AN OVERVIEW OF TWO DECADES OF SYSTEMATIC EVALUATIONS OF CANOPY RADIATIVE TRANSFER MODELS

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ABSTRACT:

Space borne observations constitute a highly appropriate source of information to quantify and monitor Earth surface processes. The reliability that may be associated with the outcome of interpretation and assimilation efforts of these data, however, relies heavily on the actual performance of the available modeling tools. Scientists, space agencies and policy makers that want to make use or support the derivation of quantitative information from space observations must therefore have access to indicators describing the quality of the models and algorithms that are used in retrievals. As a formalization of earlier model verification efforts the RAdiation transfer Model Intercomparison (RAMI) initiative was launched in 1999 in an attempt to shed light on the reliability and accuracy of physically-based canopy radiative transfer models simulating the interactions between sunlight and vegetation. This contribution documents the evolution and achievements of RAMI and provides an outlook of challenges and opportunities that still lie ahead.

1. INTRODUCTION

1.1 Purpose of Canopy Radiative Transfer Models

The exploitation of global Earth Observation data hinges more and more on physically-based radiative transfer (RT) models. These models simulate the interactions of solar radiation within a given medium (*e.g.,* clouds, plant canopies) and are used to generate look-up-tables, to train neural networks or to develop parametric formulations that are then embedded in quantitative retrieval algorithms such as those delivering the operational surface products for MODIS, MISR and MERIS, for example. Assessing the quality of RT models is thus essential if accurate and reliable information is to be derived from them. Biases and errors in RT models may also affect the outcome of new mission concept studies, as well as our capacity to quantify Earth surface processes and the reliability of downstream applications that assimilate such remotely sensed data streams. The focus of this contribution lies with the quality of physically-based models that deal with the representation of radiative processes in vegetated environments within the optical domain of the solar spectrum.

Most land surfaces are strongly anisotropic reflectors when observed from optical to thermal-infrared wavelengths. The angular dependence of their reflectance function (termed the bidirectional reflectance distribution function or BRDF) results from 1) the three-dimensional (3-D) nature of terrestrial targets, *i.e.,* the size, shape and spacings of trees in a forest or crops in a field, which produces distinct patterns of shadows that change with the direction of view (and illumination), and 2) the scattering behaviour of individual foliage, wood and soil elements together with their density and orientation with respect to the illumination and viewing directions (Ross, 1981). Physically-based canopy RT models, when used in *forward mode,* are capable to predict the BRDF of a vegetation target on the basis of architectural, spectral and illumination related descriptions. Conversely, when used in *inverse mode,* physically-based canopy RT models may, in principle, retrieve the structural and spectral canopy properties that gave rise to the directionally (and spectrally) varying reflectance observations. Knowledge of the BRDF of terrestrial surfaces is necessary for 1) the accurate retrieval of surface albedo (via a hemispherical integral of the BRDF), 2) the specification of the lower boundary condition in atmospheric corrections and for the estimation of cloud and aerosol properties (*e.g.*, Hu et al., 1999), and 3) the retrieval of sub-pixel surface characteristics (*e.g.*, Widlowski et al, 2004).

1.2 Types of Canopy RT Models

A large variety of physically-based canopy RT models have been developed over the past five decades or so. According to Qin and Liang (2000) the purpose of modelling the radiation distribution in the 1960s was primarily to estimate the canopy photosynthetic rate; in the 1970s the focus was on the calculation of surface albedo and net radiation for energy-balance and micro-meteorological research; in the 1980s and 90s canopy RT modelling was driven by the need to accurately describe the angular distribution of the reflected radiation. In the last decade or so the emphasis was placed on efficient representations of radiative processes in increasingly complex 3-D canopy architectures and the retrieval of sub-pixel surface structure information. In a landmark paper, Goel (1987) grouped canopy RT models into 4 different categories:

1. *Geometrical models,* that assume the canopy to be made up of a ground surface (of known reflective properties) with geometrical objects of prescribed shapes and dimensions (*e.g.*, spheres, ellipsoids, cones) and optical properties (reflectance, transmittance and absorption) placed on it in a defined manner (random or clustered) to represent the spatial distribution of tree crowns. The canopy reflectance is the weighted sum of four components: sunlit and shaded crown, and sunlit and shaded background. These models are best suited for small view and sun zenith angles and for sparse canopies with high leaf densities, where the effects of mutual

shading and multiple scattering are minimal (for a recent review see Chen et al., 2000),

2. *Turbid medium models* assume the canopy to be horizontally uniform and to be composed of plane parallel layers that are filled with dimensionless scatterers randomly distributed throughout the available volume and oriented in accordance with a given leaf normal distribution function. These models are best used for dense canopies with small vegetation elements (e.g., mature agricultural crops) and relatively inappropriate for open forest canopies (for a recent review see Qin and Liang, 2000),
3. *Hybrid models* represent vegetation canopies using both of the above approaches. Typically they assume that the interior of geometric objects (representing tree crowns) are uniformly filled with a 'gas' of point-like oriented scatterers of specified orientations and spectral properties. These models can be used to represent both sparse and dense canopies. However, multiple scattering is not rigorously treated and the models are often limited by one single type of crown geometries (Goel and Thompson, 2000),
4. *Computer simulation models* can represent arbitrarily complex canopy architectures using constructive solid geometry or similar computer graphics techniques. All facets of a geometric object (needle, trunk, leaf, twig, etc.) can be tagged with spectral and directional scattering properties. In ray-tracing models a Monte Carlo procedure is then used to determine the location and direction of incident light beams; the type of interaction, i.e., reflection, absorption or transmission, that such rays undergo when intersecting with an object, and in the case of a scattering event also the direction of further propagation. To compute the BRDF of a plant canopy one keeps shooting rays into the scene, follows them through their various interactions until they exit the scene and end up in certain small solid angles around predefined viewing directions. Due to the large number of photons needed for reliable statistics this type of RT model tends to be relative computer intensive (Disney *et al*., 2000).

1.3 Early Canopy RT Model Validation Efforts

With the availability of a large set of canopy RT models in the 1980s the question arose as to how one could assess their quality and reliability. Of primary interest here was the validation of 'simple' canopy RT models that – because of fast execution times and small numbers of parameters – were likely to play a role in the operational retrieval of quantitative surface information from optical remote sensing data. So far the verification of canopy RT models in forward mode has always relied on comparison strategies with respect to one or more of the following types of reference data:

1. *Air or space borne observations*, that were acquired over specific test sites and subsequently corrected on the basis of concurrently measured atmospheric properties, are used as a means to evaluate the simulations of canopy RT models based on structural, spectral and illumination related information pertaining to the same canopy target and (ideally also) the same time of acquisition as the space or air-borne observations, *e.g*., Schaaf et al., (1994), Soffer et al., (1995),
2. *In-situ or laboratory measurements*, that were acquired with sensors – typically supported by a tram system or goniometer structure – looking down at the canopy target, are used as a means to evaluate the quality of RT model simulations based on the spectral, structural and illumination characteristics of the canopy target (ideally acquired at the same time as the BRDF measurements), *e.g.*, Franklin and Duncan (1992), Strahler and Liang (1994),
3. *Canopy RT model simulations*, that were (ideally) generated by sophisticated Monte Carlo RT models on the basis of detailed 3-D description of the canopy architecture, are used to assess the output of simpler canopy RT models making use of the same canopy-target characteristics (albeit adapted to their need for input parameter specifications), *e.g*., Goel and Kuusk, (1992), Liang and Strahler (1992).

In some cases the quality of canopy RT models is also addressed in inverse mode, that is, by looking at how well a model allows to retrieve certain biophysical parameters on the basis of measured BRDF data. Such an approach is, however, more suited to comment on the numerical inversion procedure than the physical correctness of the canopy RT model. Pinty and Verstraete (1992) advocated the use of both forward and inverse modes. Their idea was to acquire detailed descriptions of the structural and spectral properties of a canopy target and to feed these into an RT model to simulate BRDF patterns of the target under a specific set of illumination and observation conditions. These forward simulations can then be compared to actual observations previously acquired over the target in question at the same viewing and illumination geometries. The RT model can then be inverted against the measured and/or simulated data sets and the output of this operation compared to the canopy characteristics that had been measured initially and used as input to the forward simulations.

Unfortunately, the verification of canopy RT models on the basis of actual measurements has always been hampered by the lack of accurate, comprehensive and self-consistent field data sets, e.g., Strahler, (1997). This situation has not changed much since the 1990s and even the use of artificial targets in laboratory environments suffer from the same difficulties, that is, instruments and methods that allow for a highly precise characterisation of 1) the light environment surrounding the target, 2) the position, orientation, size and shape of all the physical components making up the target, 3) the magnitude, directionality and spatial variation of scattering properties of all canopy and background elements, and 4) the detector location, foreoptics (if present) and spectral response functions. None of these issues are present, however, when canopy RT models are compared using virtual plant environments.

2. SYSTEMATIC RT MODEL EVALUATION

2.1 Strategy

The RAdiative transfer Model Intercomparison (RAMI) initiative was launched in the late 1990s to provide a platform for the systematic evaluation of physically-based canopy RT models (Pinty et al., 2001). Of primary relevance was the need to eliminate sources of uncertainty that affect the outcome of verification efforts but that do not pertain to the quality of the canopy RT models themselves. At the time, this strategy precluded the evaluation of RT model simulations on the basis of laboratory, in-situ, air and space-borne measurements. This was primarily due to difficulties associated with the acquisition of accurate and spatially detailed descriptions of 1) plant architectural properties, like foliage orientation and density, wood distribution and branching patterns, *etc*., 2) directional scattering characteristics of plant and background constituents suitable for inclusion into canopy RT models, and 3) directionally resolved solar radiation fields, that are all needed to guarantee a faithful reproduction of the actual 3D target (at the time of observation) within the RT models. The evaluation of models through comparison with observation requires also access to information regarding the angular and spectral resolution of the measuring devices, as well as, the uncertainties associated with eventual up-scaling and correction techniques (*e.g*., atmosphere, adjacency effect, point spread function).

To avoid these issues RAMI evaluates models under perfectly controlled experimental conditions, *i.e.*, all structural, spectral, illumination and observation related characteristics are known without ambiguity. Deviations between RT simulations can thus only be due to – explicit or implicit – assumptions and shortcuts entering model-specific implementations of the radiative transfer equation. This mathematical foundation of physically-based canopy RT models allows furthermore to verify model predictions of arbitrary sub-components of the total (absorbed, transmitted and reflected) radiation, *i.e*., quantities that could not be measured in reality, and to check that the model simulations remain consistent with physical reasoning even if the environmental conditions deviate from those encountered in nature. The latter two aspects are crucial since they allow – in a few select cases – to assess RT model performance in absolute terms, *i.e*., against analytical solutions of directionally-varying or hemispherically-integrated radiative quantities and to increase the confidence in model simulations relating to new species/biomes and phenological conditions, respectively.

As a general rule, RT model comparison activities have to deal with the fact that the true solution is not known. RAMI deals with this issue trough a three-pronged evaluation approach based on:

1. *model consistency tests*: that verify the internal consistency of RT models, for example, with respect to energy conservation, or, when radiative quantities are modelled that vary in a pre-determined manner across spectral bands, with background brightness, or, with changing illumination conditions,
2. *absolute performance tests*: that compare the magnitude of model simulated radiative quantities against those predicted by analytical solutions (which can be derived for some types of canopy targets having certain well defined characteristics),
3. *relative performance tests*: that compare simulations of different models in the light of knowledge obtained from 1) the above model consistency and absolute performance tests, and 2) an analysis of the shortcuts and assumptions contained in their respective implementations/formulations of the RT equation.

In order to obtain viable assessments of the trends, patterns and perhaps also biases in the performance of canopy RT models it is imperative to compare model simulations over an as large as possible set of structural, spectral and illumination related conditions. Such an approach is also conform with the paradigm stating that computer simulation models can never be completely validated and that efforts should focus instead on the *invalidation* of such tools (Oreskes, 1994). In other words, a model may yield the correct solution but for the wrong reasons, and therefore nothing can be said with absolute certainty about the reliability/accuracy of its predictions when applied to cases that were not actually tested beforehand.

2.2 Outcome

As an open-access and community-driven activity RAMI operates in successive phases each one aiming at re-assessing the capability, performance and agreement of the latest generation of RT models (http://rami-benchmark.ec.europa.eu/). RAMI-1 involved a small yet somewhat abstract set of canopy scenarios specifically designed to suit both 1-D and 3-D canopy RT models. The results of RAMI-1 underlined the need for model verification since many of the submitted simulations differed quite substantially between the 8 participating models (Pinty et al., 2001). In some cases, the cause of these discrepancies may have been due to operator errors or software bugs (some of which were identified during the data analysis stage). RAMI-2, therefore proposed a rerun of all earlier experiments together with two new test cases addressing issues of topography and spatial resolution. This time 13 canopy RT models participated and their agreement was much better especially for the homogeneous canopies (Pinty et al., 2004a). Expanding the set of experiments yet again, RAMI-3 concluded with an unprecedented level of agreement amid its 18 participating RT models and this for both the homogeneous and heterogeneous vegetation canopies (Widlowski et al., 2007).

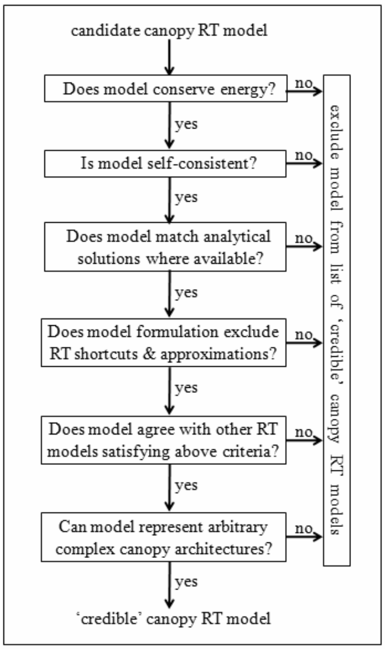

Figure 1. The selection process of 'credible' canopy RT models.

Using the process outlined in Figure 1 it was possible to identify six 3-D Monte Carlo models from among the RAMI-3 participants that differed by ~1% over several thousands of BRF and flux simulations. A 'surrogate truth' reference data set was then generated on the basis of the simulations of these 'credible' canopy RT models (Widlowski et al, 2008). This, in turn, lead to the development of the RAMI Online Model Checker (ROMC), a web-based benchmarking facility providing quasi-real time statistics of the differences existing between the simulations of a user's canopy RT model and the RAMI-3 "surrogate truth" data set (http://romc.jrc..ec.europa.eu/).

Currently, over 30 models have been registered in the ROMC and several scientific publications use ROMC-generated graphs to provide independent and traceable proof of the quality of a canopy RT model. Of particular interest here is the fact that the ROMC provides an indication of model skill, defined as:

$$Skill = 100 \cdot \frac{(1+R)^4}{\left(\frac{\bar{x}_{\mathrm{mod}}}{\bar{x}_{ref}} + \frac{\bar{x}_{ref}}{\bar{x}_{\mathrm{mod}}}\right)^2 \left(\frac{\sigma_{\mathrm{mod}}}{\sigma_{ref}} + \frac{\sigma_{ref}}{\sigma_{\mathrm{mod}}}\right)^2}$$

where R is the correlation coefficient, $\bar{x}$ is the mean value, and σ is the standard deviation of N simulations provided by the candidate model ($_{\mathrm{mod}}$) and ROMC reference data set ($_{ref}$), respectively. The skill metric depends on N and reaches 100 for a perfect match with the ROMC reference data.

With the availability of the ROMC it became feasible for RAMI to address new issues. As such, RAMI proposed to utilize 'credible' 3D Monte Carlo models to provide benchmark solutions against which the shortwave radiative flux formulations in the land surface schemes of SVATs and GCMs could be evaluated. This proposal was endorsed during the first Pan-GEWEX meeting in late 2006 and led to the launch of the RAMI4PILPS suite of experiments in 2008 (where 10 modelling groups from around the world participated). In parallel, the fourth phase of RAMI was launched in 2009 with a completely new set of test cases, some of which, were based on detailed field inventories and exhaustive in-situ and laboratory measurements of actual forest stands. In addition, RAMI-IV expanded also the range of model simulations beyond that of passive optical space sensors to include also waveform LiDAR instruments and devices typically used during *in-situ* validation campaigns of remotely sensed products. Figure 2 provides an overview of the evolution of the RAMI activity with depictions of the canopy architecture of various test cases.

The strategy of RAMI benefited 1) model developers, who were able to debug their software codes and receive indications as to where future development efforts were most needed, 2) users of canopy RT models, who can now make better choices regarding the selection of canopy RT models, and 3) the RT modelling community which, through its continuing support and active encouragement of RAMI, was able to increase its visibility and maturity. About 60–65% of all currently existing canopy RT models have voluntarily participated in the RAMI initiative.

By its very nature, RAMI and the I3RC (its sister activity dealing with clouds: http://i3rc.gsfc.nasa.gov/), are both dynamic and evolving activities. As a result, the benchmarks, reference data sets and evaluations issued by the RAMI process must be considered snapshots describing the state of the art at the time of the exercise, and not as a final, absolute and definitive judgment on the worthiness and performance of any particular model. In fact, it is through its systematic approach to RT model verification that RAMI contributes to the quality assurance of space derived information.

3. OPPORTUNITIES AND CHALLENGES

3.1 Expanding the scope of RAMI

Through its systematic benchmarking efforts the various phases of RAMI have allowed to 1) identify 'credible' canopy RT models, 2) generated 'surrogate truth' reference data sets, 3) automate the model verification process via quasi-real time web-based benchmarking facilities, and 4) gradually increased the complexity and realism of the simulated plant environments. This allows RAMI to envisage the expansion into new thematic areas (soils, coastal zones, urban areas), spectral regions (thermal, SAR), and specific instruments (both space and in-situ based). Similarly, the benchmarking of RT model simulations under truly 'controlled experimental conditions' – such as are nowadays achievable in reference laboratory facilities – should be addressed in the future. This would both strengthen the credibility of the 3-D Monte Carlo models that were used to generate the ROMC reference dataset, and also enable the set-up of a traceable quality assurance system to relate the performance of simpler canopy RT models – via the above 3-D Monte Carlo models – to a series of absolute reference standards of the real (as opposed to virtual) world.

Ultimately, however, it is the accuracy of the retrieved state variable values that counts in many RT model applications. During RAMI-1 it had already been proposed to address the inversion of RT models against predefined sets of spectral and angular observations, similar to those provided by the current fleet of space borne sensors. In this way, it was hoped, that in this manner the impact of the various structural and radiative canopy model assumptions could be thoroughly assessed since the uncertainties of the available surface BRFs were known *a priori*. This approach had to be abandoned though due to a sever lack of participants. Now, with the identification of 'credible' canopy RT models new sensor-specific (top-of-

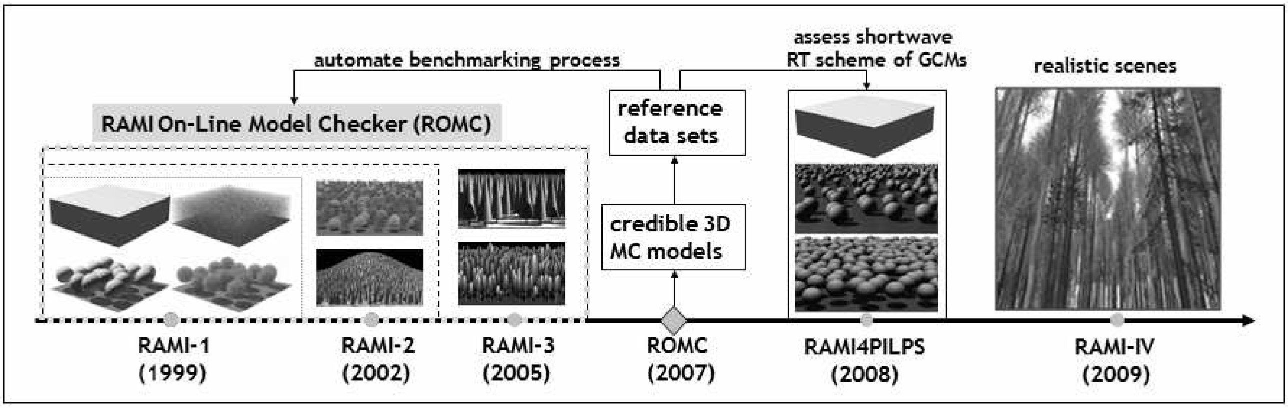

Figure 2. Evolution of the RAMI initiative.

canopy or top-of-atmosphere) data sets could be generated to revisit the model inversion issue once again.

3.2 Revisiting model evaluations with measurements

RAMI was conceived as an open-access community exercise and will continue to pursue that direction. As such its goal is to move forward in a manner that addresses the needs of the majority of RT model developers and users. With every model having its own implementation of 'reality' it has become necessary to provide as detailed descriptions as possible of increasingly realistic canopy architectures. During the fourth phase of RAMI explicit 3-D tree generations (accounting for the position and orientation of every single leaf, twig and branch) were generated on the basis of detailed forest inventory data and L-system based or interactive tree generation software tools, *e.g.*, Streit (1992) and Lintermann and Deussen (1999). Such tree representations, although realistic looking by design, are not exact copies of the trees actually present at the test sites. At best the RAMI-IV canopies agree in terms of the location of the overstorey trees and their outer dimensions and leaf content with what was present at the actual stands. Foliage orientation, distribution and colour, as well as, the branching patterns and densities in trees, however, are in all likelihood different. The same is also true for the directionality of scattering interactions between the sunlight and foliage, branch or background components, or, the directionality of the incident radiation. The apparent realism of some of the RAMI-IV test cases is thus at best an example of the capabilities of some of the 3-D canopy RT models but not proof of our abilities to generate structurally and radiatively accurate replicas of existing forest stands (that are suitable for the validation of canopy RT models).

The fourth phase of RAMI has shown that 3-D canopy RT models are capable of representing forest stands over 1 hectare or more where every single leaf/needle is accounted for. The time thus may have come to revisit our capabilities in building spectrally and architecturally accurate replicas of actual forest sites. Earlier efforts in this direction, like the work of Martens et al, (1991) and those associated with large field campaigns like BOREAS (Sellers et al., 1997) and/or the Kalahari transect (Scholes et al., 2004), were not providing sufficient structural and spectral details to allow for an unambiguous verification of RT model simulations against remotely sensed observations over actual test sites. Structural clumping – occurring at various scales within the canopy – may have a significant impact on the BRDF of a vegetation target and thus a very fine description of plant architectures are needed for model verification purposes. Recently, Coté et al, (2009) showed that terrestrial laser scans could be used to generate faithfull reconstructions of individual trees that – when ingested into state-of-the-art 3-D Monte Carlo ray-tracing models – yielded accurate simulation results whether for *in-situ* observations, like those acquired by hemispherical photography, or for medium spatial resolution optical space-borne sensors. In addition, upward pointing field goniometers now exist that can be deployed to provide multi-spectral characterizations of the incident radiation field at a given test site at the time of satellite overpass. What is still needed perhaps are suitable protocols (and instruments) allowing to characterize the scattering directionality of foliage, wood and background material (as well as their spatial variability) in a manner that is both efficient and independent of the illumination conditions at the target site.

One way top evaluate the fidelity of such 'virtual validation sites' would be to use credible canopy RT models (having known uncertainties) to simulate atmospherically-corrected air or space borne observations acquired over the same canopy targets under the *proviso* that both the characteristics of the remote sensor(s) and the directionality of the incident solar radiation at the time of overpass were accurately known. In this way canopy RT models could actively contribute toward the systematic validation of remote sensing data, products, and field protocols as promoted by the Committee on Earth Observation Satellites (CEOS).

4. CONCLUSION

Through a decade of systematic benchmarking efforts RAMI allowed to 1) identify a series of 'credible' canopy RT models, 2) generated 'community' reference data sets, 3) establish web-based benchmarking facilities, and 4) increase the realism of the simulated plant environments. A variety of thematic domains, spectral regions and individual sensors could all benefit from being included in future RAMI activities. Due to rapid improvements in space sensors and physically-based retrieval algorithms systematic RT model validation activities are essential to document whether the quality of space derived information is improving. Here, a more proactive support from space agencies, scientific bodies and policy makers may help, for example, by making the provision of funding conditional on quality certificates that testify as to the aptitude of models and/or algorithms contained in a given proposal. Automated web-based benchmarking facilities, like the ROMC, can already now deliver such quality assurance support.

REFERENCES

Chen, J. M., Nilson, T. and Strahler, A., 2000, Recent Advances in Geometrical Optical Modelling and its Application, *Remote Sensing Reviews*, 18, 227-262.

Coté, J-F., Widlowski, J-L., Fournier, R. A., Verstraete, M. M., 2009, The structural and radiative consistency of three-dimensional tree reconstructions from terrestrial Lidar, *Remote Sensing of Environment*, 113, pp. 1067-1081.

Disney, M. I., Lewis, P. E., North, P. R. J., 2000, Monte Carlo Ray tRacing in Optical Canopy Reflectance Modelling, *Remote Sensing Reviews*, 18, 163-196.

Franklin, J., and Duncan, J., 1992, Testing the Li-Strahler Four-component Canopy Reflectance Model in the Hapex-sahel Shrub Savanna Sites Using Ground Reflectance Data, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium*, pp. 200-202.

Goel, N., 1988, Models of Vegetation Canopy Reflectance and their use in Estimation of biophysical parameters from reflectance data, *Remote Sensing Reviews*, 4(1), 1-222.

Goel, N., and Kuusk, A., 1992, Evaluation of One Dimensional Analytical Models For Vegetation Canopies, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium*, pp. 505 - 505.

Goel, N., and Thompson, R., 2000, A snapshot of canopy reflectance models and a universal model for the radiation regime, *Remote Sensing Reviews*, 18, 197-225.

Hu, B. X., Lucht, W. and Strahler, A. H., 1999, The interrelationship of atmospheric correction of reflectances and surface BRDF retrieval: A sensitivity study, *IEEE Transactions on Geoscience and Remote Sensing*, 36, 724-738.

Liang, S., and Strahler, A., 1992, An Explicit Canopy BRDF Model and Inversion, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium*, Vol. 2, pp. 1487 - 1489.

Lintermann, B. and Deussen, O., 1999, Interactive Modelling of Plants, *IEEE Computer Graphics and Applications*, 19(1), pp. 2-11.

Martens, S. N., Ustin, S. L., Norman, J. M., 1991, Measurements of tree canopy architectures, *International Journal of Remote Sensing*, 12(7), pp. 1525-1545.

Oreskes, N. K., 1994, Verification, validation and confirmation of numerical models in the earth sciences. Science, 263, 641-646.

Pinty, B., and Verstraete, M. M., 1992, On the Design and Validation of Surface Bidirectional Reflectance and Albedo Models, *Remote Sensing of Environment*, 41, pp. 155-167.

Pinty, B., Gobron, N., Widlowski, J. -L., Gerstl, S. A. W., Verstraete, M. M., Antunes, M., Bacour, C., Gascon, F., Gastellu, J-P., Goel, N., Jacquemoud, S., North, P. R. J., Qin, W., Thompson, R., 2001, Radiation Transfer Model Intercomparison (RAMI) exercise. *Journal of Geophysical Research*, 106, pp. 11,937–11,956.

Pinty, B., Widlowski, J.-L., Taberner, M., Gobron, N., Verstraete, M. M., Disney, M., Gascon, F., Gastellu, J.-P., Jiang, L., Kuusk, A., Lewis, P., Li, X., Ni-Meister, W., Nilson, T., North, P., Qin, W., Su, L., Tang, S., Thompson, R., Verhoef, W., Wang, H., Wang, J., Yan, G., and Zang, H., 2004a. Radiation Transfer Model Intercomparison (RAMI) Exercise: Results from the Second Phase. *Journal of Geophysical Research*, 109, D06210.1-D06210.19, doi:10.1029/2003JD004252.

Pinty, B., N. Gobron, J.-L. Widlowski, T. Lavergne, and M. M. Verstraete, 2004b, Synergy between 1-D and 3-D radiation transfer models to retrieve vegetation canopy properties from remote sensing data, *Journal of Geophysical Research*, 109, D21205, doi:10.1029/2004JD005214.

Qin, W. and Liang, S., 2000, Plane-parallel Canopy Radiation Transfer Modeling: Recent Advances and Future Directions, *Remote Sensing Review*, 18, 281-305.

Ross, J., 1981, *The Radiation Regime and Architecture of Plant Stands*. Kluwer Academic Publishers, Boston, pp. 391.

Schaaf, C., Li, X., and Strahler, A., 1994, Validation of Canopy Bidirectional Reflectance Models with Asas Imagery of a Spruce Forest in Maine, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium: Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation*, Vol. 3, pp. 1832-1834, doi:10.1109/IGARSS.1994.399581.

Scholes, R. J., Frost, P. G. H., and Tian, Y., 2004, Canopy structure in Savannas along a moisture gradient on Kalahari sands, *Global Change Biology*, 10, 292–302.

Sellers, P. J., et al., 1997, BOREAS in 1997: Experiment overview, scientific results and future directions, *Journal of Geophysical Research*, 102, 28,731– 28,770.

Soffer, R. J., Miller, J. R., Wanner, W., and Strahler, A., 1995, Winter boreal forest canopy BRF results: comparison between airborne data, laboratory simulations and geometric-optical model data, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium:Quantitative Remote Sensing for Science and Applications*, Vol. 1, pp. 800 - 802, doi:10.1109/IGARSS.1995.520589.

Strahler, A. and Liang, S., 1994. Comparison of Radiative Transfer Models of Vegetation Canopies with Laboratory Measurements, In: *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium: Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation*, Vol. 4, doi:10.1109/IGARSS.1994.399733, pp. 2345-2347,.

Strahler, A., 1997, Vegetation canopy reflectance modeling – recent developments and remote sensing perspectives. *Remote Sensing Reviews*, 15:1, 179-194.

Streit, C., 1992, Graphtal user manual. Berne, Switzerland: University of Berne, SIG Computer Graphics.

Widlowski, J.-L., Pinty B., Gobron, N., Verstraete, M. M., Diner, D. J., Davis, A. B., (2004), Canopy Structure parameters derived from multi-angular remote sensing data for terrestrial carbon studies, *Climatic Change*, 67, 403-415.

Widlowski J.-L., Taberner M., Pinty B., Bruniquel-Pinel, V., Disney, M., Fernandes, R., Gastellu-Etchegorry, J-P., Gobron, N., Kuusk, A., Lavergne, T., Leblanc, S., Lewis, P. E., Martin, E., Mottuse, M., North, P. R. J., Qin, W., Robustelli, M., Rochdi, N., Ruiloba, R., Soler, C., Thompson, R., Verhoef, W., Verstraete, M. M., Xie, D., 2007. The Third Radiation Transfer Model Intercomparison (RAMI) Exercise: Documenting Progress in Canopy Reflectance Modelling. *Journal of Geophysical Research.*, 112, doi:10.1029/2006JD007821.

Widlowski J.-L., Robustelli, M., Disney, M., Gastellu-Etchegorry, J-P., Lavergne, T., Lewis, P., North, P. R. J., Pinty, B., Thompson, R., and Verstraete, M. M., 2008. The RAMI On-line Model Checker (ROMC) : A web-based benchmarking facility for canopy reflectance models. *Remote Sensing of Environment*, 112, doi:10.1016/j.rse.2007.07.016, pp. 1144-1150.

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