# VEGETATION CANOPY REFLECTANCE MODELING—
# RECENT DEVELOPMENTS AND REMOTE SENSING PERSPECTIVES

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**ABSTRACT:**

The modeling of the directional reflectance of vegetation canopies and vegetation-covered surfaces has been a highly active field in remote sensing within the past decade. Recent developments have refined physical models of directional reflectance; added coupled atmospheric models; included invertible models; and produced new, semiempirical models. Although models are well-formulated, more validation datasets are needed. For the EOS era, invertible models that provide useful information for global change studies are most desirable.

**KEY WORDS:** BRDF Models, Vegetation Reflectance, Global Change, Earth Observing System

## 1 - INTRODUCTION

### 1.1. Anisotropic Reflectance

The earth's surface scatters radiation anisotropically, especially at the shorter wavelengths that characterize solar irradiance. Surface scattering is described by the bidirectional reflectance distribution function (BRDF) (Nicodemus, 1977), which specifies the behavior of surface scattering at a particular wavelength as a function of illumination and viewing positions within the hemisphere. The scattering behavior of a surface also determines its spectral albedo—the ratio of radiant energy flux within a particular waveband that is scattered upward and away from the surface in all directions to the downwelling irradiance in that waveband incident upon the surface. If the BRDF is known, the albedo can be derived given knowledge of the angular distribution of incoming irradiance.

The anisotropic reflectance of the earth's surface provides an opportunity to infer information about the physical parameters of the surface cover that produce the anisotropic effect. In the case of vegetation-covered surfaces, this anisotropy derives largely from such factors as the scattering behavior of leaf surfaces; the distribution of leaf surface orientations; the size and spacing of leaves; the clumping of leaf area into individual plant crowns; the size and shape of plant crowns; the arrangement of plant crowns on the surface; and the anisotropic reflectance of the underlying layer of soil or ground cover.

Physical models of the scattering behavior of vegetated surfaces that include such factors can, under proper circumstances, be inverted from measurements of surface radiance to infer parameters that are of value in studies of global change and global ecosystem dynamics. Such parameters include the amount of leaf scattering material (leaf area index), which is useful in global ecological monitoring of ecosystem primary productivity and also governs the transfer of latent heat through transpiration in surface energy balance studies; hemispherical albedo, which describes the amount of radiation reflected (and therefore absorbed) by the soil/vegetation layer and is useful in surface energy balance studies and global climate modeling; and plant size and spacing, which condition surface roughness length and therefore turbulent energy flux and mass transfer as specified within global climate models.

Inference of these types of physical parameters requires inversion of a physical model of canopy reflectance, which in turn requires a suite of reflectance measurements of the vegetated surface obtained from different viewing positions. Since the acquisition of such measurements over large areas is possible by remote sensing with airborne or spaceborne instruments, this possibility has inspired the development during the past decade of the field of plant canopy directional reflectance modeling.

Note also that the anisotropic reflectance of earth surfaces presents a problem for inference from remotely-sensed images. Reflectance anisotropy means that radiance measurements of the same surface cover will vary with viewing position, which can lead to incorrect scene inference, especially in the case of multidate satellite imagery in which views are acquired under different geometries. Remote determination of the surface BRDF allows correction for these view angle effects through such methods as normalizing individual measurements to a standard viewing position, or integrating the BRDF to yield a hemispherical spectral albedo that is not dependent on viewing direction.

## 1.2. Overview of Canopy Reflectance Models

The anisotropy of reflectance from vegetated surfaces and its remote sensing has led to the development of a rich array of mathematical models that describe the surface BRDF. These models can be characterized as following one of two general approaches—physical or empirical. In the empirical approach, a function is fitted that describes the shape of the BRDF based on the observations at hand. That is, the BRDF is modeled as an empirical function of viewing and illumination angles and azimuths in the hemisphere (e. g., Walthall et al., 1985, for soil; Barnsley, 1993, for vegetation). For accurate fitting of a complete BRDF, however, this approach requires many observations at many combinations of viewing and illumination positions. Although simple and direct, empirical models are not very practical for satellite remote-sensing applications, because the number of angular observations of a surface typically acquired will be small. Further, the coefficients that fit empirical models cannot be readily interpreted in terms of scene or surface properties. Instead, relationships between surface properties and empirical functions must be obtained by further empirical techniques, such as correlation analyses.

In the physical approach, a physical scattering model is constructed that explains anisotropic surface scattering using physical principles (e. g., Hapke, 1981, 1984, 1986, Hapke and Wells, 1981, for soil; Suits, 1972, for vegetation). By inversion, reflectance observations are used to infer the physical parameters that drive the model (e. g., Goel, 1988). Once these are known, the BRDF of the surface may be determined for any view or illumination position without calibration by further measurements. Moreover, the parameters typically have physical interpretations in their own right that are of intrinsic interest beyond simply generating the BRDF.

Additional advantages accrue to the physical approach. To describe the complete BRDF, fewer parameters are typically required. Further, because the physical meaning of the parameters is understood, it is often possible to make reasonable *a priori* choices for their values. In addition, a carefully-drawn physical model may be simplified by successive approximations and assumptions. And, considering that some parameters are independent of waveband, fewer total parameters will be required for multiband BRDF inference using a single physical model than for a suite of multiband empirical models that must be independently calibrated for each band. Thus, the physical approach to bidirectional reflectance modeling is probably the most suitable for remote sensing applications.

A variation on these two approaches, which we may term "semiempirical," combines physical and empirical models (e. g., Roujean, 1992; Deuzé et al., 1993; Rahman et al., 1993a, 1993b). Here, the BRDF is modeled as a weighted sum of a few empirical functions that describe the shape of the BRDF. However, these functions are typically derived from physical approximations, and so have some physical meaning. The weight to be given to each function is determined empirically by fit to the observations. Thus, it is the weights of the physically-based functions that are retrieved, not a set of physical parameters governing the surface scattering.

Another type of physical model uses computation in lieu of a formally-parameterized mathematical description. Usually this type of model is applied to a scattering layer composed of numerous volume scattering elements—for example, a leaf canopy. An example is a ray tracing model (Kimes and Kirchner, 1982,; Goel et al., 1991; Lewis and Muller, 1992), in which a Monte Carlo model of scattering events is used to characterize the BRDF of a specific scattering layer or surface. Another example is the radiosity model (Borel et al., 1991), in which a sparse matrix of mutual view factors between Lambertian scattering elements within the volume layer is computed and used to find the BRDF.

## 1.3. Features of Physical Surface Scattering Models

The angular behavior of land surface reflectance is a function of at least three physical phenomena: coherence, volume scattering among scattering elements, and surface scattering effects of self-shadowing and specular reflectance according to the three-dimensional arrangement of scattering elements. For any particular surface cover, the magnitude of these effects will depend on the positions of both the sensor and source of irradiance in the hemisphere.

Coherence effects can provide a strong backscatter peak (hotspot) to the surface reflectance function, and occur when the mean free path length of multiple scattering within the medium is near the wavelength of the irradiance. Coherent backscatter is important for lunar soils and seems to explain the opposition effect observed for many planetary bodies (Hapke et al., 1993); however, since the mean free path length within a leaf canopy is very large when compared to optical wavelengths, current vegetation BRDF models ignore coherent backscatter. Volume scattering is quite important for porous media such as vegetation layers or snow, and can be described accurately by radiative transfer theory. Surface effects largely involve shadowing, or geometric, effects, in which surface projections or volume scattering elements shadow other surface projections or volume scatterers. These effects are important on scales ranging from soil surface perturbations to topographic relief. The distribution of scattering surface normals also conditions specular scattering. Geometric-optical models have been used to describe these effects. Both volume scattering and geometric effects must be accommodated in any realistic physical description of surface reflectance behavior.

Another complicating factor is the fact that more than one layer of surface scattering material may be present. A vegetation cover over soil, snow, or standing water is an example. If the upper layer is thick, as in a dense forest cover or closed crop canopy, the scattering behavior of the lower layer may be ignored or perhaps approximated as Lambertian—that is, independent of view or illumination angles. However, if the upper layer

is sparse, a physical model that explains remotely sensed data will have to accommodate both upper and lower layers. In that event, the lower boundary may be modeled fully by a separate physical model, or its behavior may be characterized empirically.

### 1.4. Atmospheric Effects

For satellite or aircraft observations of radiance, the atmosphere influences both solar irradiance reaching the surface and reflected radiance leaving the surface. Beam radiation is scattered into diffuse surface irradiance, smoothing reflectance anisotropy; scattering adds path radiance, augmenting the surface radiance received by the sensor; and absorption reduces the surface radiance on its path to the sensor. Unfortunately, atmospheric effects are not independent of the surface. As surface brightness increases, multiple scattering between the surface and the atmosphere increases, boosting path radiance and diffuse irradiance. The influence of the atmosphere varies with wavelength.

Because the atmosphere modifies land-leaving radiance, an inversion strategy that estimates the physical descriptors of the surface BRDF from remotely sensed radiance measurements must include atmospheric effects. For applications in which atmospheric scattering is small compared to surface scattering, a simple path radiance correction may be all that is required (or that is practical, given limited knowledge about the state of the atmosphere at the time of data acquisition). However, for hazy atmospheres or shorter wavebands, some form of coupled-model approach is preferable, in which a combined surface-atmosphere model is fitted to the top-of-atmosphere radiances (Liang and Strahler, 1993a, 1993b; Rahman et al., 1993a, 1993b). Note that the addition of an atmospheric model adds both a new set of physical parameters and a higher degree of complexity to any inversion process applied to remotely sensed data.

## 2 - SOME RECENT DEVELOPMENTS IN VEGETATION CANOPY REFLECTANCE MODELING

The following discussion documents a number of advances in vegetation canopy reflectance modeling that have occurred within the past two to three years. The treatment is not designed to be exhaustive or even fairly complete; rather it is designed to identify examples of new developments within the major subfields of canopy reflectance modeling.

### 2.1. Radiative Transfer Canopy Models

The modeling of the BRDF of vegetation canopies using radiative transfer (RT) theory has been significantly enhanced in the past few years by Myneni with coworkers. One line of research has been to extend the radiative transfer formulation of the finite leaf scattering medium to three dimensions, expressing leaf area density within the medium first as a polynomial (Myneni et al., 1990), then as an external parameterization derived by fractal simulation (Myneni, 1991; Myneni et al., 1992a). The radiation field is solved numerically by extending the discrete ordinates method to three dimensions. The model fits a number of angular vegetation reflectance datasets quite well, although it slightly overestimates near-infrared reflectance.

Another contribution has been to model the hotspot effect from first principles (Myneni and Ganopol, 1991; Myneni et al., 1991; Myneni and Asrar, 1991; Knyazikhin et al., 1992), using an approach that describes the canopy as a medium containing regions of scattering phytoelements (e. g., branchlets with leaves) alternating with convoluted voids lacking scatterers. Technical advances to the solution of the radiative transfer equation for the leaf canopy are provided by Ganapol and Myneni (1991a, 1991b). Their formulations increase the accuracy of the solutions, especially those obtained by the discrete ordinates method.

The 3-D model of Myneni (1991) has been simplified somewhat and extended to simulate the case of a canopy of sparse vegetation clumps, rather like a desert shrub landscape (Asrar, et al., 1992; Myneni et al., 1992b). The model demonstrates that the directional reflectance behavior of the 3-D canopy is quite different from that of the equivalent 1-D canopy. However, the fraction of absorbed photosynthetically active radiation (FAPAR), canopy photosynthetic efficiency and stomatal efficiency are all well predicted by simple relationships with the normalized difference vegetation index (NDVI) for either case.

Iaquinta and Pinty (1994) recently modified the physical model of Verstraete et al. (1990) along the lines of radiative transfer to include a (Lambertian) lower soil boundary, thus allowing its application to optically thin canopies. The radiance field is divided into uncollided, singly-scattered, and multiply-scattered radiance, with the multiple scattering component evaluated numerically using a single-angle discrete ordinates method. Calculation is rapid enough to allow inversion through forward iteration, and when tested with data simulated using other radiative transfer models, optical properties and the hotspot parameter are well retrieved. Leaf area index and soil albedo inference, however, are sensitive to the leaf area index value.

### 2.2. Coupled Atmosphere-Canopy Radiative Transfer Models

A number of models couple the atmosphere and plant canopy together. Coupled models are particularly suited to exploring satellite sensing scenarios, since orbital measurements are always influenced by the atmosphere. Because radiative transfer models of the vegetation canopy lend themselves readily to atmospheric

coupling, most of the coupled models are of this type. Coupling can be used to model surface bidirectional reflectance factors (BRFs), in which case it is the downwelling distribution of irradiance that is of concern. It can also used to analyze the effects of canopy and atmospheric parameters on radiance measured at the top of the atmosphere.

Myneni and coworkers have coupled both one- and three-dimensional radiative transfer canopy models to atmospheric radiative transfer models. In one-dimensional studies, Myneni et al. (1993) showed that the atmosphere acts to add significant path radiance to the surface radiance at red wavelengths, while the atmosphere significantly attenuates surface radiance at infrared wavelengths. A factor that converts top-of-atmosphere directional radiance measurements to (hemispherical) fluxes varies significantly with sun and view angle. In a further application (Asrar and Myneni, 1993), surface albedo is always reduced by a clear atmosphere, and the fraction of photosynthetically active radiation absorbed by the canopy is well predicted by the atmospherically-resistant vegetation index (ARVI; Kaufman and Tanré, 1992). Exercising the coupled 3-D model, Myneni and Asrar (1993) reproduced the adjacency effect well as compared to a Monte Carlo simulation, and simulated soybean reflectance with good agreement to measured data.

In the radiative transfer formulation of Liang and Strahler (1993a), the coupled atmosphere-canopy system consists of two plane-parallel layers with a non-Lambertian lower (soil) boundary. The atmosphere is parameterized by a single scattering albedo and one-term Henyey-Greenstein phase function; each is a weighted combination of values for Rayleigh and aerosol particles. The leaf canopy is described by a leaf normal distribution function, bi-Lambertian leaf scattering, and a specular reflectance parameter. The flux field is separated into unscattered radiance, singly-scattered radiance, and multiply-scattered radiance. The unscattered radiance field consists of uncollided downwelling irradiance and radiance upwelling from the soil surface. Within the canopy, the single-scattering radiance field includes the hotspot effect, as parameterized by Nilson and Kuusk (1989), while the multiple scattering field does not. The total radiance field is solved by Gauss-Seidel iteration at finite increments of optical depth, with numerical integrals evaluated using Gauss-Legendre quadrature.

Although the Liang-Strahler Gauss-Seidel model provides accurate solutions for a realistic parameterization of the radiative transfer equation of the coupled atmosphere-canopy medium, it is too cumbersome for inversion by forward iteration. Accordingly, Liang and Strahler (1993b) provide a simplified model also relying on decomposition into a three-component flux field. Atmospheric multiple scattering is approximated by a δ two-stream model, which preserves the anisotropic distribution of skylight. In the canopy, multiple scattering is approximated using asymptotic theory. An inversion from reflectance measurements of a soybean canopy (Ranson et al., 1984) retrieved leaf area index with good accuracy. Leaf angle distribution parameters were not estimated as accurately, probably due to lack of measurements near the hotspot. Later work by Liang and Strahler (in preparation) has applied a four-stream approximation to the coupled atmosphere-canopy model. This approach yields very good accuracy at useful angles with a calculation speed sufficiently rapid to extend inversion through forward iteration to large volumes of directional radiance imagery.

## 2.3. Other Coupled Models

A coupled atmosphere-canopy model is also presented by Rahman et al. (1993a). They utilize a partitioning of atmospheric radiation into direct and diffuse fields (following Tanre et al., 1983) and couple the atmosphere and canopy using a multiple reflectance parameter that depends on the proportions of direct and diffuse irradiance. The canopy is modeled following Verstraete et al. (1990) and Pinty et al. (1990), utilizing parameters describing leaf angle distribution, single-scattering albedo, phase function for the leaf, and sunfleck geometry. In a series of simulations oriented toward sensing with the NOAA AVHRR (Advanced Very High Resolution Radiometer) instrument, they show that canopy optical properties should be retrieved with good accuracy in most cases. Structural properties can also be well retrieved, if the shape of the hotspot is sampled well.

In a more practical application, Rahman et al. (1993b) simplify the canopy portion of their coupled model to a semiempirical form that includes terms representing forward-backward scattering and a hotspot. Three empirical constants calibrate the surface BRDF function. In a validation against the observed directional reflectance of a number of canopy covers, the model showed very good accuracy. For some test datasets, the authors adjusted observed reflectances for the smoothing of the BRDF that is produced by diffuse illumination, confirming the importance of coupling atmosphere and canopy. In application to AVHRR data, the coupled model retrieved reasonable values for average optical depth, water vapor content, and surface parameters for an annual sequence of measurements obtained from two North African desert sites.

Liang and Strahler (submitted) coupled an atmospheric radiative transfer model to a simple six-parameter empirical model for surface BRDF that is derived by combining the limacon model of Walthall et al. (1985) with a two-parameter negative exponential hotspot model. This formulation fits soybean, shinnery oak, and conifer forest BRDFs well, with accuracies in the range of 3-10 percent. The results emphasize the importance of including a non-Lambertian lower boundary for proper modeling of path radiance.

## 2.4. Semiempirical Models

Roujean et al. (1992) have recently proposed a three-parameter semiempirical model for surface reflectance. The model expresses BRDF as a sum of three terms. The first term represents reflectance at nadir illumination

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and view angles. Added to it is a weighted geometric scattering component, based on a physical model of Lambertian protrusions on a flat plain; and a weighted volume scattering component derived from a simple single-scattering radiative transfer model for randomly-oriented isotropic scatterers. A comparison with directional reflectance data for a range of vegetated surfaces shows a reasonably good fit for most continuous canopy covers. Forest BRDFs, however, appear to be an exception.

## 2.5 Geometric-Optical Models

New developments have also occurred in geometric-optical modeling of vegetation canopy reflectance. Li and Strahler (1992) modified their previous model (1986) to more properly accommodate the effects of mutual shadowing of individual plant crowns by one another. Their model is driven by the shape and spacing of individual plant crowns, which are taken as geometric objects that cast shadows on the background and on other crowns. The surface reflectance is modeled as a function of four scene components—sunlit crown, shadowed crown, sunlit background, and shadowed background—that are viewed in varying proportions, depending on illumination and viewing positions. The new mutual shadowing model accounts for the effect that when plant crowns are closely spaced and of similar size, the shadow of one crown tends to fall preferentially on the base of an adjacent crown. Thus, when the canopy is viewed from a low angle, only the sunlit tops of crowns are seen. This effect gives the BRDF a typical bowl-shape when plotted in hemispherical projection. The model fits the directional reflectance of conifer forests in Oregon (Abuelgasim and Strahler, 1993) and at Howland, Maine (Schaaf and Strahler, 1994), with good accuracy.

Most recently, Li et al. (1994) have developed a hybrid model combining geometric optics with principles of radiative transfer. It relies on gap probabilities and path length distributions to model the penetration of irradiance into the canopy and its single and multiple scattering in the direction of view. Within a plant crown, the probability of scattering is a negative exponential function of path length. Within-crown scattering provides the source for single scattering radiance, which exits with probabilities proportional to further path-length distributions in the direction of exitance (including the hotspot effect). Single scattering provides the source for double scattering, and then higher orders of scattering are solved successively by a convolution function. The model is parameterized by a per-meter scattering coefficient, within-crown projected leaf area as a function of angle, and statistical variables describing crown shape, count density, and the height of the canopy layer. Early validation using data from a conifer stand at Howland, Maine, shows good agreement between modeled and observed reflectance.

## 2.6. Computational Models

Mention has already been made of the computational models for vegetation scattering recently developed by Borel et al. (1991) and Goel et al. (1991, 1992). In the radiosity approach of the Borel et al., Lambertian scattering by leaves is described by a sparse matrix of view factors between leaf surfaces. The approach of Goel et al. uses ray tracing on a realistic plant model parameterized by L-systems. Lewis and Muller (1992) have recently provided ARARAT, an advanced radiometric ray tracing program, which allows an arbitrary BRDF model for scattering by surface elements. It can be used to simulate a wide range of scenes, from crop canopies to vegetation-covered topographic landscapes. Further, the program can utilize a sky radiance model for downwelling irradiance, such as that of Zibordi and Voss (1989), and thus compute bidirectional reflectance factors (BRFs) as well as the BRDF.

## 3 - DISCUSSION

### 3.1. Validation Needs

Studies of the anisotropic reflectance of the earth's vegetated surface conducted over the last decade or so have not lacked for models. There are literally dozens of models in the literature, and undoubtedly still more are lurking within the fertile brains of scientists and applied mathematicians who work in this field. These models vary widely in their abstractions of the physics of the interaction of light with the canopy, yet most seem to do a reasonable job of approximating the anisotropic reflectance of at least some type of vegetation cover. Except possibly for the coherent backscattering of leaf surfaces (Hapke et al., 1993), it would appear that no new physical mechanisms for the interaction of light with vegetated surfaces will be discovered or applied in the near future. We may expect, however, that models will continue to add degrees of complexity, such as accounting for stems and branches and accommodating more soil scattering parameters. Perhaps these models will eventually merge with microwave scattering models, providing a "unified theory" for the interaction of electromagnetic radiation with the plant cover.

What has been lacking, however, are ample quantities of directional reflectance measurements of vegetated surfaces that are sufficiently well characterized to validate the physical abstractions of their models. For example, every radiative transfer canopy model requires some parameterization of leaf angle distribution, yet there are probably less than a dozen sets of angular radiance measurements of canopies for which the leaf angle distribution has been accurately determined. Leaf scattering functions (leaf BRDFs) have been mea-

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sured and documented for only a few leaves of a few species. Even leaf area index is often lacking from sets of measurements, or is estimated only indirectly from regression relationships. Clearly, the modeling community and the experimentalists need to embark on joint ventures to collect appropriate validation data. The BOREAS experiment is an example of such a venture involving both modelers and measurers. More such opportunities are needed.

The validation of vegetation surface radiance models serves mainly to validate the physical abstractions behind them. Carefully structured repeated comparisons between models and measurements can improve our confidence in those abstractions. But once we understand the physics, what then?

Proper characterization and understanding of the BRDF of vegetated surfaces is an important building block in remote sensing of the earth. Without an understanding of the anisotropic reflectance behavior of the surface, our ability to infer the biophysical state of the surface is obviously limited. Inversion of physical models of surface scattering plays a key role here. With an appropriate array of remote measurements from spaceborne platforms, the potential exists to obtain the driving parameters that condition reflectance anisotropy for significant regions of the earth's surface. Some of these parameters (e. g., leaf area index), will be of direct use in other fields, such as ecosystem modeling or global climate modeling. Other parameters (e. g., leaf angle distribution) are not especially useful. The challenge to the BRDF modeling community is to provide invertible models that are robust, reasonably accurate, and yield useful information at the broad spatial scales that characterize the important applications of remote sensing.

### 3.2. Global Change Agenda

What are the important future applications that will rely on accurate characterization of angular surface reflectance? Here we may look to the global change agenda. Global climate modeling is probably the most important component of that agenda. For global climate modeling, surface characteristics can provide two key pieces of information—albedo and surface roughness. These parameters have heretofore only been characterized at coarse spatial scales, and as the spatial resolution of global climate models increases, climate modelers will look to remote sensing for increasingly finer-scale information. Note that climate modelers are now interested in obtaining albedo as two quantities, broken into shortwave and longwave at about $0.7\mu m$, due to the abrupt change in absorption by vegetation at that wavelength (J.-P. Muller, personal communication). The significance is that albedo is readily retrievable from the BRDF, provided that sufficient atmospheric information is available to model the angular distribution of downwelling irradiance. Moreover, because albedo varies with sun and sky conditions, climate modelers may eventually need simple empirical BRDF descriptions so that albedo may be treated as a time-variant quantity.

Another important global change application is ecosystem modeling, especially the modeling of carbon fluxes. BRDF models have shown that some important carbon-balance parameters, such as FAPAR, are well estimated by empirical measures such as NDVI. However, NDVI varies with look angle, so that a single look is not likely to characterize properly the behavior of the plant cover (Myneni et al., 1992c). Yet if the BRDF can be derived from multiangle measurements, the biophysical parameters can be properly summarized. Further, calibration of carbon balance models is dependent on the plant community. For example, a thin, continuous canopy of annual or perennial grasses will photosynthesize with quite a different efficiency than a perennial desert shrub community of the same leaf area (S. Running, personal communication). Inasmuch as the structures of these community types are differentiable by directional reflectance, so will the identification of community types be facilitated.

### 3.3. Once and Future Sensing

Global inference of BRDF, albedo, and related biophysical surface parameters at fine spatial and temporal scales will be available in the twenty-first century with the advent of sensors aboard the EOS-AM and -PM platforms, notably the MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) instruments. These instruments will provide sufficient angular radiance measurements to characterize surface BRDF and albedo at fine spatial and temporal resolutions, and inversion strategies to be used with MODIS and MISR data are under development (Running et al., 1994; Strahler et al., 1994; Diner et al., 1994). In addition, directional surface measurements will be available from the spaceborne POLDER (Polarization and Directionality of Earth's Reflectances) and ATSR-2 (Along-Track Scanning Radiometer) instruments prior to the launch of the EOS platforms in 1998 and 1999. For the present, existing airborne instruments such as ASAS (Advanced Solid-state Array Spectrometer; Irons, 1991) and the aircraft version of POLDER (Douzé et al., 1993) can simulate many of the characteristics of these future spaceborne sensors. They will be critical tools in the development phase of information-extraction algorithms that utilize directional radiance measurements.

### 4 - CONCLUSION

Significant advances in modeling the directional reflectance of vegetated land surfaces have been made in the last decade, and, notably, within the last two to three years. These advances have laid the foundation for the

retrieval of useful descriptors of the vegetation cover over large areas through the acquisition of directional radiance measurements by spaceborne instruments. This retrieval will be of special benefit to global change studies in the EOS era.

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