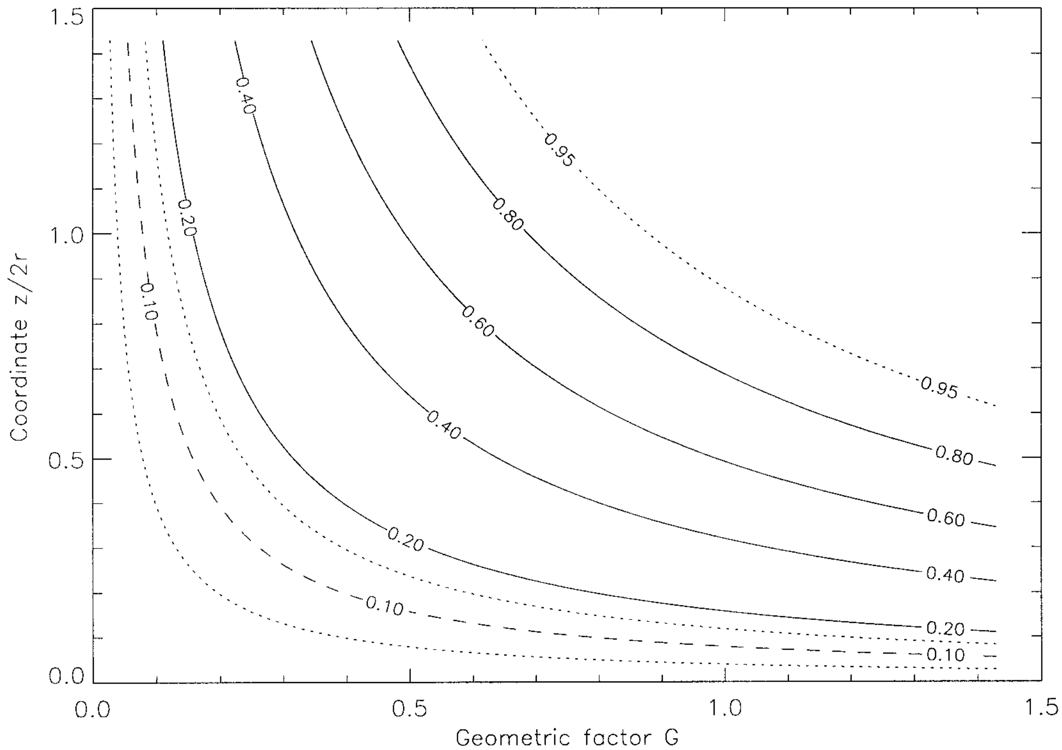

FIG. 1. Graph of the function $\tilde{O}(z, \Omega_0, \Omega)$, which is the ratio of $\tilde{\sigma}(z, \Omega_0, \Omega)$ by $\tilde{\sigma}(\Omega)$. The values of the isolines show that the departure from classical turbid conditions becomes more significant (low values of the function $\tilde{O}$) for observations close to hotspot conditions, or when canopies are composed of leaves either of large dimensions or closely packed along the vertical axis, or both.

anism to explain and quantify the hotspot effect as a function of the structure of the canopy. Obviously, the upper part of the vegetation canopy plays a major role in this phenomenon and, as any effect related to shadowing, the presence of direct illumination from the sun is required to obtain a significant effect. In fact, all pencils of radiation are able to generate a hotspot and, in actual situations where the top of the canopy is illuminated by the diffuse sky radiation [see Eq. (15)], an infinite number of hotspots are produced that, therefore, cannot be detected. Although the hotspot effect may not carry a large amount of energy, it still significantly conditions the radiance field measured on top of the canopy, which constitutes the bulk of the information useable for any remote sensing instrument operating at optical wavelengths. It is therefore essential to describe this effect in modeling the radiation transport in plant canopies in order to avoid systematic biases when performing the inversion step. Since the hotspot phenomenon is a purely geometrical effect, it occurs for any source of illumination inside or outside the canopy. Indeed, we may expect to have a similar feature occuring at the lower boundary of the canopy, provided the soil exhibits a strong bidirectional component. Inside the canopy itself, this phenomenon is quickly attenuated by the extinction and scattering properties of the leaves, which may either absorb most of the radiation after one interception event (in the visible wavelengths) or scatter quasi-isotropically the incoming radiation (at near-infrared wavelengths).

Modification of the extinction coefficient

In accordance with the arguments developed in the previous section, it seems reasonable to restrict the adaptation of the classical radiation theory to a modification of the extinction coefficient itself. We hypothesize that this coefficient may be rewritten as

$$\tilde{\sigma}(z, \Omega, \Omega_0) = \Lambda G(\Omega)\tilde{O}(z, \Omega_0, \Omega) \tag{24}$$

$$= \tilde{\sigma}(\Omega)\tilde{O}(z, \Omega_0, \Omega). \tag{25}$$

An analogous formal equation was proposed by Marshak (1989), and by Iaquinta and Pinty (1994), using the coordinate L instead of z as used above. However, since we noticed that the hot spot phenomenon is a purely geometrical effect, it is not really appropriate to work with the coordinate L. For instance, the nondimensional variable ζ_*, which controls the shape of the hot spot, is hardly defined using the L coordinate alone, which, strictly speaking, is an axis oriented positively downward and cannot take physical values above the canopy except 0 (negative values would be meaningless). However, Iaquinta and Pinty (1994) proposed a

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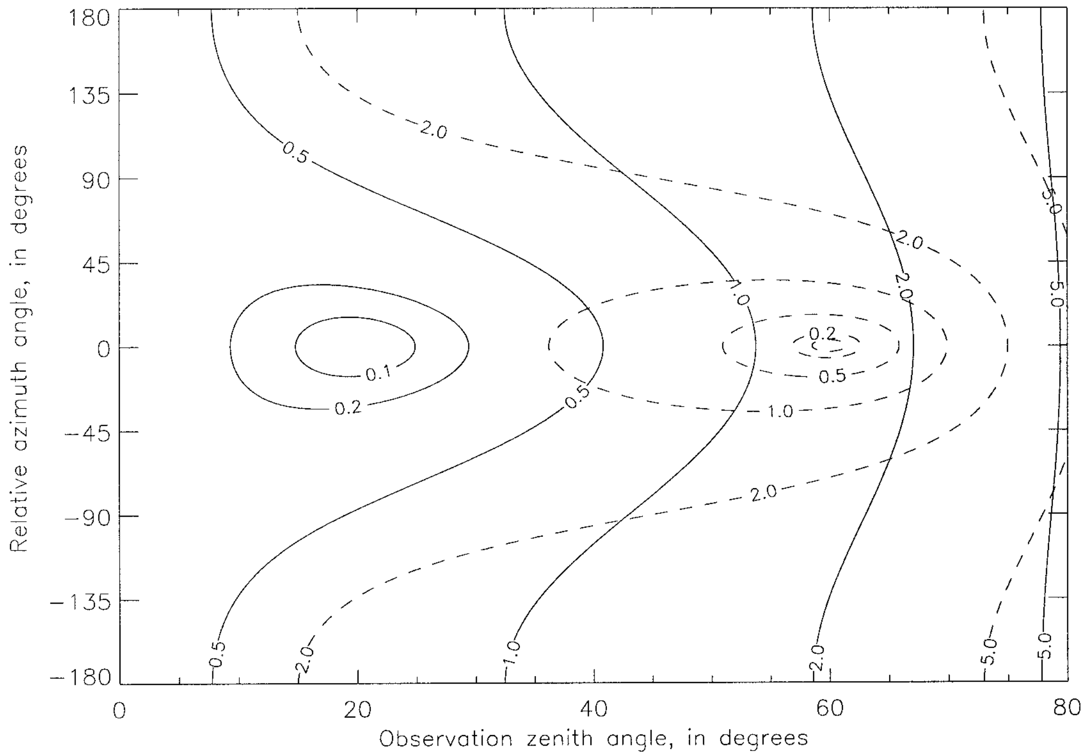

FIG. 2. Illustration of the variability of the geometric factor G_f for two particular solar zenith angles (20° and 60°), as a function of the viewing zenith and relative azimuth angles. It can be seen that this factor tends to 0 when the observation geometry approaches the hotspot conditions.

slight adaptation in order to avoid this issue and to allow the proper use of the hot spot model from Verstraete et al. (1990) with the coordinate *L*.

Equation (25) brings a fundamental modification to the radiation transport problem since it introduces a coupling between the extinction coefficient and the external sources of radiation. Although we greatly simplified the problem from the beginning by restricting the hot spot phenomenon to occur only at the upper boundary layer, as explained in section 2, and by neglecting its contribution to the multiple scattering process, the physical mechanism generating the hotspot phenomenon can be described only by expressing the dependency of the extinction coefficient on the angular position of the source of illumination (within the limitations of this radiation transfer approach). The deviation of this new radiation transport problem with respect to the standard one is illustrated in Fig. (1), which shows the ratio of the two extinction coefficients, namely $\tilde{\sigma}(z, \Omega_0, \Omega)$ over $\tilde{\sigma}(\Omega)$ for various values of the geometric factor G_f and of the canopy factor $z/2r$. This figure shows how the structure of the canopy and the geometry of illumination and observation control the correction function $\tilde{O}(z, \Omega_0, \Omega)$ for the extinction coefficient. This function approaches 0 near the hotspot conditions when either G_f (depending on the viewing conditions with respect to the given illumination) or $z/2r$ (near the top of the canopy, or when the sun fleck radius becomes large) tends to 0. It also saturates at 1 when the volume in common $\mathcal{V}_\circ$ is entirely contained within the canopy layer—that is, when the scattered light at the level of the sun fleck cannot escape from the lower layers without statistically interacting with the canopy medium. This happens when the medium is composed of small scatterers, or when it is observed at angles very different from the illumination position, or both. Figure 2 illustrates the variation of the geometric factor G_f as a function of the viewing zenith and relative azimuth angles, for two values of the solar zenith angle, namely, 20° and 60°. The minimum of this factor occurs when the viewing direction is close to that of illumination (backscattering conditions). The comparative evaluation of these two figures shows that there is a large range of angular conditions for which the correction factor is significantly different from 1. It also follows that the range of viewing conditions strongly affected by the hotspot is larger when the solar zenith angle is close to the local zenith.

This figure illustrates the importance of the canopy structure in the radiation transport problem as, for instance, the ratio of the two extinction coefficients is often lower than 1 and even reaches the value 0 when the direction of observation Ω is exactly the same as the direction of the main source of illumination Ω_0. It can also be seen that, depending on the canopy structure, the hot spot effect is not restricted to a small solid angle located around the direction Ω_0 but may affect the total

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radiance field for conditions where ζ_* is small (e.g., relatively large values of *r*).

Back to the radiation transfer equation, the boundary conditions discussed in section 3c are fully applicable here, but, from a physical point of view, we should note that the assumption of a Lambertian soil is consistent with the approximation made above with respect to the extinction coefficient (i.e., it does not depend on the direction Ω_0^z). Indeed, since the bulk of the hotspot effect is due to monodirectional radiation, the presence of a totally isotropic source significantly smooths out this specific effect.

A ''nonstandard'' canopy problem is now defined as the result of a compromise between the theoretical difficulties and the need to describe as well as possible the radiance field emerging from a vegetation canopy. By comparison with the ''standard'' canopy problem, Eq. (23) requires the specification of the hotspot parameter *r*. This issue was discussed at length in Verstraete et al's (1990) paper and a simplified equation has been proposed [Eq. (55) in the cited reference]. Note that the nature of the extinction coefficient has now changed and that it is not a measurable quantity anymore since it depends not only on the intrinsic properties of the scattering elements, but also on their geometrical arrangement.

5. Extraction of information from remote sensing data on terrestrial surfaces

Some applications do not require the complete solution of the radiation transfer problem exposed above. Indeed, when the goal is to describe the nature of the terrestrial surfaces through a simple classification of broad land-cover types, focusing on the general spatial, temporal, spectral, or directional signatures may be sufficient. This approach naturally leads to the development and use of spatial variability measures, time series techniques, spectral indices, etc. Clearly, these approaches also imply various hypotheses on the nature and value of the other state variables of the geophysical media that influence the measurements. For instance, the interpretation of spectral indices implies various assumptions or a priori knowledge on the state variables of the soil–plant canopy–atmosphere system. In other words, an analysis of the measured boundary condition without trying to understand the fundamental physical processes that must have resulted in these observations relies on many hypotheses about their nature and importance.

However, when the objective is to characterize the intrinsic properties of these surfaces, a radiation transfer model must be inverted against the measurements so that the state variables of the problem can be optimally estimated. It is important to remember, however, that the interpretation of remote sensing data always relies on the analysis of upward radiances, which represent only one of the four boundary conditions of the radiation transfer problem, the other three being the incident solar flux at the top of the atmosphere and the angular distributions of radiances up and down at any arbitrary level within the observed system. The latter may, but does not have to, correspond to the boundary between two particular geophysical media.

In practice, the solution of this inverse problem always relies on the minimization of the difference between the simulated radiances and the measurements, which constitute the only observed boundary condition. The solution of this minimization problem can be achieved with nonlinear numerical methods, or searched among predefined solutions implemented in the form of look-up tables. In this latter case, the method may yield one or more acceptable solutions within the space of possible solutions allowed by the look-up tables. In the case of a nonlinear inversion procedure, a much larger set of solutions is explored, at a much higher computing cost, particularly when there are many variables to retrieve or when advanced techniques must be used to avoid local minima. In both of these cases, it is necessary to solve the radiation transfer equation.

Technically, Eqs. (1) and (2) can be solved for any set of boundary conditions using a numerical method allowing for the discretization of the angular space (mainly to compute the integral part in the source term) and the vertical coordinate (to solve the differential part of the governing equation). Obviously, the use of a numerical method implies that numerical errors are accumulated, especially in the case of thick canopies and/or under conditions where the differential scattering coefficient exhibits rather complicated three-dimensional shapes. When the latter conditions occur, a large number of discrete directions have to be used, leading to a significant cost in terms of computer time. Because of the hotspot phenomenon, the plant canopy problem requires that the zero- and first-order scattering be separated from higher orders to limit the number of discrete ordinates for which the computation must be made.

Furthermore, since the zero and first orders play a significant role in the optical domain, it is quite appropriate to search for analytical solutions. Marshak (1989), and more recently Iaquinta (1995), gave examples of the mathematical developments needed to achieve this step. Accordingly, the transport equation may be solved by separating the uncollided $I^0(z, \Omega)$ and the single-scattered $I^1(z, \Omega)$ intensities from the intensities $I^M(z, \Omega)$ that have been scattered twice or more in the canopy. The total intensities $I(z, \Omega)$ are then written as

$$I(z, \Omega) = I^0(z, \Omega) + I^1(z, \Omega) + I^M(z, \Omega), \qquad (26)$$

where the first two terms can be expressed analytically while the third one requires a numerical solution. The discrete ordinates method of Shultis and Myneni (1988) constitutes a good solution to this problem. Other studies, conducted in the field of planetology, suggest an adaptation of a classical adding/doubling algorithm (Peltoniemi 1993). Technically, when performing the integration over the two angular coordinates defining

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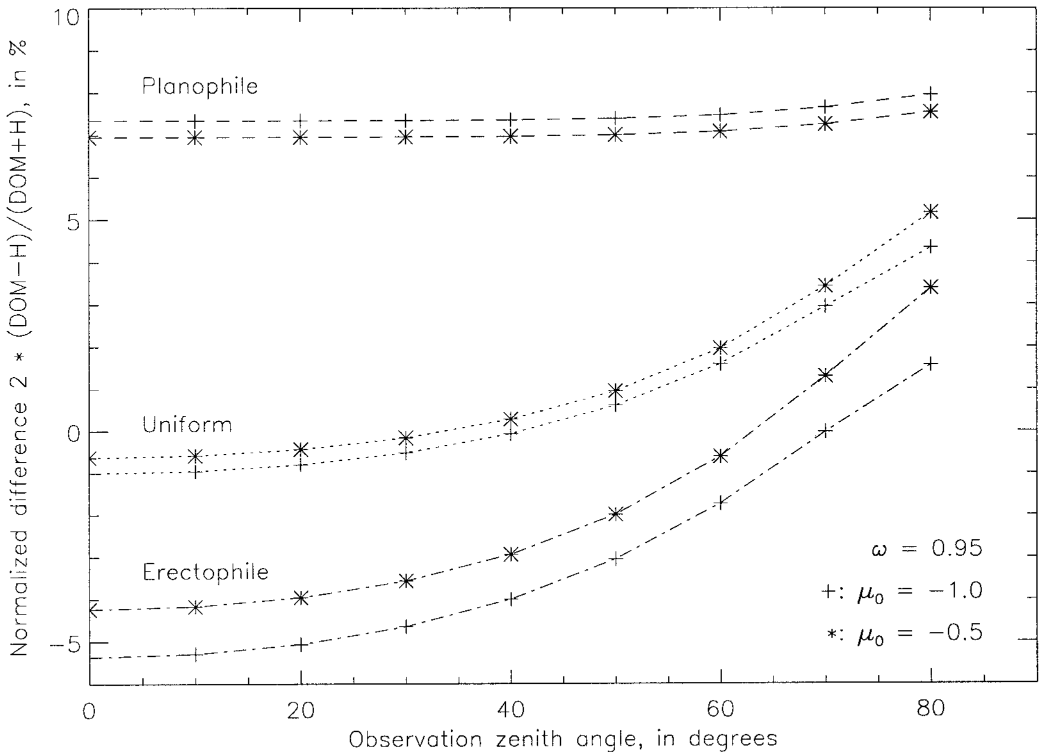

FIG. 3. Comparison between the solution to the multiple scattering provided by Eq. (27) and the solution provided by the discrete ordinates method, for three types of leaf orientations and two solar zenith angles.

the direction Ω, namely, θ and ϕ, the unit sphere has to be divided into a few angular sectors that determine the directions of quadrature. Clearly, the integration over the azimuthal coordinate ϕ significantly increases the number of computations to be made. At the same time, owing to the shape of the differential scattering coefficients that can be expected for a leaf canopy, the variations of the bidirectional reflectance fields along this azimuthal coordinate are generally much less pronounced than those occurring along the zenithal coordinate θ. Accordingly, it seems appropriate to investigate the potential simplifications on the source term of the transport equation that could arise from assumptions on the scattering phase function. Such an attempt has been proposed and tested by Iaquinta and Pinty (1994) and Liang and Strahler (1995), who used a two-stream approximation for representing the radiance field due to second and higher orders of scattering.

In the particular case of a semi-infinite canopy, Dickinson et al. (1990) have adapted an approximation of Chandrasekhar's $\mathcal{H}$ functions (Hapke 1981) for a semi-infinite medium of isotropic oriented scatterers. The modified $\mathcal{H}$ function is given by a simple expression:

$$\mathcal{H}(z = 0, \mu) = \frac{1 + x}{1 + (1 - \omega_l)^{1/2}x}, \qquad (27)$$

where $x = \mu/G(\mu)$. Figure 3 shows a comparison between the solutions obtained using the modified $\mathcal{H}$ functions against the full solution of the radiation transport equation for isotropic scatterers. It can be seen that, in the worst case corresponding to high ω_l values (as is the case for typical healthy leaves in the near-infrared domain), the two solutions agree to better than 5% for the three major leaf angle distribution functions and over a major part of the angular domain of interest for remote sensing applications. Obviously, the differences between the numerical and analytical solutions are much lower, of the order of 0.5%, for smaller ω_l values corresponding to observations made in the visible domain. Although these functions provide very attractive solutions (computationally very fast) for the inverse problem, they can be applied only where and when it is known a priori that the medium behaves as a semi-infinite medium for the frequency domain of measurements.

6. Discussion

This paper reviewed the various theoretical difficulties and practical solutions that can be envisaged to solve the radiation transfer problem in the context of remote sensing at solar wavelengths. Although the use of a photon transport equation appears justified in many respects, this approach also shows intrinsic limitations as a vegetation canopy hardly fullfills the required con-

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ditions for using the standard radiation transfer theory. However, it was seen that the extinction and differential scattering coefficients can be adapted to extend the domain of applicability of the classical theory. These changes were made as simple as possible, in keeping with the remote sensing context in which such models are to be repetitively inverted against data.

The suggested modifications to the extinction and differential scattering coefficients lead to a very complicated issue since these coefficients are then depending on the location of the sources of illumination. Even in the simplest approach, the extinction coefficient still depends on the direction of the main source of illumination, namely the sun. As a consequence and for practical reasons, the radiation transfer equation must be solved after splitting the intensities into a minimum of three terms, the radiation that has not collided with the leaves, the radiation that has collided once, and the remaining part, which has interacted more than once with the canopy.

The proposed solution is based on a theory that assumes a continuous medium to describe the changes in radiation intensity in this medium. That is, the derivatives of the field of radiation intensity with respect to the vertical axis is always defined. However, in actual situations, such an assumption can be very questionable, especially when the vegetation canopy is constituted of a limited number of large leaves. Indeed, there exists an infinity of combinations of numbers and sizes of leaves that yield the same leaf area density. The nature of this problem was discussed by Verstraete (1987), who demonstrated that the attenuation of direct radiation could be represented by a classical Beer law only when the number of leaves is high enough. As a matter of fact, the next important step to model the radiation transfer in plant canopies should certainly be to investigate practical solutions to this specific canopy problem. Technically, this does not seem unfeasible since a separation of the zero and first orders of scattering is required anyway for the correct modeling of the hotspot phenomenon. Initial work in this direction has already been performed (Gobron et al. 1997).

Although remote sensing applications are our main concern and imply specific constraints on how the problem is approached and solved, it is worth resetting the issue of modeling plant canopies in the broader context of earth system simulation. Specifically, the vegetation layer can be seen as one of the main components of the general geophysical system, which also includes atmospheric and cloud layers along the vertical axis. It is clear that the vertical coupling between these media is quite strong, as can be easily deduced from an inspection of the boundary conditions. In fact, we could write the same radiation transfer equation and modify the extinction and scattering coefficients along the vertical axis. The remaining difficulties would be the numerical issue of the angular discretization for representing the scattered field of intensities. Indeed, the properties of scatterers in each of the media does exhibit quite specific features and, in particular, very specific values for the single-scattering albedos and more or less complicated shapes for the phase functions.

The vegetation problem brings significant levels of complexity because 1) it behaves as a medium made up of closely packed finite size particles and 2) the two boundary conditions are generally unknown a priori. By comparison, the complexity of the atmospheric problem is due to the very high values of the single scattering albedo and the rather erratic shapes of the phase functions of aerosols, water droplets, and ice crystals (as opposed to the case of a vegetation canopy), which require a very accurate treatment of the source term. From this point of view, it is clear that the particular case of a cirrus cloud made up of three-dimensional ice crystals is especially tricky because this medium is generally optically thin and since the lower boundary condition must be accurately specified.

Despite its intrinsic complexity, significant progress has been achieved in the modeling of radiation transfer in plant canopies over the last decade, thanks to the groundbreaking contributions of a few pioneers. These achievements are now well established and should help improve communications between the various disciplines in geosciences interested in radiatively coupled media.

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REFERENCES

Borel, C. C., S. A. W. Gerstl, and B. J. Powers, 1991: The radiosity method in optical remote sensing of structured 3D surfaces. *Remote Sens. Environ.*, **36,** 13–44.

Bunnik, N. J. J., 1978: The multispectral reflectance of shortwave radiation of agricultural crops in relation with their morphological and optical properties. Tech. Rep., Mededelingen Landbouwhogeschool, Wageningen, the Netherlands.

Dickinson, R. E., 1983: Land surface processes and climate—surface albedos and energy balance. *Advances in Geophysics,* Vol. 25, Academic Press, 305–353.

——, B. Pinty, and M. M. Verstraete, 1990: Relating surface albedos in GCM to remotely sensed data. *Agric. For. Meteor.,* **52,** 109–131.

Gerstl, S. A. W., and C. C. Borel, 1992: Principles of radiosity method versus radiative transfer for canopy reflectance modeling. *IEEE Trans. Geosci. Remote Sens.,* **30,** 271–275.

Gobron, N., B. Pinty, M. M. Verstraete, and Y. Govaerts, 1997: A semidiscrete model for the scattering of light by vegetation. *J. Geophys. Res.,* **102,** 9431–9446.

Goel, N. S., and D. E. Strebel, 1984: Simple beta distribution rep-

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resentation of leaf orientation in vegetation canopies. *Agron. J.*, **76,** 800–803.

Govaerts, Y., and M. M. Verstraete, 1995: Evaluation of the capability of BRDF models to retrieve structural information on the observed target as described by a three-dimensional ray tracing code. *Proc. European Symp. on Satellite Remote Sensing, EUROPTO-SPIE Conf.*, Vol. 2314, Rome, Italy, IEEE, 9–20.

——, S. Jaquemoud, M. M. Verstraete, and S. Ustin, 1996: Three-dimensional radiation transfer modeling in a dicotyledon leaf. *Appl. Op.,* **35,** 6585–6598.

Hapke, B., 1981: Bidirectional reflectance spectroscopy. Part I: Theory. *J. Geophys. Res.,* **86,** 3039–3054.

Iaquinta, J., 1995: Champ de rayonnement émergeant des surfaces terrestres: modélisation et inversion dans le cas de milieux optiquement finis et couplés avec une couche atmosphérique. Ph.D. thesis, Université Blaise Pascal. 24 Av. des Landais, F-63177, Aubière, Cedex, France.

——, and B. Pinty, 1994: Adaptation of a bidirectional reflectance model including the hot-spot to an optically thin canopy. *Proc. Sixth ISPRS Int. Symp. on Physical Measurements and Signatures in Remote Sensing*, Val d'Isère, France, CNES, 683–690.

Jacquemoud, S., and F. Baret, 1990: PROSPECT: A model of leaf optical properties spectra. *Remote Sens. Environ.*, **34,** 75–91.

Knyazikhin, Y. V., and A. L. Marshak, 1991: Fundamental equations of radiative transfer in leaf canopies, and iterative methods for their solution. *Photon–Vegetation Interactions,* R. Myneni and J. Ross, Eds., Springer-Verlag, 9–43.

——, ——, and R. B. Myneni, 1992: Interaction of photons in a canopy of finite-dimensional leaves. *Remote Sens. Environ.,* **39,** 61–74.

Liang, S., and A. H. Strahler, 1993: Calculation of the angular radiance distribution for a coupled atmosphere and canopy. *IEEE Trans. Geosci. Remote Sens.,* **31,** 491–502.

——, and ——, 1995: An analytic radiative transfer model for a coupled atmosphere and leaf canopy. *J. Geophys. Res.,* **100,** 5085–5094.

Marshak, A. L., 1989: The effect of the hot spot on the transport equation in plant canopies. *J. Quant. Spectrosc. Radiat. Transfer,* **42,** 615–630.

Myneni, R., and B. Ganapol, 1991: A simplified formulation of photon transport in leaf canopy with scatterers of finite dimensions. *J. Quant. Spectrosc. Radiat. Transfer,* **46,** 135–140.

——, J. Ross, and G. Asrar, 1989: A review on the theory of photon transport in leaf canopies. *J. Agric. Forest Meteor.,* **45,** 1–153.

——, A. L. Marshak, and Y. Knyazikhin, 1991: Transport theory for a leaf canopy of finite-dimensional scattering centers. *J. Quant. Spectrosc. Radiat. Transfer,* **46,** 259–280.

Myneni, R. B., S. Maggion, J. Iaquinta, J. L. Privette, N. Gobron, B. Pinty, D. S. Kimes, M. M. Verstraete, and D. L. Williams, 1995: Optical remote sensing of vegetation: Modeling, caveats, and algorithms. *Remote Sens. Environ.,* **51,** 169–188.

Nilson, T., and A. Kuusk, 1989: A reflectance model for the homogeneous plant canopy and its inversion. *Remote Sens. Environ.*, **27,** 157–167.

Peltoniemi, J., 1993: Radiative transfer in stochastically inhomogeneous media. *J. Quant. Spectrosc. Radiat. Transfer,* **50,** 655–671.

Pinty, B., and M. M. Verstraete, 1992: On the design and validation of bidirectional reflectance and albedo models. *Remote Sens. Environ.,* **41,** 155–167.

Ross, J., 1981: *The Radiation Regime and Architecture of Plant Stands.* W. Junk, 342 pp.

——, and T. Nilson, 1968: A mathematical model of radiation regime of plant cover (in Russian). *Actinometry and Atmospheric Optics,* R. Myneni and J. Ross, Eds., Valgus, 263–281.

——, and A. L. Marshak, 1988: Calculation of the canopy bidirectional reflectance using the Monte-Carlo method. *Remote Sens. Environ.,* **24,** 213–225.

——, and ——, 1991: Monte Carlo methods. *Photon–Vegetation Interactions* R. Myneni and J. Ross, Eds., Springer-Verlag, 441–467.

Sellers, P. J., 1985: Canopy reflectance, photosynthesis and transpiration. *Int. J. Remote Sens.,* **6,** 1335–1372.

Shultis, J. K., and R. B. Myneni, 1988: Radiative transfer in vegetation canopies with anisotropic scattering. *J. Quant. Spectrosc. Radiat. Transfer,* **39,** 115–129.

Simmer, C., and S. A. Gerstl, 1985: Remote sensing of angular characteristics of canopy reflectances. *IEEE Trans. Geosci. Remote Sens.,* **23,** 648–658,

Verstraete, M. M., 1987: Radiation transfer in plant canopies: Transmission of direct solar radiation and the role of leaf orientation. *J. Geophys. Res.,* **92,** 10 985–10 995.

——, B. Pinty, and R. E. Dickinson, 1990: A physical model of the bidirectional reflectance of vegetation canopies. Part 1: Theory. *J. Geophys. Res.,* **95,** 11 765–11 775.

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