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# Introduction to special section: Modeling, measurement, and exploitation of anisotropy in the radiation field

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## 1. Introduction

Over the past four decades or so, advances in satellite remote sensing technology have resulted in the development of a wide variety of sensors and platforms of Earth observation. Flying at altitudes from a few hundred to a few thousand kilometers above the planet's surface, these sensors generate their data by absorbing the radiation reflected or emitted by the planet in their direction. Passive sensors rely on external sources of radiation (typically the Sun for visible and near-infrared measurements, or the Earth itself for thermal emission), while active sensors (e.g., synthetic aperture radars) embark their own sources of electromagnetic radiation. The latter will not be discussed further in this paper. In all cases the extraction of useful information from the raw data hinges on the availability of reliable and accurate models describing how these radiation fields interact with the targets of interest (and with other media that may not be of direct interest, such as atmospheric constituents in the case of surface studies) as well as with the observing instrument itself.

By necessity the process of information extraction relies on the analysis of the variability of the measurements with respect to independent variables, which describe how the data are acquired [*Verstraete and Pinty*, 2000b]. In particular, the exploitation of remote sensing data in the solar spectral domain has traditionally relied on the analysis of the spectral, spatial, and temporal variations in the measurements. It is only rather recently that the potential benefits of directional and polarimetric dimensions of the data have been demonstrated, mostly through theoretical developments or thanks to the operation of innovative sensor designs, such as the POLDER instrument of the Centre National d'Études Spatiales, Toulouse (CNES) on the Japanese ADEOS platform and the MISR instrument of the Jet Propulsion Laboratory (JPL) on the NASA EOS Terra platform.

It is now generally recognized that all natural and man-made surfaces reflect solar light differently in different directions. The Sun glint on water surfaces and the hot spot observable over terrestrial surfaces are some of the best known examples of anisotropy in the visible spectral domain. As a matter of fact, the production of truly isotropic scattering surfaces, for instance to serve as reference panels, remains a significant industrial challenge.

The description and quantitative characterization of the anisotropic reflectance of material objects has a long history, firmly rooted in astronomy and astrophysics. *Galilei* [1610] was probably the first to correctly explain why the Moon appears brighter during its opposition phase than at any other time. Lord Rayleigh (1903) and Helmholtz (1924), cited by *Chandrasekhar* [1960], appear to have been among the first to formally propose the reciprocity principle, which has proved quite useful in describing the properties of geophysical systems that behave as turbid media. Oepik suggested to describe the reflectance of arbitrary surfaces in terms of a power of the cosine of the illumination zenith angle. *Minnaert* [1941] later extended this parametric formula to include the cosines of both the illumination and the observation zenith angles, by applying the reciprocity principle. Numerous studies described the anisotropy of planetary surfaces: see *Kieffer et al*. [1977], for instance, in the case of Mars.

The nature and importance of the anisotropy of the reflected radiation field was fully recognized by the atmospheric scientists who pioneered the exploitation of satellite remote sensing data for meteorological and climate purposes. The Earth Radiation Budget Experiment, and in particular the exploitation of the Nimbus data [e.g., *Jacobowitz et al*., 1984], is a case in point. Since then, many other field, airborne, and spaceborne instruments of Earth observation have amply shown that all our planet's surfaces (continents, oceans, snow, and ice fields) and, indeed, the atmosphere itself (gases, clouds, as well as aerosols), all scatter light anisotropically. *Gobron et al*. [2000], *Pinty and Ramond* [1987], *d'Entremont et al*. [1999], *North et al*. [1999], *Leroy et al*. [1997], and *Diner et al*. [1998] are some of the investigators who discussed the issues associated with or the opportunities arising from the anisotropy of the reflectance fields, based on the advanced very high resolution radiometer (AVHRR), Meteosat, Geostationary Operational Environmental Satellite (GOES), Along-Track Scanning Radiometer (ATSR), Polarization and Directionality of the Earth Reflectance (POLDER), and Multiangle Imaging Spectroradiometer (MISR) instruments.

Reflectance anisotropy has been shown to occur over a wide range of spatial scales. For instance, a variety of airborne instruments have acquired multiangular and multispectral data over diverse targets [e.g., *Kriebel*, 1978; *Irons et al*., 1991; *Diner et al*., 1998a], and the data collected clearly exhibit anisotropic effects. Similarly, field sensors have been deployed to obtain measurements over much smaller areas, and these also have demonstrated strong variations in the reflected field as a function of illumination and observation angles [e.g., *Deering and Leonoe*, 1986; *Sandmeier and Itten*, 1999]. Compilations of anisotropic field data have also been generated [e.g., *Kimes et al*., 1985]. Studies at even finer spatial resolutions have been conducted in specialized laboratories, on targets between 1 and 100 cm [e.g., *Woessner and Hapke*, 1987; *Brakke et al*., 1989; *Gao and Zhu*, 1997; *Hosgood et al*., 2000; *Bonnefoy et al*., 2000]. Last but not least, these authors have shown that the anisotropy of the reflectance is different at different wavelengths, and both simulation studies and observation campaigns have



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suggested an intrinsic relation between the structure of the observed geophysical system and its anisotropy: the latter is thus also varying in time for dynamically evolving systems.

In fact, it has proven very difficult to design an isotropic surface, i.e., one that scatters radiation equally in all directions, even within the controlled environment of a laboratory. Indeed, the smoother one makes such a surface, the more specular the reflectance tends to be. On the contrary, the rougher the surface, the stronger the hot spot or opposition effect. Plain paper and barium sulfate powders have been used as approximations of isotropic white surfaces. More recently, Spectralon, a registered product of Labsphere, has been used to create solid panels that can be used in the field or embarked on space platforms to help in the calibration of instruments, such as MISR and MERIS. In any case, even this versatile material is not perfectly Lambertian [e.g., *Flasse et al*., 1993].

These findings have various major implications: First, these anisotropic effects should be accounted for explicitly in the analysis and interpretation of remote sensing measurements derived from imaging sensors operating in the solar spectral domain, especially when a certain degree of accuracy or reliability is required. Second, since the interaction of light with geophysical media results in the generation of anisotropic reflectance fields, the observed angular variations may be used to characterize this interaction, provided (1) suitable models are available to explain how anisotropy results from the elementary scattering processes and (2) suitable inversion procedures are available to exploit this opportunity. Third, the classical turbid medium models of radiation transfer, as developed and used by astrophysicists and atmospheric scientists, for instance, are inadequate to account for these effects [*Pinty and Verstraete*, 1998] because they are based on the so-called "far field approximation," which is not verified when the linear dimension of the scatterers (such as plant leaves and branches) are of the same order of magnitude or larger than the wavelength of the radiation. Under these circumstances the reflectance field exhibits specific features such as the hot spot or opposition effect, and more complex models must be designed to account for these effects. Here again, pioneering studies were made for both planetary surfaces and Earth environments [e.g., *Hapke*, 1981; *Simmer and Gerstl*, 1985; *Verstraete et al*., 1990; *Myneni and Ross*, 1991; *Peltoniemi*, 1993].

The benefit derived from using more complex but more appropriate models lies in the opportunity of deriving new or more reliable information on the geophysical media from the remote sensing data, both within the atmosphere (e.g., aerosol properties, as shown by *Iaquinta and Pinty* [1997], *Kahn et al*. [1998], *Martonchik et al*. [1998a], and *Pinty et al*. [2000a]) and at the surface [e.g., *Pinty et al*., 1990; *Myneni et al*., 1995; *Martonchik et al*., 1998b; *Knyazikhin et al*., 1998; *Gobron et al*., 2000]. Even meteorologists and climatologists interested primarily in the transfer of radiation in the atmosphere will benefit from specifying an accurate lower boundary condition, because of the multiple scattering of radiation between the atmosphere and the surface. The potential benefits of exploiting the anisotropy of the reflectance field in remote sensing applications were further discussed by *Diner et al*. [1999].

From a practical point of view, the acquisition of simultaneous multiangle measurements from a given target provides significant additional constraints (with respect to the spectral dimension of the data set, for instance) on the inversion procedure. The latter, in turn, may then yield a more reliable estimate of the values of state variables characterizing the observed media. More precisely, these additional constraints lead to a reduction of the uncertainty with which these state variables are estimated: Since inverse problems are often ill-conditioned, the procedure often leads to the identification of multiple possible solutions. Hence the availability of additional constraints results in a very useful pruning of the solution set. More importantly, the proper analysis of these data may lead to a characterization of the structure of the target, thus yielding information that cannot be derived by other means. Multiangular data sets at critical wavelengths are thus highly desirable to characterize the geophysical media of interest. The two key ingredients required to fully exploit such data sets, when they exist, are (1) tools to model accurately enough the transfer of radiation within the atmosphere and the surface layers, as well as to represent the anisotropic radiation fields present at the relevant geophysical interfaces, and (2) techniques to efficiently invert these models in an operational context.

## 2. IWMMM-2 Conference

The scientific issues outlined in section 1 were debated at the Second International Workshop on Multiangular Measurements and Models (IWMMM-2), which took place in Ispra, Italy, September 15–17, 1999, under the auspices of the ENAMORS project (a concerted action organized under the fourth Framework Programme of the European Commission) and with additional support from the Space Applications Institute of the Joint Research Centre, the U.S. National Aeronautics and Space Administration (NASA), and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO).

The objectives of the IWMMM-2 were (1) to establish the state of the art in direct and inverse modeling techniques, (2) to review current and future multiangular airborne and spaceborne missions, as well as latest developments in field and laboratory instruments, and (3) to demonstrate the usefulness of multiangle data in practical applications, through the generation of new or better geophysical products.

The number and diversity of contributions to this international conference (some 80 papers were presented), as well as personal preferences, called for a concomitant flexibility in publishing the proceedings. As a result, arrangements were taken to publish a special section on these topics within the *Journal of Geophysical Research* (JGR)-Atmospheres and a special issue of *Remote Sensing Reviews*. The present JGR special section contains some of the keynote papers presented at the conference.

### 2.1. Theme 1: Simulations, Inversions, and Model Intercomparisons

Extensive research and development on the simulation of the anisotropy of land surfaces and the overlying atmosphere took place over the past decades. Modeling the bidirectional reflectance factor (BRF) of terrestrial targets and the techniques of inversion of such models against multiangular data sets have progressed significantly, in part thanks to the stimulation provided by current or upcoming availability of laboratory and field campaigns, as well as airborne and spaceborne missions permitting the acquisition of multiangular data. A number of models have already been proposed in the literature; they do not need to be discussed or summarized again. However, a few new developments were presented at the conference, as can be seen from the papers by *Lyapustin and Kaufman* [this issue], *Leroy* [this issue], and *Li et al*. [this issue].

The time had come, however, to take stock of the progress made and to propose a clear perspective of the field to current and prospective users of existing and upcoming multiangular and multispectral measurements and models. While preparing this conference, it was thought appropriate and timely to initiate a long-term exercise of Radiative Model Intercomparisons (RAMI), similar to those that have been conducted in meteorology, atmospheric radiation, land surface processes, and many other fields of geophysics. The first set of results were presented at the conference, and the paper by *Pinty et al*. [this issue] provides ample details concerning the setup of the benchmark as well as the results of the comparison.

The RAMI initiative, originally conceived as a self-organized activity of the BRDF community, was (and continues to be) instrumental in (1) quantifying the similarities and differences between canopy radiation transfer models, (2) identifying model discrepancies and diagnosing possible pathological behavior of some models under specific observational scenarios, and (3) benchmarking three-dimensional model simulations and verifying their coherency in well-defined homogeneous and heterogeneous target conditions. The results gathered so far permit to assess the state of the art in radiation transfer models and to quantify the performance of the participating models. This ongoing exercise illustrates the level of maturity of the BRF modeling community. RAMI may thus serve as a test bed against which future model developments can be evaluated. This exercise will also foster the exchange of codes within the community and, perhaps in the long run, the development of community-approved BRF tools and libraries. The extension of RAMI to include intercomparisons in inverse mode has been proposed and will be pursued. The ENAMORS web site (http://www.enamors.org/) continues to provide information on this activity.

### 2.2. Theme 2: Laboratory, Field, Airborne and Spaceborne Measurements

The second theme of the conference addressed the latest technological developments and scientific strategies for the acquisition of improved multiangular data. Oral and poster presentations described a variety of laboratory, field, airborne and spaceborne sensors designed to provide this type of data. Visits were organized to the European Goniometer (EGO) and European Microwave Signature Laboratory (EMSL), both facilities of the European Commission Joint Research Centre, and a variety of field instruments, notably the Field Goniometer System (FIGOS) of the University of Zurich, the Wide Angle Airborne Camera (WAAC) of the German Aerospace Centre-Berlin, and the Mobile Unit for Field Spectroscopic Measurements (MUFSPEM) of the Technical University of Munich were exhibited in working condition. Other field instruments were discussed but not exhibited, such as the PARABOLA. This latter instrument was originally developed at NASA Goddard Space Flight Center (GSFC). A version of that sensor is currently operational at NASA JPL. Two of the papers presented at the conference appear below. These are the contributions of *Nandy et al*. [this issue] and *Abdou et al*. [this issue]; both are relative to field instruments.

The acquisition and exploitation of airborne data were discussed in the context of specific campaigns, for instance, to support the Earth's Radiation Budget Experiment (ERBE) and Clouds and Earth Radiant Energy System (CERES), conducted at the Atmospheric Radiation Measurement (ARM) sites. Similarly, results from AirMISR campaigns demonstrated the potential of multiangular data over selected sites. One major advantage of these airborne data sets is to permit the evaluation of the performance of models and inversion procedures and to show the actual usefulness of these data in concrete applications.

Presentations on new space instruments provided an intriguing glimpse of what the future may bring in this field. Three new concepts were discussed at length, namely, Leonardo, a multiplatform system of small satellites flying in formation to observe the same target from different directions, from NASA Goddard Space Flight Center; Triana, a Sun-orbiting platform to be located at Lagrange L-1 point so that it keeps observing the illuminated face of the Earth in the NASA Small Earth Probes program; and the Land Surface Processes and Interactions Mission, a proposed Earth Explorer hyperspectral and multidirectional polar orbiting platform from the European Space Agency. Although these missions are expected to evolve in time, for instance in the light of the results and experience acquired with the MISR instrument on the NASA Terra platform, they already capitalize on the concept of quasi-simultaneous multiangular data acquisitions. The opportunity to obtain such data in the thermal domain is also expected to lead to significant improvements in our understanding of critical climatic and ecological processes, and to allow new applications.

These various observational systems do provide complementary information and ultimately help, jointly, in the full interpretation of remote sensing data. They will stimulate and motivate the modelers in their efforts to provide better tools and techniques of Earth observation and the joint efforts of the remote sensing community to generate more reliable and accurate products.

### 2.3. Theme 3: Multiangular Applications

The third theme addressed in this meeting had to do with the demonstration of the practical usefulness of multiangular observations in remote sensing. Although the researchers working in this field have long been convinced of the necessity to acquire and analyze multiangular data to take full advantage of remote sensing products (in the optical as well as in the thermal spectral domains), this community has not been sufficiently forceful or convincing to promote its findings among the providers of remote sensing data (in terms of designing multiangular sensors earlier) or the users of such products (in terms of systematically addressing these issues as part of their processing).

Why does the exploitation of the anisotropy of the radiation fields remain confined to what may appear as a small group of purists, when the analysis of the spectral, spatial, or temporal variations in the signals seems so obvious? Elements of response include (1) historical and technological developments (it is worth remembering that remote sensing is rooted in the visual interpretation of photographic images), (2) the unavailability of simultaneous multiangular measurements for decades during which detailed spectral and spatial measurements were acquired, (3) a lack of awareness, outside the inner circle of specialists, of the actual importance of anisotropic effects on the measurements, or the mistaken belief that these effects can be neglected, (4) the relatively greater complexity of the underlying theories, or (5) the lack, until a few years ago, of a wide panoply of tools, both models and inversion procedures, usable in practical applications.

Once an initial intellectual and material investment is granted, the benefits of exploiting this new dimension in signal variability unfold. A number of presentations described the state of the art in the use of multiangular data. These included, among others, the derivation of surface albedo and aerosol optical thickness information from monospectral but multidirectional data acquired with a geostationary satellite [*Pinty et al*., 2000a, 2000b], or the derivation of surface and atmospheric properties from multispectral and multidirectional sensors such as the POLDER and AirMISR instruments. The Multiangle Imaging Spectroradiometer (MISR) sensor, launched on NASA's Terra platform in December 1999, was described and the main algorithms that have been developed to analyze its data were outlined. The very significant technological improvements brought about by the new generation of space instruments, especially in terms of onboard calibration, very high signal to noise ratio, much better navigation, as well as higher spatial and spectral resolutions, will exacerbate the detrimental effects of anisotropy if they are not taken into account but also offer new opportunities to exploit this source of variability in its own right. Three of these presentations appear as papers in this issue: these are the contributions of *Kahn et al*. [this issue], *Menenti et al*. [this issue], and *Kuusk and Nilson* [this issue].

Through the various presentations made during the meeting, it became clear that the two main advantages to be derived from the analysis of multiangular data are (1) products similar to those already available but of much higher accuracy and reliability and (2) new products that cannot be derived in any other way, for instance, on the structure of surface targets. These findings, in turn, justify a posteriori the limited investments already made in this field and the need for further efforts to now take full advantage of these incipient theoretical and observational capabilities.

Although the accumulation of monodirectional observations over a long period of time does allow a documentation of anisotropic effects, such an approach is impractical, unreliable or impossible to implement for the routine analysis of remote sensing data, because of the varying atmospheric conditions as well as the intrinsic evolution of the surface over these periods. Hence the necessity to acquire multidirectional data quasi-simultaneously has been amply demonstrated.

## 3. Conclusion

In summary, great advances have been achieved during the past decades in the simulation of radiation transfer processes, both in the atmosphere and in the geophysical media that constitute terrestrial surfaces (vegetation and soils). More recently, geographically extensive data sets of high-quality multispectral and multidirectional data have become accessible, at spatial resolutions hitherto unavailable. These multiangular data permit a much more reliable and accurate estimation of the BRF fields at the land surface and of the products derived from these quantities, since they provide a much more severe constraint on the inversion process, especially with regards to accounting for atmospheric processes. These developments, in turn, allow the joint characterization of both the surface and the atmosphere at once.

As a result, concrete steps toward bridging the gap between theoretical studies of the anisotropy and practical applications to exploit these features are one of the major recent achievements of the remote sensing community. Last but not least, since both multiangular data and anisotropy models and research algorithms do now exist, the bottlenecks in the exploitation of these data reside in the operational implementation of these research tools and in the systematic processing of the very large data sets being generated. It is expected that current and near-future advances and achievements will both justify a posteriori the intellectual and material investments, which have been made in this area over the last couple of decades, and promote the development and systematic exploitation of both spectral and directional signatures in future instruments. These findings should thus affect the design of sensors as well as ground segments for years to come. The IWMMM-2 conference provided an excellent opportunity to take stock of recent advances and plan scientific and institutional activities for the future.

The papers contained in this special section, together with those included in the special issue of *Remote Sensing Reviews*, provide a broad introduction to the scientific issues related to the anisotropy of the reflected solar radiation fields and describe the state of the art in some aspects of these questions. It is hoped that they will prove a useful stepping stone for future developments. Last but not least, a set of recommendations was adopted and has already been published [*Verstraete and Pinty*, 2000a]. They are also available directly from the ENAMORS web site at http://www.enamors.org/.

## References

Abdou, W. A., M. C. Helmlinger, J. E. Conel, C. J. Bruegge, S. H. Pilorz, J. V. Martonchik, and B. J. Gaitley, Ground measurements of surface BRF and HDRF using PARABOLA 3, *J. Geophys. Res*., this issue.

Bonnefoy, N., O. Brissaud, B. Schmitt, S. Douté, M. Fily, W. Grundy, and P. Rabou, Experimental system for the study of planetary surface materials's BRDF, *Remote Sens. Rev*., in press, 2000.

Brakke, T. W., J. A. Smith, and J. M. Harnden, Bidirectional scattering of light from tree leaves, *Remote Sens. Environ*., *29*, 175–183, 1989.

Chandrasekhar, S., *Radiative Transfer*, Dover, Mineola, N. Y., 1960.

Deering, D. W., and P. Leonoe, A sphere-scanning radiometer for rapid directional measurements of sky and ground radiance, *Remote Sens. Environ*., *19*, 1–24, 1986.

d'Entremont, R. P., C. B. Schaaf, W. Lucht, and A. H. Strahler, Retrieval of red spectral albedo and bidirectional reflectance using AVHRR HRPT and GOES satellite observations of the New England region, *J. Geophys. Res*., *104*, 6229–6239, 1999.

Diner, D. J., et al., The Airborne Multi-angle Imaging Spectroradiometer (AirMISR): Instrument description and first results, *IEEE Trans. Geosci. Remote Sens*., *36*, 1339–1349, 1998a.

Diner, D. J., et al., Multi-angle Imaging Spectroradiometer (MISR) instrument description and experiment overview, *IEEE Trans. Geosci. Remote Sens*., *36*, 1072–1087, 1998b.

Diner, D. J., G. P. Asner, R. Davies, Y. Knyazikhin, J.-P. Muller, A. W. Nolin, B. Pinty, C. B. Schaaf, and J. Stroeve, New directions in earth observing: Scientific applications of multiangle remote sensing. *Bulletin of the American Meteorological Society*, *80*, 2209–2228, 1999.

Flasse, S., M. M. Verstraete, B. Pinty, and C. Bruegge, Modeling Spectralon's bidirectional reflectance for in-flight calibration of Earth-orbiting sensors, in *Proceedings of the SPIE Conference on Recent Advances in Sensors, Radiometric Calibration, and Processing of Remotely Sensed Data*, pp. 100–108, Int. Soc. of Opt. Eng., Bellingham, Wash., 1993.

Galilei, G., *Sidereus Nuncius (Le Messager des Etoiles)*, Editions du Seuil, Paris, 1610.

Gao, F., and Q. Zhu, Process system of measured bidirectional reflectance in Changchun laboratory, *J. Remote Sens*., *1*, 123–130, 1997.

Gobron, N., B. Pinty, M. M. Verstraete, J. V. Martonchik, Y. Knyazikhin, and D. J. Diner, Potential of multiangular spectral measurements to characterize land surfaces: Conceptual approach and exploratory application, *J. Geophys. Res*., *105*, 17,539–17,549, 2000.

Hapke, B., Bidirectional reflectance spectroscopy, 1, Theory, *J. Geophys. Res*., *86*, 3039–3054, 1981.

Hosgood, B., S. Sandmeier, J. Piironen, G. Andreoli, and C. Koechler,

Goniometers, in *Encyclopedia of Electronical and Electronics Engineering*, edited by J. Webster, vol. 8, pp. 424–433, John Wiley, New York, 2000.
Iaquinta, J., and B. Pinty, The radiation field in a multilayered geophysical medium: The ice-water-aerosol-vegetation-soil (IWAVES) model, *J. Geophys. Res.*, *102*, 13,627–13,642, 1997.
Irons, J. R., K. J. Ranson, D. L. Williams, R. R. Irish, and F. G. Huegel, An off-nadir imaging spectroradiometer for terrestrial ecosystem studies, *IEEE Trans. Geosci. Remote Sens.*, *29*, 66–74, 1991.
Jacobowitz, H., H. V. Soule, H. L. Kyle, and the Nimbus ERB Experiment Team, The Earth Radiation Budget (ERB) experiment: An overview, *J. Geophys. Res.*, *89*, 5021–5038, 1984.
Kahn, R., P. Banerjee, D. McDonald, and D. J. Diner, Sensitivity of multiangle imaging to aerosol optical depth and to pure-particle size distribution and composition over ocean, *J. Geophys. Res.*, *103*, 32,195–32,213, 1998.
Kahn, R., P. Banerjee, D. McDonald, and J. Martonchik, Aerosol properties derived from aircraft multiangle imaging over Monterey Bay, *J. Geophys. Res.*, this issue.
Kieffer, H. H., T. Z. Martin, A. R. Peterfreund, and B. M. Jakosky, Thermal and albedo mapping of Mars during the Viking primary mission, *J. Geophys. Res.*, *82*, 4249–4291, 1977.
Kimes, D. S., W. W. Newcomb, C. Tucker, I. Zonneveld, W. Van Wijngaarden, J. de Leeuw, and G. Epema, Directional reflectance factor distributions for cover types of northern Africa in NOAA 7/8 AVHRR bands 1 and 2, *Remote Sens. Environ.*, *18*, 1–19, 1985.
Knyazikhin, Y. V., J. V. Martonchik, D. J. Diner, R. B. Myneni, M. M. Verstraete, B. Pinty, and N. Gobron, Estimation of vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from atmosphere-corrected MISR data, *J. Geophys. Res.*, *103*, 32,239–32,256, 1998.
Kriebel, K. T., Measured spectral bidirectional reflection properties of four vegetated surfaces, *Appl. Opt.*, *17*, 253–259, 1978.
Kuusk, A., and T. Nilson, Testing the directional properties of a forest reflectance model, *J. Geophys. Res.*, this issue.
Leroy, M., Deviation from reciprocity of bidirectional reflectance, *J. Geophys. Res.*, this issue.
Leroy, M., J. L. Deuze, F. M. Bréon, O. Hautecoeur, M. Herman, J. C. Buriez, D. Tanré, S. Bouffies, P. Chazette, and J. L. Roujean, Retrieval of atmospheric properties and surface bidirectional reflectances over land from POLDER/ADEOS, *J. Geophys. Res.*, *102*, 17,023–17,038, 1997.
Li, X., F. Gao, J. Wang, and A. Strahler, A priori knowledge accumulation and its application to linear BRDF model inversion, *J. Geophys. Res.*, this issue.
Lyapustin, A. I., and Y. J. Kaufman, Role of adjacency effect in the remote sensing of aerosol over land, *J. Geophys. Res.*, this issue.
Martonchik, J. V., D. J. Diner, R. A. Kahn, T. P. Ackerman, M. M. Verstraete, B. Pinty, and H. Gordon, Techniques for the retrieval of aerosol properties over land and ocean using multiangle imaging, *IEEE Trans. Geosci. Remote Sens.*, *36*, 1212–1227, 1998a.
Martonchik, J. V., D. J. Diner, B. Pinty, M. M. Verstraete, R. B. Myneni, Y. Knyazikhin, and H. Gordon, Determination of land and ocean reflective, radiative, and biophysical properties using multiangle imaging, *IEEE Trans. Geosci. Remote Sens.*, *36*, 1266–1281, 1998b.
Menenti, M., L. Jia, Z.-L. Li, V. Djepa, J. Wang, M. P. Stoll, Z. B. Su, and M. Rast, Estimation of soil and vegetation temperatures with multiangular thermal infrared observations: IMGRASS, HEIFE, and SGP 1997 experiments, *J. Geophys. Res.*, this issue.
Minnaert, M., The reciprocity principle in lunar photometry, *Astrophys. J.*, *93*, 403–410, 1941.
Myneni, R., and J. Ross, *Photon-Vegetation Interactions*, Springer-Verlag, New York, 1991.
Myneni, R. B., S. Maggion, J. Iaquinta, J. L. Privette, N. Gobron, B. Pinty, D. S. Kimes, M. M. Verstraete, and D. L. Williams, Optical remote sensing of vegetation: Modeling, caveats, and algorithms, *Remote Sens. Environ.*, *51*, 169–188, 1995.
Nandy, P., K. Thome, and S. Biggar, Characterization and field use of a CCD camera system for retrieval of bidirectional reflectance distribution function, *J. Geophys. Res.*, this issue.
North, P. R. J., S. A. Briggs, S. E. Plummer, and J. J. Settle, Retrieval of land surface bidirectional reflectance and aerosol opacity from ATSR-2 multiangle imagery, *IEEE Trans. Geosci. Remote Sens.*, *37*, 526–537, 1999.
Peltoniemi, J., Radiative transfer in stochastically inhomogeneous media, *J. Quant. Spectrosc. Radiat. Transfer*, *50*, 655–671, 1993.
Pinty, B., and D. Ramond, A method for the estimate of broadband directional surface albedo from a geostationary satellite, *J. Clim. Appl. Meteorol.*, *26*, 1709–1722, 1987.
Pinty, B., and M. M. Verstraete, Modeling the scattering of light by homogeneous vegetation in optical remote sensing, *J. Atmos. Sci.*, *55*, 137–150, 1998.
Pinty, B., M. M. Verstraete, and R. E. Dickinson, A physical model of the bidirectional reflectance of vegetation canopies, 2, Inversion and validation, *J. Geophys. Res.*, *95*, 11,767–11,775, 1990.
Pinty, B., F. Roveda, M. M. Verstraete, N. Gobron, Y. Govaerts, J. V. Martonchik, D. J. Diner, and R. A. Kahn, Surface albedo retrieval from Meteosat, 1, Theory, *J. Geophys. Res.*, *105*, 18,099–18,112, 2000a.
Pinty, B., F. Roveda, M. M. Verstraete, N. Gobron, Y. Govaerts, J. V. Martonchik, D. J. Diner, and R. A. Kahn, Surface albedo retrieval from Meteosat, 2, Applications, *J. Geophys. Res.*, *105*, 18,113–18,134, 2000b.
Pinty, B., et al., Radiation transfer model intercomparison (RAMI) exercise, *J. Geophys. Res.*, this issue.
Sandmeier, S. R., and K. I. Itten, A field goniometer system (FIGOS) for acquisition of hyperspectral BRDF data, *IEEE Trans. Geosci. Remote Sens.*, *37*, 978–986, 1999.
Simmer, C., and S. A. Gerstl, Remote sensing of angular characteristics of canopy reflectances, *IEEE Trans. Geosci. Remote Sens.*, *GE-23*, 648–658, 1985.
Verstraete, M. M., and B. Pinty, The 2nd International Workshop on Multiangular Measurements and Models (IWMMM-2), *Earth Obs.*, *12*, 21–24, 2000a.
Verstraete, M. M., and B. Pinty, Environmental information extraction from satellite remote sensing data, in *Inverse Methods in Global Biogeochemical Cycles*, *Geophys. Monogr.*, vol. 114, edited by P. Kasibhatla, M. Heiman, P. Rayner, N. Mahowald, R. G. Prinn, and D. E. Hartley, pp. 125–137, AGU, Washington, D. C., 2000b.
Verstraete, M. M., B. Pinty, and R. E. Dickinson, A physical model of the bidirectional reflectance of vegetation canopies, 1, Theory, *J. Geophys. Res.*, *95*, 11,765–11,775, 1990.
Woessner, P., and B. Hapke, Polarization of light scattered by clover, *Remote Sens. Environ.*, *21*, 243–261, 1987.

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