Advanced Models for Multiangular Remote Sensing Data Interpretation

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Abstract The interpretation of satellite remote sensing data in terms of land surface properties requires the use of radiation transfer models and inversion procedures. Various approaches are briefly mentioned, including Monte Carlo ray tracing, physically-based 1-D models, and parametric formulations capable of representing the general anisotropic behavior of natural surfaces. Some of the assumptions made in each approach, as well as their implications are reviewed, and the intrinsic difficulty of dealing with radiation transfer in a medium as inhomogeneous as a plant canopy is underscored. The need to pursue further research to take full advantage of the upcoming generation of advanced Earth Observation sensors is stressed.

Key words Inversion, Radiation transfer, Bidirectional reflectance

Various approaches have been pursued to retrieve useful information from remote sensing measurements for a variety of applications, taking into account additional requirements such as limitations in the sampling with which the data are acquired, in the accuracy of the measurements, in the availability of ancillary and complementary data, and in the human and computer resources available for the processing. The proper interpretation of remote sensing observations, however, implies the use of tools and techniques of information extraction which implement, in a formal or hidden way, the inversion of a model describing the measurement process against these data.

In a recent review of interpretation tools used in the solar spectral domain, Verstraete[1] assigned such models to four main classes, namely (1) the fully explicit models describing both the scene being observed and the transfer of radiation explicitly[2-5] (Monte Carlo, and radiosity methods), (2) classical radiation transfer models, typically in plane—parallel media, with or without ad hoc corrections for particular effects such as the hot spot[6-9], (3) parametric models which represent the anisotropy of the target of interest but without providing an explanation of the mechanisms responsible for these observed effects[10,11], and, finally, (4) empirical approaches such as spectral indices. These approaches were graphically arranged in the following figure:

$$
\begin{array}{ccccc}
 & & \mathbf{S}_\infty & & \\
 & & \downarrow f & & \\
\mathbf{S}_1(\vec{r},t,\lambda) & \xrightarrow{f_1} & \mathbf{Z}(\vec{r},t,\lambda,\Omega) & \xrightarrow{h} & \mathbf{P}(\vec{r},t) \\
\downarrow f_2 & & \downarrow g, g(VI) & & \\
\mathbf{S}_2(\vec{r},t) & \xrightarrow{g_s} & \mathrm{Y}(\vec{r},t) & \xrightarrow{g_h} & \mathbf{H}
\end{array}
$$

where $\vec{r}$, t, λ and Ω, represent the space, time, spectral and directional independent variables, respectively, and where **Z** and **Y** are the measurements and the variables of interest. f stands for the very detailed explicit three dimensional models which depend on a very large set $\mathbf{S}_\infty$ of parameters, f_1 and f_2 represent typical analytical radiation transfer or leaf reflectance models based on much reduced sets **S** of state variables, **H** is a parametric model depending on the set **P** of empirical parameters, and g_h indicates that the variables of interest **Y** often depend on other variables **H** which are hidden from the point of view of remote sensing, because they do not affect the transfer of radiation.

A state of the art Monte Carlo ray-tracing model has been described elsewhere in this document[3]. Two other recently developed models will be discussed here, namely a parametric model suitable for representing the anisotropy of natural surfaces, and an advanced model based on a discrete representation of the canopy for the first orders of scattering. These models focus on the description of the directional signature of natural surfaces within a particular spectral band. It is recognized that other tools have been proposed to exploit spectral signatures, such as linear mixing methods, but these will not be discussed here.

The principal rationale for developing parametric bidirectional models is to provide a simple, convenient representation of the effect of the surface for other models requiring a realistic quantitative and accurate description of the net effect of the surface. Atmospheric radiation transfer models typically require such a surface specification. The main requirement is thus to represent the bidirectional reflectance field in an accurate but computationally efficient way, so that the model can be easily inverted against the measurements. Since the angular sampling of this field is often rather crude, it is advisable to ensure that the model capitalizes on the latest advances of physically-based models and parameterizes the field in terms of mathematical functions known to approach the usual form of the reflectance field.

As far as the inversion procedure is concerned, it may be advantageous to be able to use linear rather than non-linear approaches, especially for operational applications or when access to computing resources is limited. Clearly, this does not imply that the model itself needs to be linear in the parameters to be retrieved, but only that the model can be manipulated in such a way that the inversion problem can be resolved through the solution of a linear set of equations.

Our work in this area has been motivated by the need for a simple, reliable, accurate operational model to represent the bidirectional reflectance of most terrestrial surfaces for the purpose of retrieving the aerosol type and amount, as well as the albedo of the surface, from the Multi-angle Imaging Spectro-Radiometer (MISR) of NASA/JPL, which is due to fly on the upcoming EOS-AM1 platform[12]. Design requirements included the need to select a unique model applicable over all or most terrestrial surfaces, in particular to describe dense dark vegetation, and a limit of three or four free parameters, of which at most one (an overall multiplicative parameter) could be left free in the case of dense dark vegetated surfaces. Investigations were initiated along the lines of the model proposed by Rahman *et al.*[10], but the usability of the model was first extended by replacing the phase function proposed by Henyey and Greenstein[13] by an exponential function of the illumination and observation angles. This allowed the model to reduce to a simpler form such that the logarithm of the model could be inverted against the logarithms of the measurements, solving a set of linear equations. The parameters retrieved are later transformed back into the values they should assume in the original non-linear model. The applicability of this model has been tested by inverting it against a large number of reflectance factor data sets for a variety of surface types, as well as against actual remote sensing data by Eengelsen *et al.*[14] Fig. 1 exhibits an example of the capacity of this modified model to reproduce BRF measurements. This approach can be extended to account for particular effects, such as the specularity of leaves, while still satisfying the requirements expressed above, including those related to the inversion procedure.

For all applications which demand the accurate description of the relevant processes rather than a simple representation of the anisotropy, a physically-based model is required. It may still be an advantage to have a simple analytical formulation and a limited number of free parameters, but the correct representation of the physics of radiation transfer is also important. Within the large class of such models, there remain a significant need for models to represent the transfer of radiation in complex media such as plant canopies in terms of a single (usually vertical) dimension. The forthcoming launch of a new generation of Earth Observing space instrument with significantly increased spatial resolution will certainly reinforce the need and practical usefulness of such models.

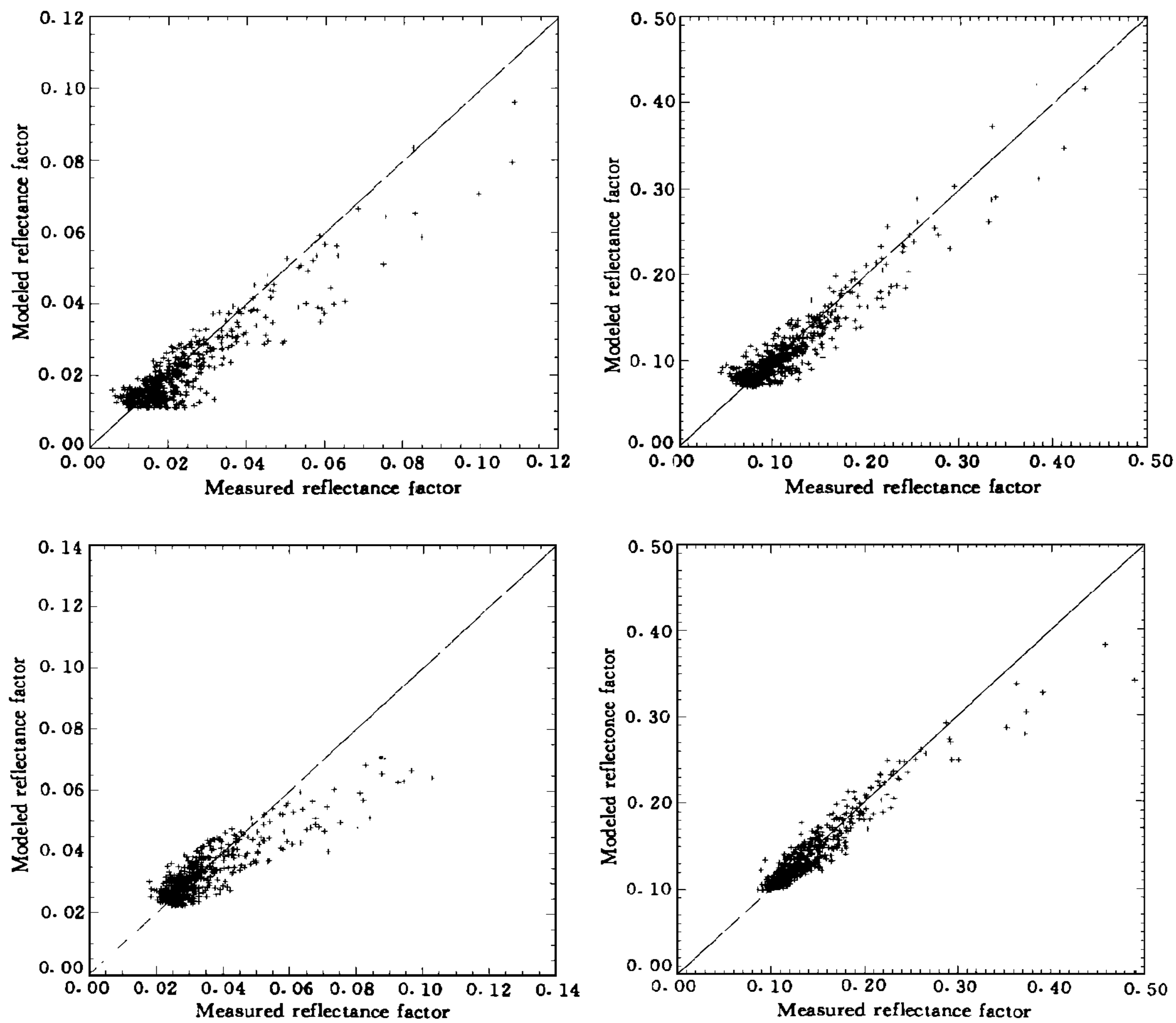

Fig. 1 Comparison between measured and modeled reflectance factors over Black Spruce (top) and Old Jack Pine (bottom) forest (Deering, BOREAS 94), in the red (left) and near-infrared (right) spectral bands

As has been shown in the literature, it is not possible to represent the effect of leaves of finite size and orientation without modifying the conceptual meaning of the extinction coefficient in the radiation transfer equation. In fact, the modifications brought about to the extinction coefficient by Marshak[15], Liang and Strahler[16], Iaquinta and Pinty[17] among others, blur the distinction between the optical depth and this coefficient. To avoid the hypothesis of assuming a continuous medium along the vertical, and to recognize the discrete nature of the medium, an advanced model has been designed[18]. This model uses a statistical description of the spatial distribution and geometrical properties of the leaves (e.g., size and orientation) to represent the vegetation canopy. Typically, the average size of the leaves, their number per unit volume and the total height of the canopy constitute a set of independent architectural parameters from which the leaf area index, a biophysical variable of great interest in various applications, can be straightforwardly computed. The solution of the radiation transfer problem using such a limited but statistical representation of the vegetation canopies can be formally expressed at all orders of scattering following the spatial discretization of the medium. It is however noticeable that the impact of the discrete properties of a canopy as compared to a turbid-like medium is mainly significant for the very first few orders of scattering. Indeed, it may reasonably be expected that the multiple scattering events tend to smear out the specific architectural features of the vegetation canopy. This has long been recognized by Marshak[15] and others (including, for instance, Liang and Strahler[16] and Iaquinta and Pinty[17]) who recommended to find separate analytical solutions for the intensities that have been scattered only once either by the underlying soil or by the leaves. The remaining contributions due to higher orders of scattering can be estimated by more classical radiation transfer methods applicable to the case of turbid media.

We adopted a similar approach in finding the full solution of the radiation transfer problem for our semi-discrete model: The first orders of scattering (by the soil and by the leaves) are calculated in the three-dimensional space after an adaptation of the original discrete model developed by Verstraete[19] for the extinction of the direct incoming solar radiation. The statistical representation of the canopy architecture allows to model explicitely the hot spot phenomenon in the first two orders of scattering following an adaptation of the model developed by Verstraete[8]. The latter logically fits into the discrete approach we use for describing the state of the canopy. The multiple scattering contribution is calculated with a Discrete Ordinates Method using an azimutally averaged expression of the anisotropic scattering phase function proposed by Shultis and Myneni[20].

This model has been compared in direct mode with reflectance factors generated with the Raytran model, a Monte Carlo ray tracing code, and illustrates how the two models compare (Fig. 2). The semidiscrete model appears very accurate for representing the bidirectional reflectance factors in the principal plane where most of the variability occurs. This good performance is, as expected, particularly effective in the red simulated wavelength since most of the signal is due to the very first orders of scattering by the soil and the leaves. Somewhat larger inaccuracies are sometimes found in the near-infrared domain, and mainly originate from the simplified simulation of the multiple scattering contribution in the case of dense canopies. Additional tests based on the inversion of the semi-discrete model against field data show that the model is capable of representing the anisotropy of the reflectance field while generating reasonable

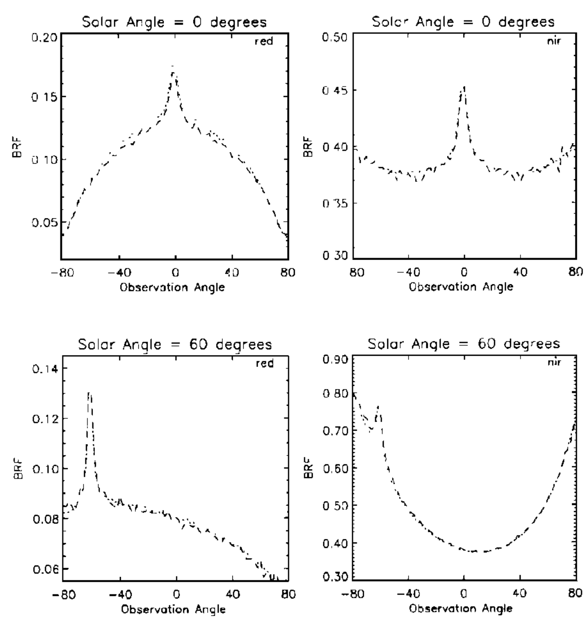

Fig. 2 Comparisons between the semi-discrete (dotted lines) and the ray tracing (dashed lines) models for a plant canopy with a leaf area index of 1, a height of 1m, an average leaf diameter of 0.1m, leaf reflectances and transmittances of 0.075 (0.5) and 0.05 (0.45) in the red (near-infrared) spectral band, respectively. Soil albedo was set at 0.25 (0.35), and the leaf orientation distribution is erectophile

values of the model state variables. The impact of the underlying soil boundary condition has also been studied, and the conditions for which a Lambertian soil is acceptable have been documented.

Over the last few years, the land surface community interested in the exploitation of satellite remote sensing data for Earth Observation in the solar spectral domain has developed and implemented a number of advanced tools and techniques for the extraction of the relevant information from these data sets. The selection of the model to be used needs to be made in terms of the requirements of the application of interest. However, the selection of a model capable of representing the full three-dimensional heterogeneity of the scene of interest implies major costs in computing resources compared with the requirements of models designed to describe homogeneous scenes only. By contrast, parameterized models of wider applicability do not suffer from the same constraints.

It will be interesting for this BRF community to evaluate the major remaining issues in modeling homogeneous and heterogeneous scenes. Specifically, it appears that the trend is to invest more thought and resources in a more realistic description of the scenes of interest than on the solution of the radiation transfer equation itself. Similarly, it will be important to reflect on the best way to promote the tools that have been developed already, in the context of empirical approaches such as spectral indices.

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改进的多角度遥感数据解译模型

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摘　要　利用卫星遥感数据解译地表特性需要应用辐射传输模型与反演。文中简要提到几种方法，包括蒙特卡洛光线追踪，一维物理模型，以及能够描述自然表面的整体各向异性特征的参数化公式。回顾了每种方法中所作的假设，并强调指出了处理在植被冠层这样的非均匀介质中的辐射传输问题的内在困难。在新一代改进型地球观测探测器时代的到来之际，指出进行深入研究的迫切性。

关键词　反演，辐射传输，二向性反射