Comparison of measured and modeled BRDF of natural targets

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ABSTRACT

The Bidirectional Reflectance Distribution Function (BRDF) plays a major role to evaluate or simulate the signatures of natural and artificial targets in the solar spectrum. A goniometer covering a large spectral and directional domain has been recently developed by the ONERA/DOTA. It was designed to allow both laboratory and outside measurements. The spectral domain ranges from 0.40 to 0.95 µm, with a resolution of 3 nm. The geometrical domain ranges 0-60° for the zenith angle of the source and the sensor, and 0-180° for the relative azimuth between the source and the sensor. The maximum target size for nadir measurements is 22 cm.

The spatial target irradiance non-uniformity has been evaluated and then used to correct the raw measurements. BRDF measurements are calibrated thanks to a spectralon reference panel.

Some BRDF measurements performed on sand and short grass are presented here. Eight bidirectional models among the most popular models found in the literature have been tested on these measured data set. A code fitting the model parameters to the measured BRDF data has been developed. The comparative evaluation of the model performances is carried out, versus different criteria (root mean square error, root mean square relative error, correlation diagram ...). The robustness of the models is evaluated with respect to the number of BRDF measurements, noise and interpolation.

Keywords: BRDF, measurement, reflectance model.

1. INTRODUCTION

Several applications using airborne and satellite image data need an accurate knowledge of spectral, directional and radiometric properties of each scene element. These applications are, for instance, the determination of the optimal spectral channels to improve the best contrast between a target and the background, or the determination of the radiometric attributes of an area in a scene simulation. The lambertian assumption is often done to model the reflectances of natural and artificial materials. To improve the control of the reflectance a way is to use a goniometer to access to the BRDF. In order to get BRDF of specific materials, we have developed a goniometer according to our geometrical, spectral and temporal constraints1.

This BRDF measurement device operates indoors with an artificial source, or outdoors. It has been calibrated indoors, taking into account the spatial and temporal variations of the source irradiance at the target level, thanks to a spectralon reference panel.

There are many goals to modelize BRDF data, which are first compression of the information, since a complete BRDF data set is very voluminous, then the ability to interpolate the BRDF data between the measured points. Thus, a lot of models are developed and reported in the literature. However, it seems that most of the models have a restricted geometrical validity, and are not able to well modelize other types of data than those they were designed for. That’s why we have decided to evaluate the performances of several models, on BRDF data measured with our goniometer, to chose the best model attached to a given material.

The models performances are firstly evaluated in a global way (raw performances), then in term of robustness (sensibility to noise and number of measurements), and finally in term of geometrical interpolation.

The definition of the BRDF (Bidirectional Reflectance Distribution Function) introduced by Nicodemus2 is :
Where $dL_r$ is the differential reflected radiance, $dE_i$ the differential incident irradiance. $\lambda$ is the wavelength, $\theta_r$ is the zenithal reflection angle and $\phi_r$ the azimuth reflection angle, $\theta_i$ is the zenithal incident angle and $\phi_i$ the azimuth incident angle. $\phi = \phi_i - \phi_r$ is the relative azimuth angle between the sensor and the source (figure 1).

\[
\rho = \frac{dL_r(\theta_r, \phi_r, \lambda)}{dE_i(\theta_i, \phi_i, \lambda)}
\]  

Fig. 1 – Angles for the definition of the BRDF

2. GONIOMETER DESCRIPTION

The transportable goniometer system installed at the ONERA/DOTA, Toulouse Center, is designed to work in laboratory and outdoors. Laboratory measurements are easier and more accurate, but rather adapted to samples which can be brought.
The system height, limited by the ceiling of the laboratory, is 2.7 m. The distances between the target and the analyzer head is 2 m, and 2.4 m from the lamp to the target. The weight is 850 kg, but the goniometer can be disassembled into elements weighting no more than 50 kg. In order to measure materials with some spatial inhomogeneities, an area of the target up to 22 cm of diameter is viewed from the detection head at nadir. Mainly, the structure consists in a ring supported by forth feet with jacks to adjust the horizontally. For inside measurements, a source arm can be fixed on the support. A sensor arm is fixed to a ring, which can rotate defining the azimuth angle (figure 2).

The source and viewing zenith angles can range from 0 to 60°, and the relative azimuth between the source and the sensor (180° is the specular direction) from 0 to 180°. All axes are motor-driven with a positioning precision better than 0.5° and a minimal increment of 1°. The three motions concentricity is better than 0.5°. For targets with a random structure, an acquisition in the azimuth geometrical domain 0–180° gives a complete knowledge of the BRDF. For targets with geometrical symmetry, this leads to an incomplete BRDF description. We can access to the complete description of the BRDF by rotating the target. The mapping time is less than 7 min for one source position, 0<θ<60° and 0<φ<180°, with a 10° angular step.

In the following, we will describe the different elements of the goniometer.

The main source characteristics must be : a slow variation on a wide spectral spread, a spatial stability (which eliminate arc lamps), a good spectral and spatial uniformity, a temporal stability. For this, the best choice is a QTH (Quartz Tungsten Halogen) lamp. Theoretically, the BRDF is defined with a collimated beam. The ideal source for our system would be a large (50 cm at target level) collimated beam, with a good spectral and irradiance uniformity. These features are very difficult to obtain in a little volume so we have chosen to use a classical projector. After studying the uniformity of different projectors, the best results were obtained for a projector with a parabolic emboss rear reflector. Front diffusers can be added to improve the irradiance uniformity. The best compromise is found with a 650 W QTH video studio lamp. The current supply is stabilized and regulated with a precision of 10-4. A preprocessing is done to compensate the divergence of the incident beam, and come down to a collimated beam.

The detection head and the spectral analyzer have to cover the spectral domain ranging from 400 to 1000 nm, with a spectral resolution less than 3 nm, a short acquisition time for outdoors measurements and a light weight. The best choice is a deprived collection optical head linked to a spectrometer by a fiber-optic bundle. The flux is collected by an objective whose focal fixes the integrated area of the target. With an 8.5 mm focal, the integrated area is a 22-cm diameter disk (at nadir viewing); with a 100 mm focal the diameter is about 2 cm. A video camera is used to look at the target.

The bundle is 5 meters long, made up of 59 elementary multimode fused silica fibers with a diameter of 100 µm and a 0.22 numerical aperture. The bundle is used to make an anamorphosis between the collection optical head (1-mm diameter disk) and the spectrometer (0.1 x 6 mm rectangular slit). The bending losses were evaluated to 3.10-3 for a 40 mm bending radius.

The spectrometer is an ORIEL Multispec, the focal is 125 mm and the effective aperture is F/3,7. With a 400 lines grating blazed at 500 nm, the primary wavelength region is 300 to 1200 nm. A CCD matrix ORIEL Instaspec 4V acquires the spectra with 1024 x 256 pixels. It can be cooled to −30°C to reduce the electronic noise. The signal is digitized with a 16-bit converter. The true spectral range is 420–950 nm with a 0.6-nm step and an actual resolution of 3 nm. The minimum exposure time is 25 ms. Instaspec IV includes complete spectrometric software for acquisition and first signal processing.

The choice of the fiber bundle was also made for the depolarization of the light before striking the grating, which the efficiency depends on the polarization. By this way, the measurement is always independent of the light scattered by the target (often light is polarized by targets). So when we use a front polarizer, the part of light transmitted through the polarizer is depolarized along the 5 meters multimode fiber before striking the grating, and this permits a polarimetric reflectance analysis.

A BRDF data set acquired with a 10° step and covering the whole 1/4 sphere comprise 931 ASCII files, with 1024 lines on 16 bits (corresponding to 1024 wavelengths). This requires an automatic process to control the acquisition conditions.

The system is calibrated with a spectralon reference panel, which the spectral albedo is known. A BRDF measurement is performed on the panel for θ=0, φ=0 and 0<θ<86° (the panel is inclined to make possible the measurements between 60 and 86°). The spectralon BRDF being isotropic, the calibration coefficient is adjusted so that the integral of the BRDF signal is equal to the spectralon albedo. This coefficient gives the correspondence between the numerical counts of the detected signal and the BRDF. This BRDF measurement method includes several sources of error, which have been evaluated. The absolute precision of the BRDF should be better than 5% 0-peak between 450 and 900 nm, and 2% at 700 nm.
3. BRDF MEASUREMENTS

BRDF measurements of several materials have been performed with our bench: sand, green and dry grass. These measurements are presented here.

The BRDF measured for each material depends on the wavelength. To present the results, we have chosen two wavelengths: one in the visible spectrum (600 nm) and the other one in the near infrared spectrum (800 nm). There are several ways to present a BRDF. Here, the BRDF is plot among the observation zenithal angle $\theta_r$, for several relative azimuth angles $\phi$, at fixed wavelength and fixed zenithal source angle $\theta_i$. The sampling step is $10^\circ$ for $\theta_i$ and $\theta_r$, and $20^\circ$ for $\phi$. The BRDF measurements are given for $\theta_i=30^\circ$ and 3 azimuth angles $\phi=0^\circ$, $60^\circ$ and $180^\circ$ on figure 3.

Fig. 3 – BRDF of dry grass, green grass and sand for $\theta_i=30^\circ$ and $\lambda=600$ nm and 800 nm
The measurement in the backscattering direction is missing ($\theta_r=30^\circ$ and $\phi=0^\circ$), since the detector head is masking the source for this direction. The BRDF of the grass is important in the backscattering plane. The BRDF of the sand is quite lambertian, with a weak signature in the backscattering plane.

4. BRDF MODELIZATION

4.1. BRDF models

A state of the art study has been conducted on the modelization of natural and artificial target BRDF. Thirty-five models have been studied. We have classified BRDF models in a similar way as Roujean3:

- Numerical models: they modelize the surface geometry and use a ray-tracing technique and/or a Monte-Carlo method.
- Analytical models: the BRDF is described with an analytical formula comprising 3 to 6 parameters, fitted on measured data. The formula can be built in several ways:
  - Theoretical models: use a physical theory to build the formula describing the BRDF; the geometrical optics for geometrical models, radiative transfer theory4 for turbid models, or a combination of these two theories for hybrid models.
  - Empirical models: mathematical models develop the BRDF on a vectorial base; semi-empirical models combine a theoretical model with empiric parameters.

We have chosen 8 models among the most recent ones for the evaluation of their performances. These models are from Deering et al5 (geometrical, 5 parameters), Oren and Nayar (geometrical, 4 parameters)6, Roujean et al7 (hybrid, 3 parameters), Snyder and Wan6 (hybrid, 7 parameters), Meister et al9 (empirical, 7 parameters), Rahman et al10 (semi-empirical, 4 parameters), Schlick11 (semi-empirical, 6 parameters), and based on Legendre polynomial12 (mathematical, 6 parameters). For convenience, these models will be named "Deering", "Oren", "Roujean", "Snyder", "Meister", "Rahman", "Schlick"and "Legendre". The chosen models only depend on $\phi=\phi_r-\phi_i$; they are only able to modelize isotropic surfaces. Notice that we have not chosen turbid models, since they mainly concern vegetation that can not be measured with our goniometer.

4.2. Fitting method

We have developed a code to estimate the model parameters. As we want to fit linear and non linear models, the regression method consist in minimizing a cost function with the simplex method13. This method is pretty slow, but one of the most robust and easy to implement. However, tests have shown a dependence of the results with the initial conditions. Thus, several optimizations are performed with different values of initial parameters, and the best result is chosen.

No constraints are imposed on the parameters. It means that some parameters, which have a physical signification, are able to take even values with no physical sense. As a matter of fact, the models cannot pretend modelize completely the reality, and most of them are far from the physics. More, we are not interested in physical information given by the parameters, only in the quality of the fit.

The chosen cost function should have been the (chi)$^2$, but most of times the measurements errors are not known. So we have used the classical root mean square error:

$$\sigma = \frac{1}{N} \sum (\rho_{\text{model}} - \rho_{\text{measure}})^2$$  \hspace{1cm} (2)

Where N is the number of measurement points. To evaluate the performances of the models, several criteria have been implemented in our code and are available. These criteria are the root mean square error (2), the relative root mean square error (3) (frequently used), the mean relative error (4) and the maximum relative error (5).

$$\sigma_r = \frac{1}{N} \sum \left(\frac{\rho_{\text{model}} - \rho_{\text{measure}}}{\rho_{\text{measure}}}\right)^2$$  \hspace{1cm} (3)
\[ \delta = \frac{1}{N} \sum \left| \frac{\rho_{\text{model}} - \rho_{\text{measure}}}{\rho_{\text{measure}}} \right| \]

\[ \delta_{\text{max}} = \max \left( \frac{\rho_{\text{model}} - \rho_{\text{measure}}}{\rho_{\text{measure}}} \right) \]

The modeled BRDF can also be plot versus the measured BRDF. The fit is as good as points are closed to the first bissectrice.

The code has been validated in two ways. First the minimization routine has been validated on several mathematical functions which the minimum is known. Then, the parameters of the models have been fitted with POLDER data. The performances obtained are equal or better than those of the model used by Cosnafroy et al\textsuperscript{14}.

5. PERFORMANCES OF THE MODELS

The 8 models have been fitted on three data set measured on sand, dry and green short grass. For each material and each wavelength, the data are made up of 474 points, corresponding to 7 zenithal source angles, 7 zenithal observation angles, and 10 azimuth angles.

5.1. Global performances of the models

The results are given with the relative root mean square error (formula 3) in the table 1. The best fits are obtained for Rahman’s model, excepted for green grass at 600 nm, where Snyder’s model has better results. Notice on figure 3 that the BRDF level for green grass is very low at 600 nm (about 0.015 sr\(^{-1}\)), so that the quality of the measurements may be poorer here. Notice too that the Roujean’s model has results comparable to Snyder’s model with only 3 parameters, when Snyder’s model has 7 parameters. Oren, Deering and Schlick’s models are based on a geometrical representation of the surface, with an important specular part. The studied targets do not present such specular behavior, that explains the difficulties encountered by these models to fit the data.

<table>
<thead>
<tr>
<th>Relative RMS error (%)</th>
<th>Sand (600 nm)</th>
<th>Dry grass (600 nm)</th>
<th>Green grass (600 nm)</th>
<th>Sand (800 nm)</th>
<th>Dry grass (800 nm)</th>
<th>Green grass (800 nm)</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahman</td>
<td>1.8</td>
<td>3.4</td>
<td>6.2</td>
<td>1.9</td>
<td>2.7</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Snyder</td>
<td>3</td>
<td>4.2</td>
<td>5.3</td>
<td>2.5</td>
<td>3.1</td>
<td>2.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Roujean</td>
<td>2.9</td>
<td>4.3</td>
<td>6.5</td>
<td>3</td>
<td>3.5</td>
<td>3.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Meister</td>
<td>3.8</td>
<td>5.6</td>
<td>6.7</td>
<td>3.7</td>
<td>4.1</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Legendre</td>
<td>3.8</td>
<td>5.6</td>
<td>6.6</td>
<td>3.5</td>
<td>4.4</td>
<td>4.2</td>
<td>4.7</td>
</tr>
<tr>
<td>Deering</td>
<td>4.2</td>
<td>7.4</td>
<td>9.3</td>
<td>4.1</td>
<td>5.4</td>
<td>4.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Schlick</td>
<td>5</td>
<td>8.2</td>
<td>11.6</td>
<td>4.6</td>
<td>6.2</td>
<td>5.3</td>
<td>6.8</td>
</tr>
<tr>
<td>Oren</td>
<td>5.8</td>
<td>10.7</td>
<td>11</td>
<td>5.8</td>
<td>8.8</td>
<td>6.8</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Tab. 1 - Relative RMS error between modeled and measured BRDF in %

In the following of this study, only Rahman, Snyder, Roujean, Meister and Legendre’s models will be kept. We have plot on figure 4 the modeled BRDF versus one measured BRDF. The table 2 gives for each model the percent of modeled BRDF points presenting less than 4% of relative error. One data point represents 0.2% of the 474 BRDF data.
The BRDF models seem to underestimate the big values of BRDF, and to over-estimate the low values of BRDF, as if they were unable to model strong variations of BRDF. The most important dispersions are obtained for Legendre and Meister’s models. The points far from the first bissectrice mainly correspond to high reflectance values, and to high incident angles. Thus, Rahman’s model presents the best fit to the measurements. Roujean and Snyder’s models show pretty good performances, Meister and Legendre’s models show mean performances. The results of Deering, Oren and Shlick’s models are insufficient for the data with which they are used.
### 5.2. Robustness of the models

It is interesting to know how the measurement uncertainty has an influence on the modeling. We have simulated a gaussian noise, and added it to the measured BRDF data set. New data is obtained from the measured data with the formula (6), \( X \) being an aleatory variable pulled between -1 and +1, and \( \sigma \), the relative standard deviation of the gaussian distribution.

\[
\rho_{\text{noise}} = \rho_{\text{measured}} \times \left(1 + \sigma, \times \text{sign}(X) \times \sqrt{-2 \log(1 - |X|)}\right)
\]  

The model parameters are estimated on the noisy data. The evaluation criteria (here the relative RMS error) is computed by comparison of the model BRDF and the original non-noisy BRDF measurements. The results are given figure 5.

![Fig. 5 - Relative RMS error between modeled and measured BRDF of sand for noisy measurements](image)

The relative RMS error is growing with the noise standard deviation. All the studied models have the same behavior. However, Snyders’s model performances fall for high noise a bit more quickly than those of other models.

The number of available measurements can also have an influence on the quality of the modelization. For satellite data, angular domains are usually limited. Thus, models parameters have been fitted on a restricted number of measured BRDF, and tested on a complete data set. When the number of used measurements decreases, the performances of the models evaluated on the complete BRDF data set also decrease. We have computed the number of necessary measurements so that the root mean square error between the modeled BRDF and the complete measured BRDF should not increase more than 15%. This new evaluation criteria, \( \kappa \), is called the relative deviation to optimum relative root mean square error (\( \kappa \) is calculated in %):

\[
\kappa = 100 \times \frac{\sigma^2 - \sigma_{\text{optimum}}^2}{\sigma_{\text{optimum}}^2}
\]  

### Tab. 2 - Percent of modeled BRDF of less than 4% of relative error

<table>
<thead>
<tr>
<th>% of points error &lt; 4%</th>
<th>Sand (600 nm)</th>
<th>Dry grass (600 nm)</th>
<th>Green grass (600 nm)</th>
<th>Sand (800 nm)</th>
<th>Dry grass (800 nm)</th>
<th>Green grass (800 nm)</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahman</td>
<td>96.8%</td>
<td>79.1%</td>
<td>52.3%</td>
<td>97.1%</td>
<td>89.5%</td>
<td>84.8%</td>
<td>83.3%</td>
</tr>
<tr>
<td>Snyder</td>
<td>81.9%</td>
<td>67.9%</td>
<td>49.4%</td>
<td>90.1%</td>
<td>79.1%</td>
<td>84.6%</td>
<td>75.5%</td>
</tr>
<tr>
<td>Roujean</td>
<td>83.5%</td>
<td>65.4%</td>
<td>44.1%</td>
<td>80.2%</td>
<td>72.2%</td>
<td>76.4%</td>
<td>70.3%</td>
</tr>
<tr>
<td>Legendre</td>
<td>75.1%</td>
<td>57.8%</td>
<td>52.5%</td>
<td>80.8%</td>
<td>67.1%</td>
<td>70.9%</td>
<td>67.4%</td>
</tr>
<tr>
<td>Meister</td>
<td>71.7%</td>
<td>54.4%</td>
<td>43.7%</td>
<td>75.5%</td>
<td>68.1%</td>
<td>76.6%</td>
<td>65.0%</td>
</tr>
</tbody>
</table>

Tab. 2 - Percent of modeled BRDF of less than 4% of relative error
For instance, if the RMS relative error obtained for a model is 4% when it is fitted on the complete data set, for \( \kappa = 15\% \), the new relative RMS error required is 115\% of 4\%, so 4.6\%. The results are presented table 3, which also indicate the number of parameters for each model.

<table>
<thead>
<tr>
<th>Number of measurements</th>
<th>Sand (600 nm)</th>
<th>Dry grass (600 nm)</th>
<th>Green grass (600 nm)</th>
<th>Sand (800 nm)</th>
<th>Dry grass (800 nm)</th>
<th>Green grass (800 nm)</th>
<th>Mean</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roujean</td>
<td>15</td>
<td>25</td>
<td>20</td>
<td>5</td>
<td>25</td>
<td>15</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Legendre</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>70</td>
<td>10</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>Rahman</td>
<td>15</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>35</td>
<td>10</td>
<td>28</td>
<td>4</td>
</tr>
<tr>
<td>Meister</td>
<td>40</td>
<td>25</td>
<td>45</td>
<td>45</td>
<td>30</td>
<td>20</td>
<td>34</td>
<td>7</td>
</tr>
<tr>
<td>Snyder</td>
<td>270</td>
<td>35</td>
<td>170</td>
<td>270</td>
<td>25</td>
<td>60</td>
<td>140</td>
<td>7</td>
</tr>
</tbody>
</table>

Tab. 3 - Number of measurements necessary for \( \kappa < 15\% \)

The more the model have parameters, the more the number of BRDF data needed to have a good fit is high. Roujean, Legendre and Rahman’s models present very good performances, since they need only about 20 data to give a good fit. At the opposite, Snyder’s model needs more than 100 data.

5.3. Capacity of geometric interpolation

We examine here the capacity of each model to interpolate when the number of azimuth planes is weak. The models parameters have been estimated for five azimuth configurations presented figure 6. Then they have been tested on the complete BRDF measurement data set. The deviation \( \kappa \) to optimum relative RMS error is computed and presented Table 4.

![Initial configuration](image1)

![Configuration 1](image2)

![Configuration 2](image3)

![Configuration 3](image4)

![Configuration 4](image5)

![Configuration 5](image6)

Fig. 6 - Azimuth configurations for interpolation

The results don’t depend on the type of the target. Each result of the table 4 corresponds to the average value of the 6 \( \kappa \) obtained for each 6 materials. One can see that the configuration 2, with only 4 azimuth angles, presents pretty good results : the relative RMS error is only 10\% superior to the value for the initial configuration. Configurations 4 and 5 are insufficient for most of the models, which confirms the necessity to make measurement outside the principal plane (\( \phi = 0 \)). However,
Snyder and Roujean’s models present a very good capacity to interpolate according to the azimuth angle, even for measurements done only in the principal plane.

<table>
<thead>
<tr>
<th></th>
<th>Config. 1</th>
<th>Config. 2</th>
<th>Config. 3</th>
<th>Config. 4</th>
<th>Config. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snyder</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>46</td>
<td>8</td>
</tr>
<tr>
<td>Roujean</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Rahman</td>
<td>2</td>
<td>9</td>
<td>10</td>
<td>27</td>
<td>41</td>
</tr>
<tr>
<td>Meister</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Legendre</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>173</td>
<td>95</td>
</tr>
</tbody>
</table>

Tab. 4 – Capacity to interpolate: \( \kappa \) for the several configurations

6. CONCLUSION

The ONERA goniometer has been described. It allows both laboratory and outdoors measurements. The maximum target size for nadir measurements is 22 cm, which allows measurements on natural targets like grass. The spectral domain covered ranges from 0.40 to 0.95 \( \mu m \), with a resolution of 3 nm, while the geometrical domain ranges 0-60\(^\circ\) for source and sensor zenith angle, and 0-180\(^\circ\) for the relative azimuth between the source and the sensor. The indoor source is a QTH lamp, and the outdoors source is the sun. The detection head is composed of an objective, an optic fibers bundle, and a multicanal spectrometer. A polarizer can be put before the objective, to make the analyze in polarized light. This instrument is calibrated thanks to a spectralon reference panel.

Some BRDF measurements have been performed on sand, green grass and dry grass.

A bibliographic study on BRDF models has been performed. Models have been classified, and eight of them have been chosen among the most recent ones, in several classes (physical, empirical…). These models are from Deering et al\(^7\) (geometrical), Oren and Nayar (geometrical\(^8\), Roujean et al\(^1\) (hybrid), Snyder and Wan\(^9\) (hybrid), Meister et al\(^10\) (empirical), Rahman et al\(^11\) (semi-empirical), Schlick\(^11\) (semi-empirical), and based on Legendre polynomial\(^12\) (mathematical). A code fitting the models to the measured BRDF data has been developed. The fit is obtained by the minimization of the RMS error between the modeled and measured BRDF. The code has been validated.

The comparative evaluation of the models performances is carried out, versus different criteria (root mean square error, root mean square relative error, and correlation diagram). Rahman’s model presents the best results. Hybrid models (Roujean and Snyder) have pretty good results too. The robustness of the models is evaluated with respect to number and noise of the BRDF measurements. The different models have the same behavior in front of noise data, which decreases the quality of the fit. The more the model has parameters, the more the number of BRDF data needed to have a good fit is high. Interpolation according to azimuth angle has been performed. Only four azimuth angles (0, 60, 120 and 180\(^\circ\)) are sufficient to obtain a good fit.

There are many perspectives to this work. First, the code will be improved with a more performing optimization method. New existing models will also be included in the code. The evaluation of the model performances could also be done on other materials.

7. REFERENCES