

Evaluation of a 3-D Radiative Transfer Model against Goniometer Measurements on an Artificial Target

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Abstract This paper focuses on the evaluation of a new model of radiation transfer in heterogeneous three-dimensional media, based on the Monte Carlo ray tracing technique. This model is conceived as a virtual laboratory, where the targets can be individually characterized, and where the interactions between the radiation field and these targets can be explicitly controlled. The model can be used to generate reflectances as well as absorption profiles for arbitrarily complex three-dimensional targets, such as an individual plant leaf or a complete forest canopy. The model performance is evaluated by comparing model simulations with laboratory measurements obtained over an artificial target. Observations have been carried out by the Advanced Techniques unit of the Space Applications Institute in the European goniometer (EGO) facility. Comparisons with laboratory measurements demonstrate the capability of our model to reproduce the actual observed reflectance factors of a fully documented target, and even to characterize the performance of this laboratory.

Key words Monte Carlo, Ray tracing, Goniometer measurements, Radiative transfer modeling

1 INTRODUCTION

The full exploitation and the proper evaluation of existing and future space borne sensors require the development of high performance tools and techniques to extract reliable and accurate information from the data gathered by these platforms. In turn, the quantitative interpretation of remote sensing data must be based on a clear understanding of the radiative processes which control the measurements, at the spatial scales and resolutions sampled by the observing instrument. In the case of optical sensors observing land surfaces, the radiation received by the instrument may have interacted with one or more geophysical media, namely the atmosphere, the vegetation canopy when one is present, and the underlying surface. The interpretation of these data is further complicated by the spatial heterogeneity of terrestrial surfaces and the variability of the atmosphere in time. One-dimensional vertical models of radiation transfer have been successfully applied to the description of the broad patterns of light absorption and scattering in reasonably layered geophysical media such as the at-

mosphere, soils and fully developed vegetation canopies. However, in many situations, the heterogeneity of the scene is such that the proper interpretation of the measurements requires more advanced models.

The Raytran model described in the following section represents a new attempt to simulate the transfer of radiation in complex three-dimensional scenes. The Monte Carlo ray tracing technique and its implementation in this model assumes that the application falls within the domain of applicability of geometric optics. This model is independent of scale, provided the size of the simulated objects is much larger than the wavelength of the radiation. The scene of interest can be described completely independently from the problem of radiation transfer, and the physics of the interactions between the radiation and the objects in the scene is described through the selection of appropriate physical mechanisms and the assignment of the corresponding optical properties of the objects.

The accuracy of this model as well as the validity of the assumptions can be evaluated by comparison with comprehensive reflectance measurements, pro-

vided exhaustive descriptions of the optical and structural properties of the target are also available. Unfortunately, such comprehensive data sets are rare, principally due to the difficulty of measuring all of the target's optical and structural properties simultaneously. One way to avoid these difficulties is to evaluate the model against an artificial target which can be fully characterized in the laboratory. This paper describes such an approach.

2 DESCRIPTION OF THE MODEL

The target structural properties are represented by a set of geometrical solid objects. The radiative transfer is solved on a ray-by-ray basis using Monte Carlo ray tracing techniques, generating rays in the forward direction, i.e., from the energy source to the scene. In the present case, Monte Carlo procedure are used to generate incident radiation, to define the type of interaction when ray-object interactions occur, and to compute the scattering angles. Basically, three main preliminary steps are necessary to set up an experiment with this model. The first one consists in creating the target and assigning an interaction model to each object. The description of the scene is therefore completely independent of computation of the ray trajectories, which is a major advantage of this approach. Energy sources from which the rays are generated need next to be characterized. Finally, one has to perform measurements by defining filters to extract relevant information from ray paths. The computation of the radiation transfer in the scene is itself composed of 4 main steps: (1) Generation of the rays; (2) Localization of the ray-object intersection; (3) Determination of the type of interaction and the scattering direction; (4) Extraction of relevant information from the ray paths. Steps 1 to 4 are executed for all generated rays, while steps 2 and 3 are repeated until rays are either absorbed or leave the outer boundary of the modeled scene. The computed ray paths include the exact position of each collision point with the associated intercepted object identification and type of interaction. It is therefore possible to extract very easily any kind of statistics from these trajectories, such as the mean free path distribution

or the vertical extinction profile in the canopy. Different measurements may be defined simultaneously. Basically, two types of physical values or measurements are extracted from the ray paths: the radiation regime in the scene and the bidirectional reflectance factor (BRF). For comparisons with observations, it is desirable to reproduce as faithfully as possible the actual measurement conditions, such as the detector aperture A_r and field-of-view ψ . We thus simulate the front-of-detector BRF g_i of a typical instrument located at a given distance R from the center of the target as

$$g_i(\theta_0, \phi_0, \theta_i, \phi_i) = \frac{\pi N_{A_r, i}^\psi R^2}{NA_r \cos \theta_i} \quad (1)$$

where $N_{A_r, i}^\psi$ refers to the number of rays hitting the detector of area A_r located in R , Q_i, ϕ_i with a central direction included in the cone defined by the detector field-of-view. A detail description of this model can be found elsewhere^[1].

3 COMPARISONS WITH GONIOMETER MEASUREMENTS

The "verification" of a numerical model (the establishment of its truth), or the "validation" of a natural system (its legitimacy) is extremely difficult, if not impossible to achieve^[2]. The adequacy of a model to represent specific conditions can however be confirmed by comparisons with laboratory tests. These direct comparisons simply demonstrate that a model matches observations over a particular range of conditions under consideration. Further, the observations require the precise knowledge of the position, size and shape of each element of the scene as well as their optical properties, simultaneously with the values of the bidirectional reflectance of the scene and the lighting conditions. Since natural target exhibits extremely complex structure that may be difficult to measure and to represent, comparisons have been done with observations of a man-made target.

Bidirectional reflectance factor measurements for an artificial target have been acquired in the laboratory to evaluate the performance of the model. These

observations have been carried out by the Advanced Techniques unit of the Space Applications Institute in the new goniometer facility. The European Goniometer laboratory (EGO) is a double T angle iron structure composed of a platform that is to receive the sample target, and two rotating arcs, a quarter circle for the light source and a semi-circle for a detector^[3]. The system allows the independent positioning of the light source and the detector anywhere on a 2 m radius hemisphere around the target and thereby measurement of bidirectional reflectances (Fig. 1).

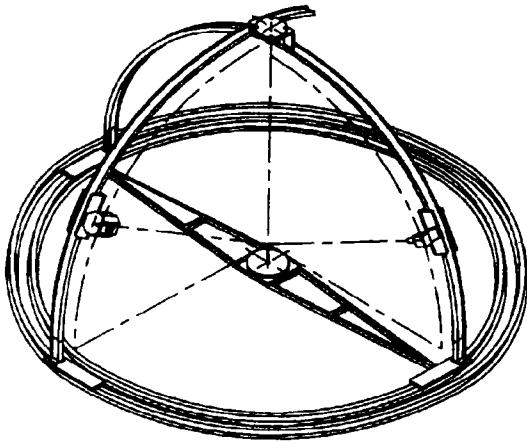


Fig. 1 Perspective view of the European Goniometer facility

The specifications of the artificial target must be carefully thought out if the latter is to be used to evaluate the model. As previously explained, the structural properties of a natural scene would be difficult to characterize. Therefore, for the purpose of this evaluation, we worked on simple artificial surfaces, whose geometrical and optical properties can be characterized *a priori* in the laboratory and represented explicitly within the Raytran simulations. Specifically, the choice of the target has been motivated by the following requirements: (1) the target should be easy to manufacture; (2) the geometry of the rough surface should be relatively easy to characterize and simple to represent in Raytran; (3) the bidirectional reflectance anisotropy of the target must be clearly observed; and finally (4) the optical pro-

perties of the material should be known or independently measurable. The target has accordingly been designed as a 25×25 cm side matrix or lattice of cubes over a plane surface made of duralumin. To ensure uniformity of properties, the rows of cubes have actually been carved out of a thick plate (Fig. 2). All vertical and horizontal exposed faces have been sanded. The shape factor, i. e., the ratio between the sides S_c of the cubes and the distance d_c between the cubes have been chosen to enhance the target structural effects and are such that ($S_c = (5/3) d_c$) with $d_c \approx 2$ mm and $S_c \approx 3.3$ mm.

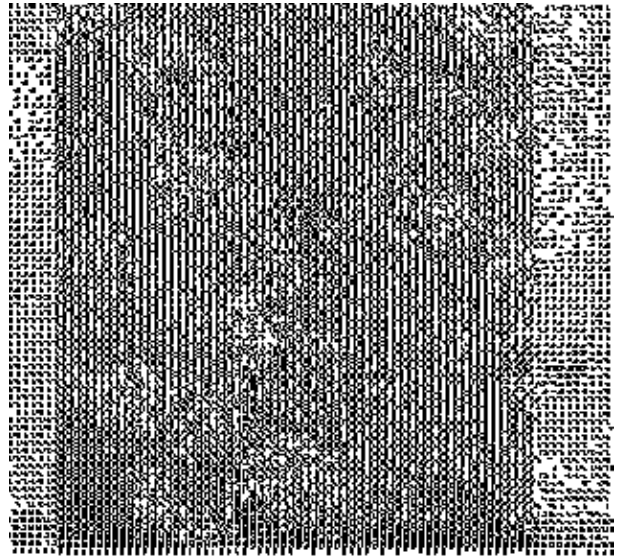


Fig. 2 Sanded duralumin target plate for comparison with goniometer measurement; Detail of the lattice of 2.5 mm side cubes

The lighting source is a compact self-contained He-Ne laser emitting at $0.6328 \mu\text{m}$. A beam expander provides a beam with a usable diameter of 48 mm. The detector is a simple silicon photo-diode with an active area of 100 mm^2 . To control the field-of-view of the detector, a 100 mm long tube with a diameter of 50 mm is placed in front of it, ensuring a field-of-view of 28° . Illumination zenith angles are 3° , 26° and 56° and every 15° with respect to the target rows in azimuth. Observations have been performed every 10° in zenith and 15° in azimuth. A Spectralon panel lit with an illumination zenith angle of 3° was used for the calibration of the data in order to evaluate

the reflectance factor.

Modeling the bidirectional reflectance of the lattice target first requires the characterization of the bidirectional properties of the cube sides. For that purpose, we prepared a third target consisting simply of a flat panel of duralumin with the same finishing process. The Torrance and Sparrow model^[4] has been used to characterize the BRDF of this plate. This model has been specifically designed to simulate the reflectance of rough surfaces composed of randomly distributed mirror-like micro-facets. The parameters of the Torrance-Sparrow model have been retrieved by inversion against the reflectance factor of the reference target.

The structural properties of the lattice target are simulated with boxes laid out on a square base within Raytran. The laser beam is simulated with a circular energy source whose normal is oriented through the center of the target. The emitted rays are parallel to that normal. The origin of the rays are uniformly distributed in the energy source area. The scene is lit with 200×10^6 rays which insures an estimated error of the simulated reflectance better than 0.5%. The reflectance factor is computed with equation (1) which accounts for the aperture and field-of-view of the detector.

Fig. 3 compares the modeled reflectance factors to the observed ones, for an illumination azimuth angle of 45° with respect to the target rows. Simulations reproduce correctly the reflectance variations, both in shape and intensity, due to the rows structure of the lattice, although some quantitative differences are noticeable. Two major sources of discrepancy have to be explored; the inaccuracies of the representation of the target optical and structural properties, and the errors of measurement.

The Torrance and Sparrow model does not fit exactly the observed reflectances of the reference panel. Moreover, observations for an illumination zenith angle of 56° show backscattering effects which may be due to the hot spot or coherent backscattering^[5] that are not represented in the Torrance-Sparrow model. In addition, the regularity of the target macro structure (there are only five different normal directions)

makes the target reflectance anisotropy particularly sensitive to the material directional properties. In natural media, the angular dispersion of the scattering elements is much wider so that the effects of their directional properties are averaged. Consequently, further efforts are needed to improve the characterization of the optical properties of this type of material surface.

Among the other possible sources of differences, the problem of measurement inaccuracies must be pointed out. First, the Spectralon reference panel is not a perfect Lambertian surface, even for an illumination zenith angle of 3° ; The reflectance at a zenith angle of observation of 56° is 12% lower than at the nadir. As a result, normalized measured reflectances should be overestimated at large zenith angles of observations and underestimated at lower ones. Second, the comparison of the left and right side of the reflectance factors with respect to the principal plane in case of a row-aligned azimuthal illumination has revealed a bias in the observations especially in the specular direction for an illumination at 56° . Further investigations are required to determine if this bias may be due to a defect of the goniometer structure or a slight misalignment of the detector. To the extent that such a defect can be identified and quantified, it will be possible to simulate it with Raytran and therefore to correct it.

4 CONCLUSION

In this paper, we presented a new radiative transfer model based on the Monte Carlo ray tracing techniques for elastic scattering process modeling in scenes of arbitrary complexity. These techniques allow the description of a variety of three-dimensional scenes with realistic optical properties, under simulated natural or artificial illumination conditions. Raytran allows the study of a number of radiative transfer issues in relation with the remote sensing observation of terrestrial surfaces such as sensitivity studies, target spectral signature analysis, sensor and retrieval procedure evaluation, etc. Comparisons with laboratory measurements have shown the capability of

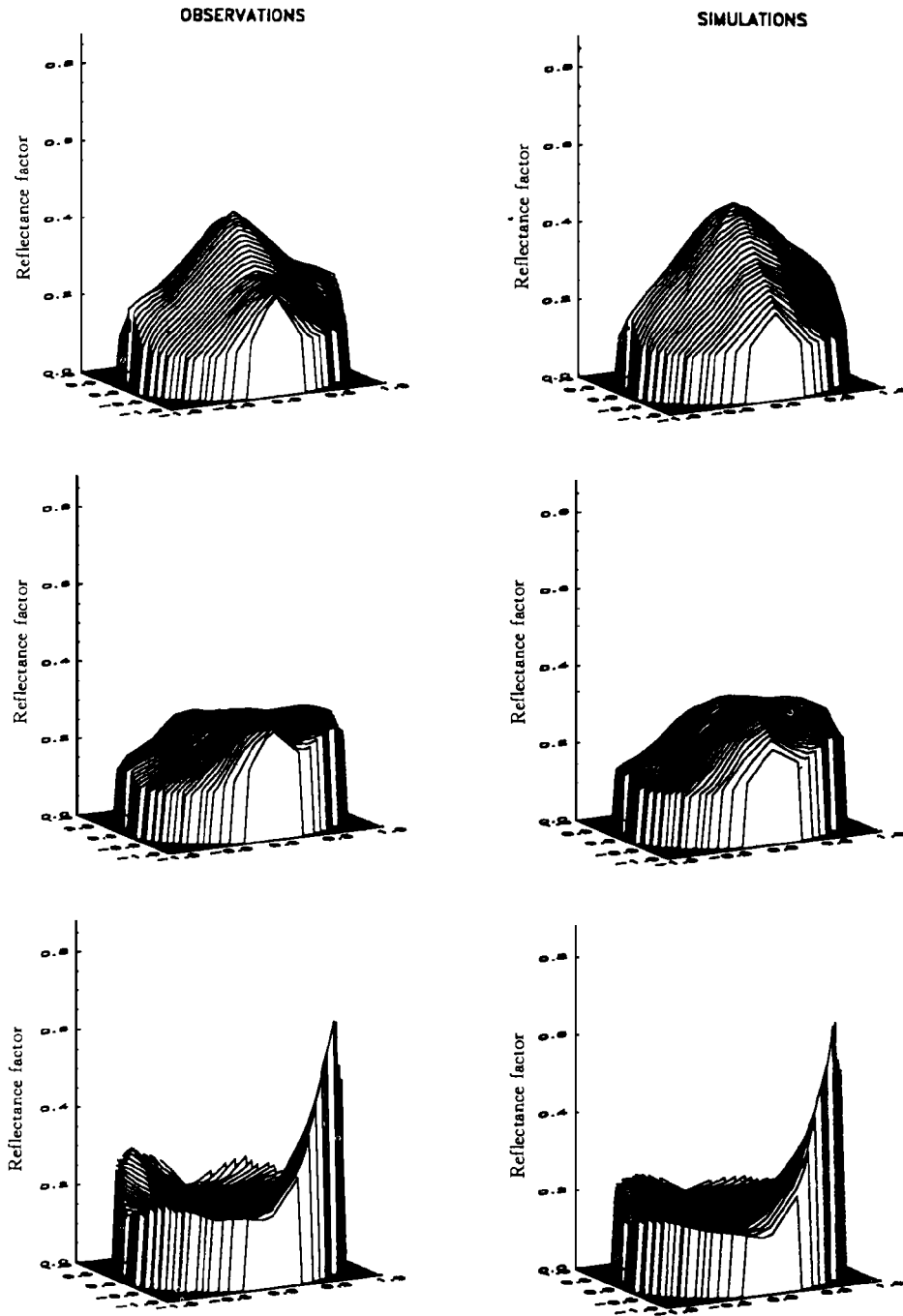


Fig. 3 Observations (left column) of the reflectance factors of the lattice target, and simulations (right column) for three different illumination zenith angles: 3° (first row), 26° (second row) and 56° (third row). The values are plotted in cylindrical coordinates. The distances from the origin of the horizontal axes represent the cosine of the zenith angle of observation. The lattice of cubes is illuminated with an azimuth angle of 45° with respect to the rows

Raytran to reproduce the actual observed reflectance factors of a fully documented target taking into account as precisely as possible of the observation conditions.

ACKNOWLEDGMENTS

This research would not have been possible without the generous access to the Centro Svizzero di Calcolo Scientifico (CSCS) in Manno, Switzerland. They thank B. Pinty for fruitful discussions and extensive comments on this paper.

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依据对一个人造物体的角度测量, 评价一个三维辐射传输模型

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摘要 该文基于蒙特卡洛光线追踪技术评价一个新的三维不均匀介质的辐射传输模型, 这一模型是按一个虚拟实验室来构思的。在这个实验室中可以把多个物体分别表征, 并可以显示控制辐射场与这些物体的相互作用。对于任意复杂的三维物体, 此模型都可以用来产生反射及吸收的纵剖面图, 例如一片植物的叶子或是一个完整的森林冠层。通过对一个人造物体的模型仿真及实验测量结果的比较, 我们评估了这一模型的性能。空间应用研究所的高技术利用室利用欧洲测角计 (EGO) 设备进行了观测, 与实验室的测量比较表明我们的模型可以再生一个与实际相符合的物体的实际观测反射因子, 甚至可以表征实验室的性能。

关键词 蒙特卡洛, 光线追踪, 测角计测量, 辐射传输建模