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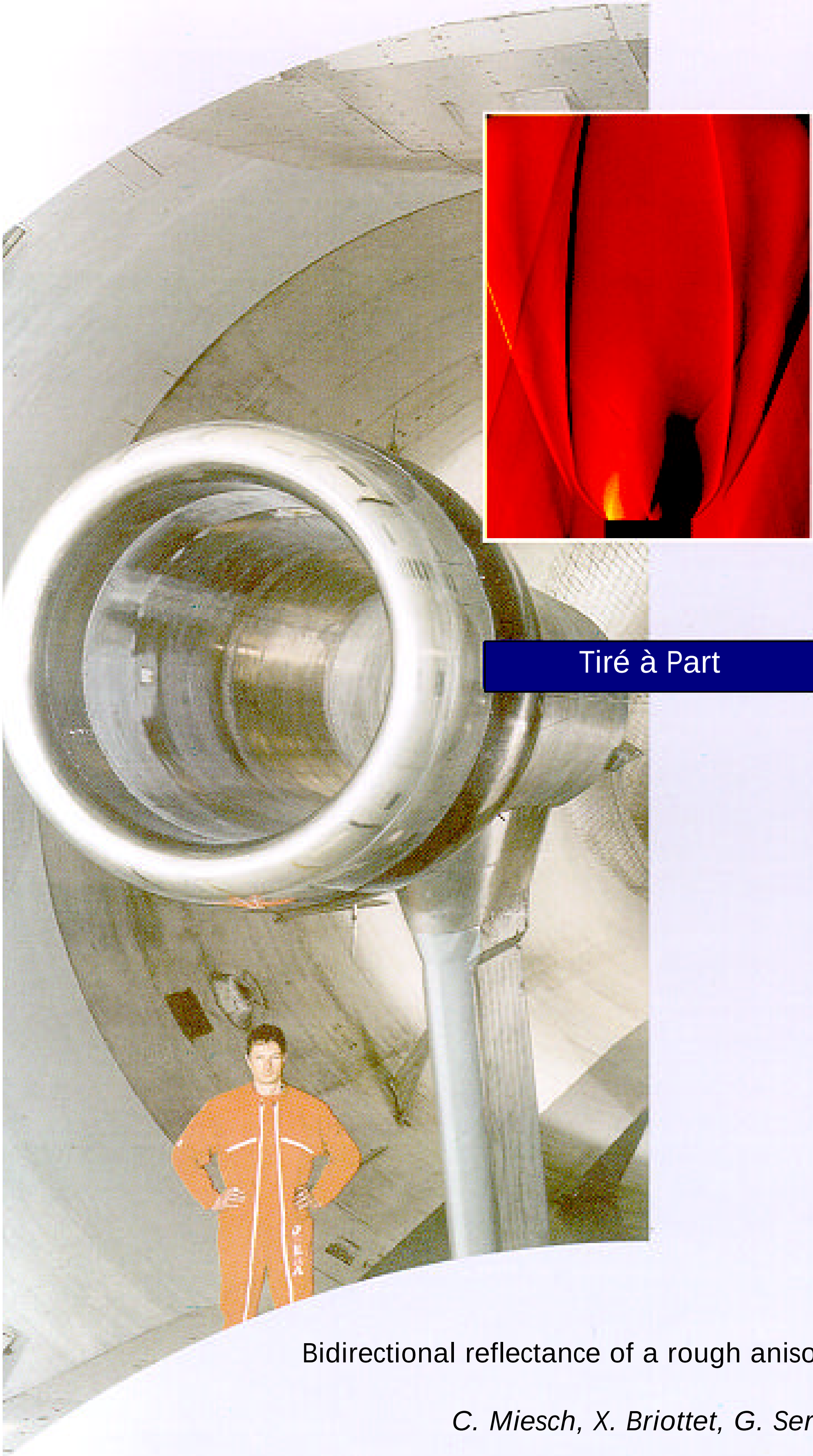

Tiré à Part

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Réflectance bidirectionnelle d'une surface rugueuse anisotropique

par

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Résumé : L'objectif de ce travail était de démontrer que l'hypothèse usuelle d'isotropie et de symétrie de la réflectance bidirectionnelle n'est pas valide pour une surface présentant une anisotropie spécifique. Deux méthodes illustrant cela sont présentées. La première est basée sur l'utilisation d'un goniomètre afin de mesurer la réflectance bidirectionnelle de la surface considérée et la seconde utilise un code de simulation Monte Carlo. Les résultats des deux méthodes ont été analysés à différentes longueurs d'onde et diverses configurations angulaires. Pour la surface analysée, ils ont montré que la réflectance bidirectionnelle était significativement asymétrique par rapport au plan principal. Dans le cas extrême, la différence entre les deux côtés du plan principal était quasiment 30 % de la valeur moyenne de la réflectance.

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Bidirectional reflectance of a rough anisotropic surface

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Abstract. The goal of our work was to demonstrate that the usual assumptions of isotropy and symmetry of the bidirectional reflectance factor (BRF) are not valid for a specific anisotropic ground surface. Two methods illustrating this point are presented. The first method is based on goniometer measurements, and the second method uses a Monte Carlo algorithm. The results of both methods were analysed at different wavelengths and angular configurations. For the surface studied here, they showed that the BRF was significantly asymmetric with respect to the principal plane. In the extreme case, the difference between the two sides of the principal plane reached almost 30% of the mean reflectance value.

1. Introduction

The availability of multi-angle spaceborne optical sensors (such as POLDER, MISR or VEGETATION) requires adequate vicarious multi-angular calibration over well characterized ground surfaces (e.g. Hagolle *et al.* 1999, where North African desert areas are used). This characterization implies, in particular, the assessment of the bidirectional reflectance of the calibration sites. Many studies have been undertaken to understand the bidirectional effects of reflectance (Liang *et al.* 2000). It appears that most of them consider that the bidirectional reflectance factor (BRF) is symmetric in relation to the principal plane. However, current work using POLDER data over a linear sand dune desert in Algeria suggests that this assumption is not valid for such an anisotropic architecture.

The goal of this work was to quantify the asymmetry of the BRF for a particular rough surface. The first part of our work consisted of choosing an adequate surface architecture that would introduce enough surface roughness effects to generate significant anisotropy (and therefore asymmetry) in the BRF signature. Once the surface was completely defined, we needed to evaluate its BRF for various observation conditions and, to this end, two methods were considered. First a goniometer was used to measure the surface BRF. Then a Monte Carlo algorithm capable of solving the direct radiative transfer problem allowed us to simulate the BRF values for each angular configuration. The results obtained by both methods are compared and discussed in the last section.

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2. Experiment description

To be able to make both measurements and simulations, the target used needed to be easy to reproduce and its geometrical and optical properties had to be well known. For these reasons, a sample made of dry sand was selected. Its `topography' consisted of linear dunes generated with a linearly translated template (figure 1(a)). The linear dunes were 1.5 cm high and 4 cm wide and were separated by a 1 cm wide flat band. These dimensions produced slopes of about 35° on both sides of the dunes and good stability of the sand grains (figure 1(b)). The anisotropy was introduced here entirely by the roughness effects.

As our goal was to quantify the asymmetry of the BRF, we focused on a reduced set of BRF values on both sides of the principal plane for a single incident direction which was likely to introduce maximum asymmetry. The principal plane was then oriented 45° off the linear dune direction, and the zenith angle of the source was set to 45°. The BRF values were estimated for two different viewing zenith angles of 30° and 50° on both sides of the principal plane, i.e. for relative azimuth angles from 0° to 180° (right side) and from 360° to 180° (left side) respectively as illustrated in figure 2. The BRF was evaluated for two wavelengths, 550 and 850 nm.

3. BRF estimation methods

3.1. *Measurements*

A goniometer has been developed at ONERA (Office National d'Etudes et de Recherches Aérospatiales) to measure the bidirectional reflectance of materials and small surfaces for a large part of the hemisphere (Serrot *et al.* 1998). The goniometer mainly includes a lamp and a spectroradiometer that entirely cover the visible spectrum. They are able to move all around the sample placed under them, and the zenith angle range is [0;60°]. The goniometer is, however, not able to make measurements in the backscattering angular domain, since the source is then masked by the sensor. The measurement protocol gives a peak-to-peak uncertainty less than 5% on the absolute BRF and less than 3% on relative measurements. In the present experiment, the integrated target surface was 20 cm in diameter, so as to obtain results representative of the surface roughness effects.

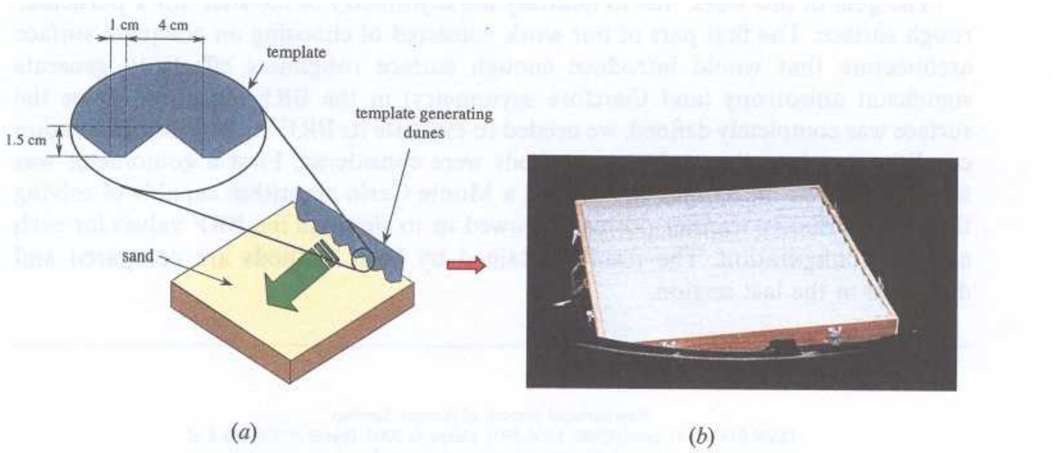

Figure 1. Sample of linear sand dunes.

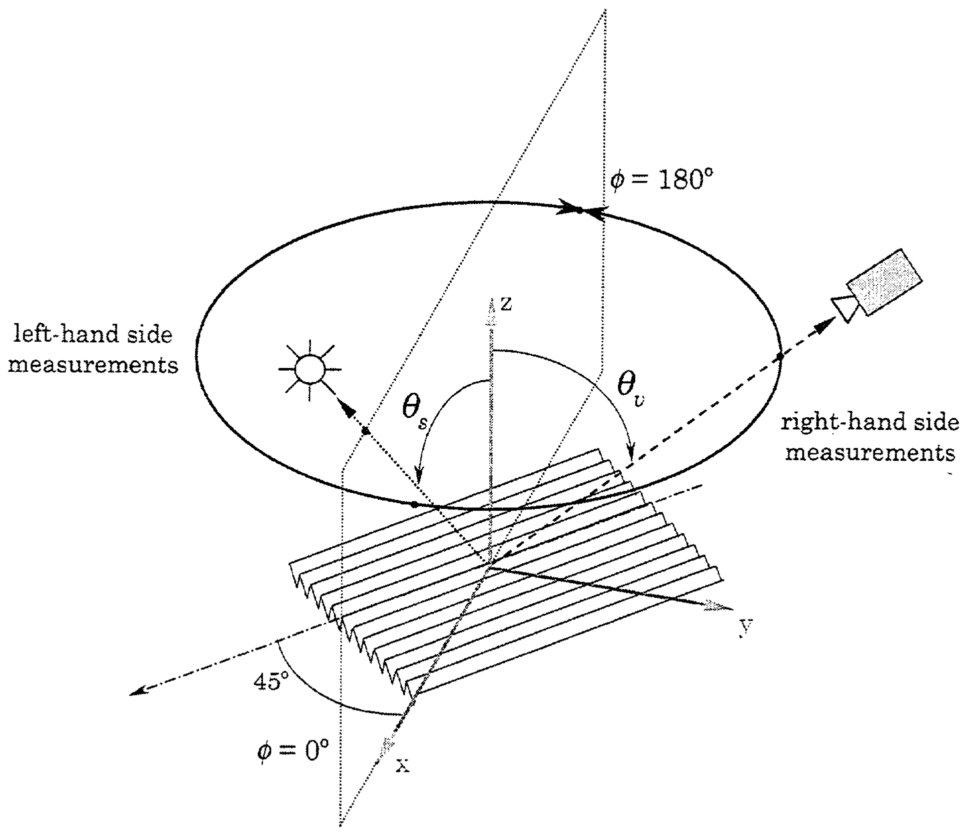

Figure 2. Geometrical configurations for BRF estimation.

3.2. *Monte Carlo simulation model*

A Monte Carlo algorithm was also used. This algorithm, described in detail in Miesch *et al.* (1999), considered a transparent atmosphere in the present case (i.e. non-scattering and non-absorbent) to focus on target BRF simulation. The code then computed only the components illustrated in figure 3. The code works with a digital elevation model (DEM) of the relief which is associated with a map of BRF models characterizing each cell of the DEM. Whereas the DEM was straightforward here, the flat sand BRF needed to be characterized. To this end, the goniometer described previously was used again, and measurements taken over flat sand were then fitted by usual BRF models in order to select the most appropriate. Rahman's model (Rahman *et al.* 1993) gave the most accurate results for both wavelengths (cf. figures 4 and 5). As mentioned above, no measurements were available for the backscattering domain. The behaviour of the BRF around the hot spot was consequently derived directly from Rahman's model with no possibility of validation. Also, no measurements were available for zenith angles greater than 60°. However, like several other models, Rahman's model became unstable for large zenith angles. Since the behaviour of the BRF was not well known for these oblique incidences,

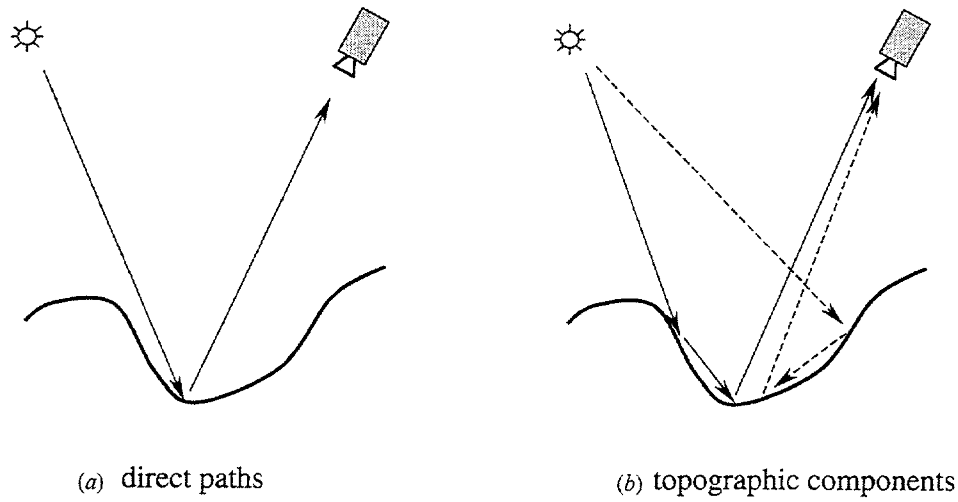

Figure 3. Radiance components modelled by the Monte Carlo code.

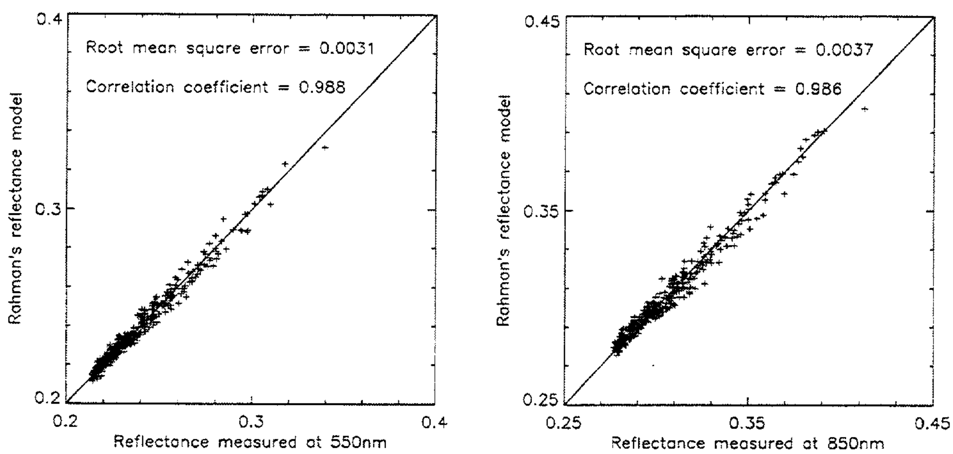

Figure 4. Rahman's model compared with measurements at 550 and 850 nm.

we opted for a constant value above 60° as this seemed to be the most reasonable solution.

4. Results and discussion

For both measurements and simulations and for each wavelength and viewing zenith angle, the BRF values for the left-hand and right-hand sides are shown in figure 6 as a function of the relative azimuth of the sensor (from 0° to 180°). First of all, both measurements and simulations had similar behaviours. The right-hand side values were systematically greater than the left-hand side ones. The maximum difference was almost 30% of the mean BRF value for the viewing zenith angle of 50°, and was lower for the viewing zenith angle of 30°. Both wavelengths showed the same effects. The asymmetry can be explained easily: when the sensor moved on the right side, the well-irradiated slopes were facing the sensor, whereas when it

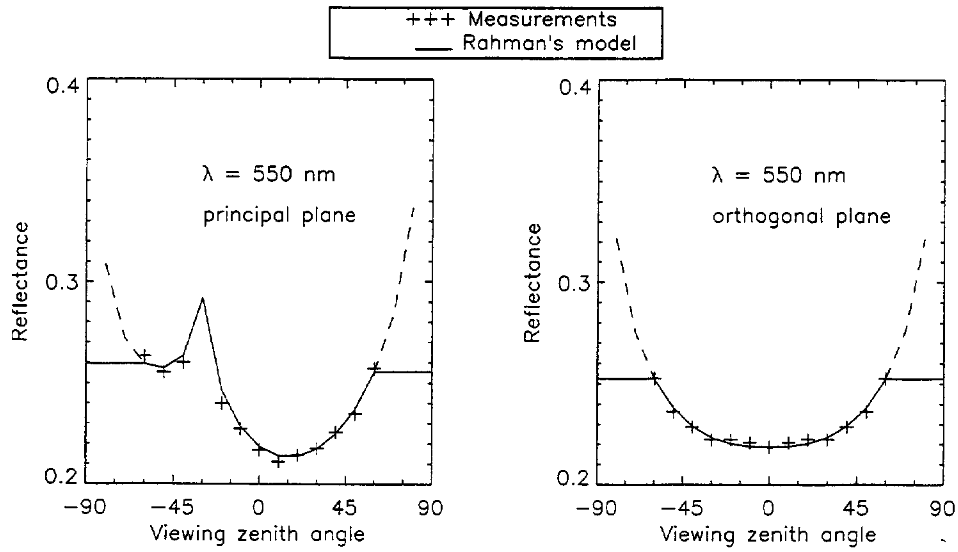

Figure 5. BRF of flat sand (measured and modelled), for $\theta_s = 30°$, in the principal and orthogonal planes, at 550 nm.

moved on the opposite side, its field-of-view was mainly filled by poorly exposed slopes leading to lower values of the BRF. Other characteristics were also reproduced by both methods, e.g. an inflection point was visible on the right-hand side plots for the viewing zenith angle of 50°. This effect was due to the fast decrease in the BRF when moving away from the backscattering domain. Consequently, the measured and computed BRF led to the same conclusion: anisotropy of the ground surface may introduce significant anisotropy in the BRF. As a result, in the present case, if the BRF is assessed only considering the left-side measurements (plotted in figure 6) with the symmetry assumption, the bias on the opposite side reaches a maximum of 36% (in the case corresponding to: $\theta_v = 50°$, $\theta_s = 45°$, $\Delta\phi = 135°$, $\lambda = 850$ nm).

However, it appeared that the magnitudes of the BRF were greater for the Monte Carlo datasets. Possible causes of these biases are discussed below.

First of all, the goniometer introduces a relative measurement uncertainty that has been estimated at 3% for a flat surface (Serrot *et al.* 1998). Moreover, characterization of the flat sand BRF was not complete. The BRF around the backscattering domain was estimated approximately by Rahman's model and was undoubtedly overestimated. The hot spot was arbitrarily reduced by 10%, with the result that the BRF values computed by the Monte Carlo method were modified. This fact is shown at 550 nm (the results were similar at 850 nm) in figure 7 on which the first Monte Carlo simulations and the second Monte Carlo simulations are plotted (with a reduced hot spot). The influence of the modification concerned only low relative azimuth angles, for which the second Monte Carlo dataset was closer to the measurements. Also, there was a similar problem for zenith angles greater than 60° where the directional behaviour was only suggested. Again, if this behaviour was slightly modified, and if, for instance, the BRF values over 60° were slightly increased, the Monte Carlo outputs were modified as shown in figure 8 for a viewing zenith angle of 50° at 550 nm (again, the results were similar at 850 nm). Using higher BRF values

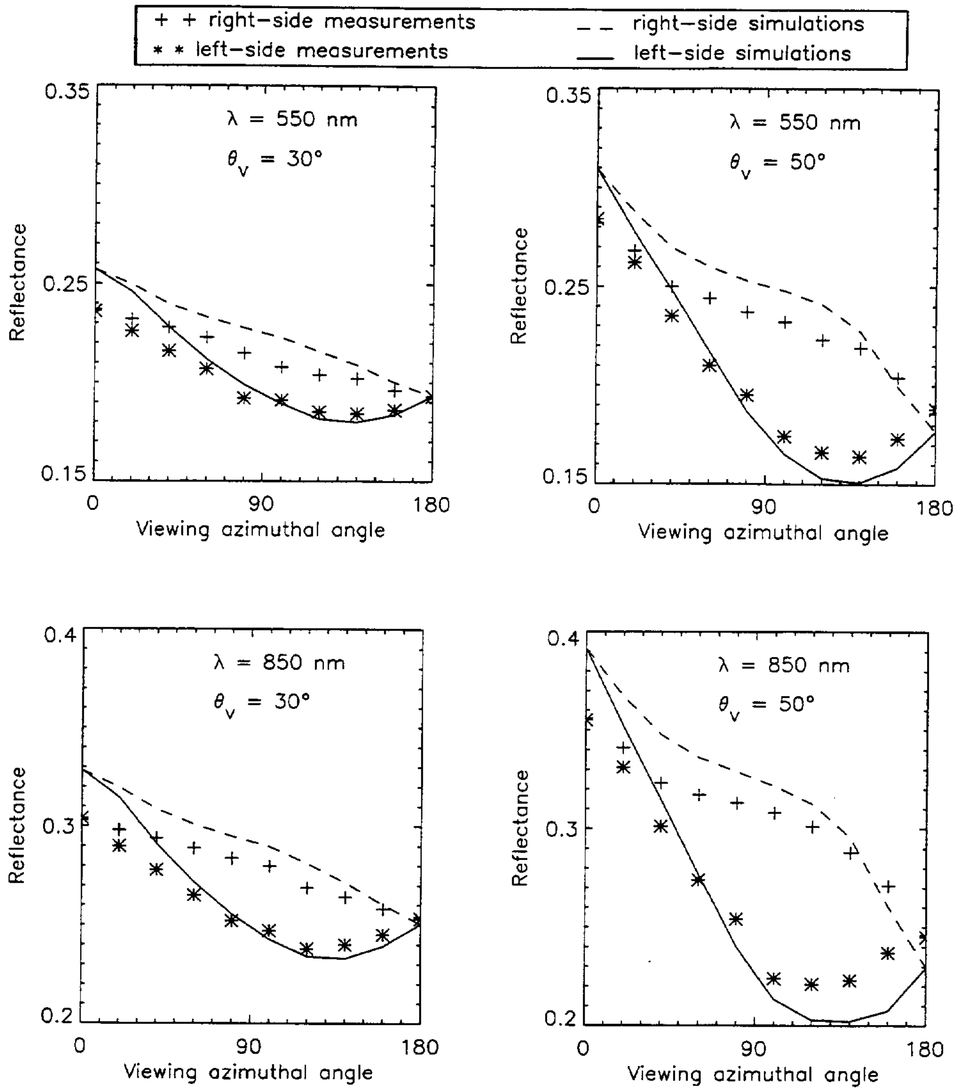

Figure 6. BRF results (measured and simulated), for $\theta_s = 45°$, on both sides of the principal plane, at 550 and 850 nm.

increased the correspondence between model and measurement for relative azimuths above 100°. Thus, the BRF model used for flat sand introduced uncertainties.

There were other sources of error. The imperfections of the generated linear sand dunes and the non-directionality of the source irradiation (aperture about 3°) and the sensor field-of-view (6° aperture) also tended to damp variations of the BRF. It was difficult to quantify these effects but they may have introduced additional uncertainty in the results.

5. Conclusion

In this study, a measurement device and a simulation method were used to assess the BRF of a rough sand surface with a specific anisotropic architecture. Both

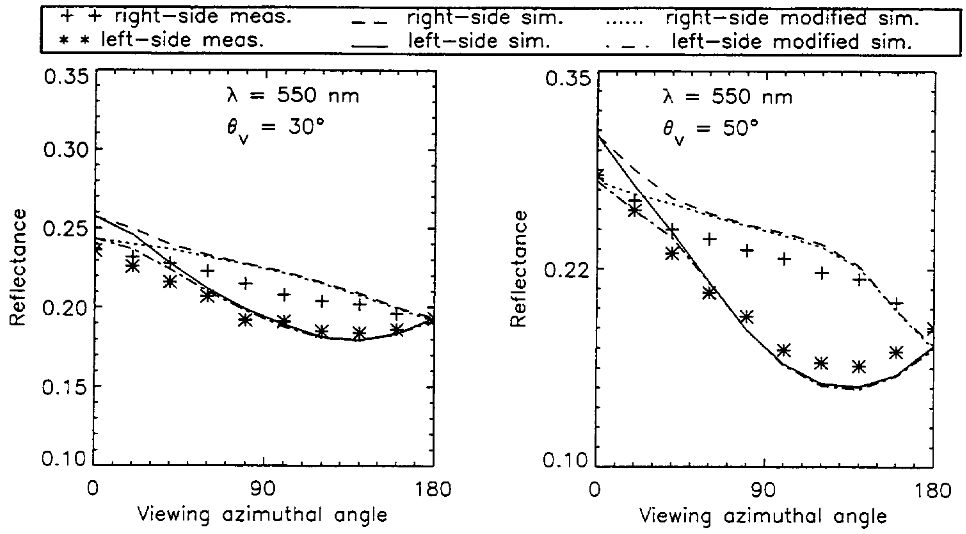

Figure 7. Effect of a reduced hot spot of the flat sand on Monte Carlo results at 550 nm.

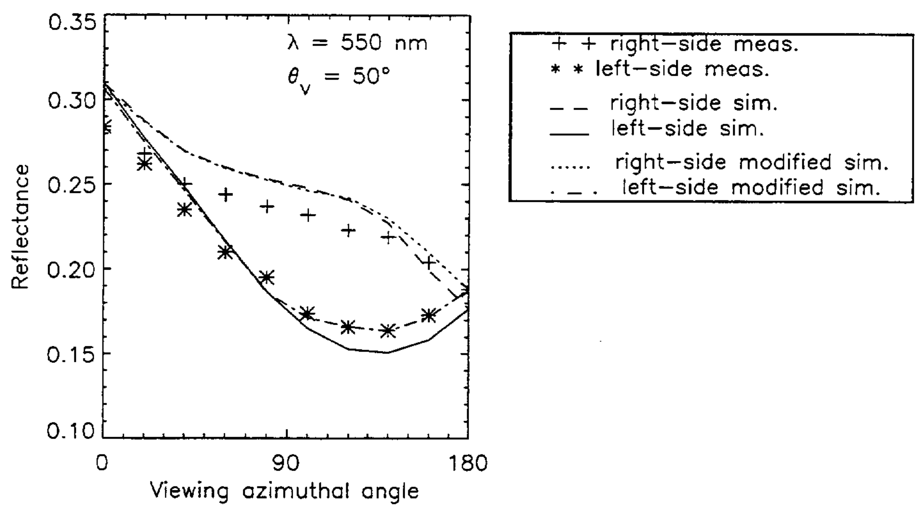

Figure 8. Effect of increased large zenith reflectance values of the flat sand on the Monte Carlo results at 550 nm.

measurements and simulations showed a clear asymmetry of the BRF in relation to the principal plane, especially for large incident zenith angles. The difference reached almost 30% of the mean value in the extreme configuration. The results demonstrated that the usual assumption concerning isotropy has to be used with care above some specific targets, or large errors can be introduced.

The comparison of both datasets led to quantitative differences that were mainly attributed to uncertainties in the characterization of the flat sand BRF. The results showed the necessity for a better characterization of this BRF, even for the backscattering domain and large zenith angles.

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