Diffuser properties and according performance in BSDF and spectral features in remote sensing applications

Bilgehan Gür[a], Hedser van Brug[a], Man Xu[a], Elizabeth Vela[a]
[a]TNO Science and Industry, Stieltjesweg 1, 2628CK Delft, The Netherlands

ABSTRACT

The "Bi-Directional Scattering Function" BSDF of a diffuser depends on several parameters, such as surface properties, observational conditions and further. This paper describes experimental activities to achieve a better understanding about the interaction between diffuser properties and performance with regards to its scattering behavior. For this purpose a set of 24 diffusers with defined surface properties have been manufactured and systematically been investigated in a dedicated radiometric calibration measurement facility. The experimental data are compared with existing theoretical models.

Keywords: BSDF, Diffuser, Radiometric Calibration

1. INTRODUCTION

Diffusers are widely used in space instruments as parts of the on-board calibration unit. Its influence on the quality and accuracy of L2 products makes the adequate definition of diffuser properties to one of the key tasks in the design of on-board calibration units. Each instrument however, due to its possibly unique mission and configuration, requires an individual definition of a diffuser with regards to its surface properties, material, coating and further parameters. Previous activities have shown discrepancies in experimental and modelled performance, thus making it more difficult to design suitable components for future earth observation missions. The present paper describes our efforts in improving the understanding in the interaction of diffuser properties and according performance with regards to its scattering properties and spectral features, i.e. speckle induced non uniformities in the recorded spectra. For a systematic approach a set of diffusers were manufactured with known surface properties and according experimental measurements performed. In this paper we present first preliminary and observed patterns in BSDF and speckle behavior.

2. FUNCTIONALITY AND TYPES OF DIFFUSERS

Once an earth observation instrument is in orbit regular calibration procedures have to be performed. Satellites for spectroscopic analysis of the earth atmosphere take the sun as an illumination source, the spectra that are achieved after passing the atmosphere are then compared to direct sun observations. In very simple means it can be stated that the earth radiance is compared to the sun irradiance, thus the "Bi-Directional Scattering Function" BSDF of the earth (*BSDF = radiance_earth / irradiance_sun*) is determined. To mimic the scattering of the earth diffusers are part of the calibration unit. Furthermore since it is obvious that the sun irradiance is significantly larger than the earth radiance thus an additional function of the diffuser can be described as to get a homogeneous illumination of the entrance slit.

A further diffuser related topic is the observance of so-called spectral features. In the past it has been reported several times that noise-like patterns have been observed in calibrated spectra of earth observation satellites that could not be identified as absorption features in the atmosphere. These structures are caused by speckle patterns that are generated by the diffuser in the entrance slit of the spectrometer [1].

There are basically three types of diffusers:

- Surface diffuser: This is typically a glass or metal substrate that is ground to obtain a surface roughness with a peak to valley range that is large as compared to the wavelength for which the diffuser is being used. A commonly used metal for diffusers is aluminum.

Earth Resources and Environmental Remote Sensing/GIS Applications V, edited by Ulrich Michel,
Karsten Schulz, Proc. of SPIE Vol. 9245, 92450I · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2067500

- Volume diffuser. These are made of materials that scatter via material inhomogeneities, i.e. small areas inside the material that have a different refractive index than the bulk of the material. A typical example of this type of diffuser is the Spectralon diffuser.
- Quasi volume diffuser (QVD): QVD's consist of transparent material that have roughened surfaces. Some of the light is being scattered, while some is transmitted. The transmitted part is scattered while propagating towards the back surface, which is also rough. The idea behind this diffuser is to have multiple scattering surfaces, thereby mimicking the characteristics of the volume diffusers.

In the recent years TNO has tended increasingly towards QVD's. The reason is twofold: First, less degradation in orbit compared to spectralon or aluminum diffusers, second, smaller non-uniformities in the recorded spectra as mentioned above [2]. An example of the latter is displayed in the following graphics [3]. The figure shows two instruments (GOME-2 FM2 and FM2-1) which are identical in design, but contain different diffusers in the calibration unit. The recorded spectra of FM2-1 with a QVD shows significantly smaller spectral features.

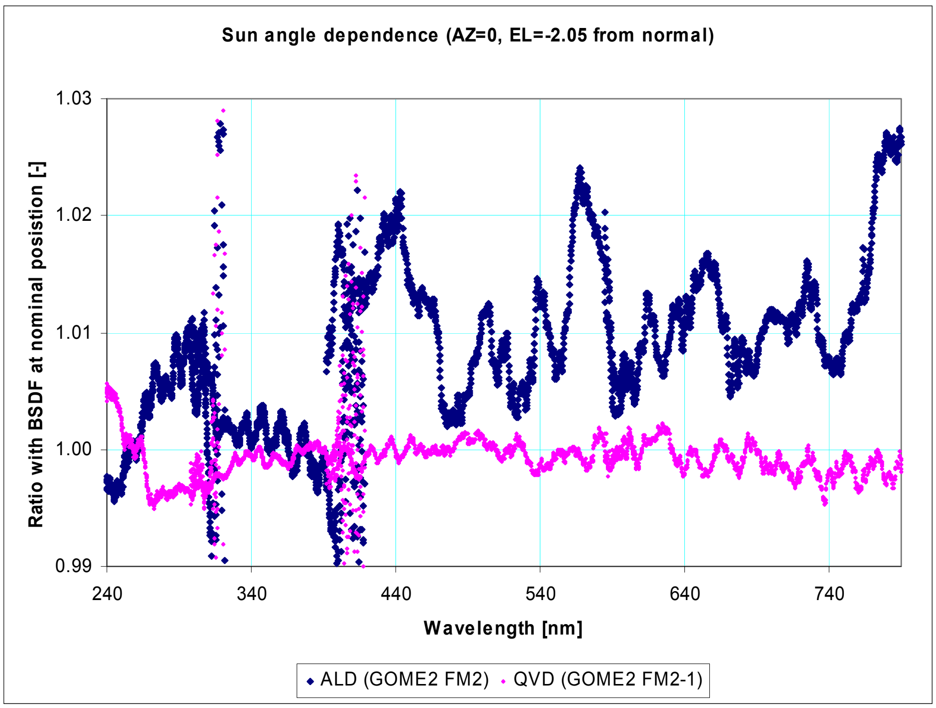

Figure 2-1 Comparison of spectral features with two different diffusers

One drawback of QVD's however is the still existing lack of knowledge of the interaction between diffuser properties and performance. The performance of a QVD, such as the BSDF for instance, depends on several parameters, such as

- angle of incidence of illumination
- angle of detection
- wavelength range
- material
- surface properties
- coating

and further. The current work therefore focuses on QVD's. For the intended systematic approach a set of 24 diffusers (diameter 50mm, thickness 5mm) have been manufactured with different surface properties, i.e. with varying roughness parameters R_q. The roughness ranges from 0.5µm to 3.2µm. The used material was fused silica in order to allow measurements in the UV range. 12 diffusers were designed for transmission, the other 12 for reflection with Al coating on one side. A further variable was the number of rough surfaces, i.e. each diffuser with a given surface roughness had either 1 or two rough surfaces. In case of two rough surfaces both surfaces had the same indicated roughness. The following table lists the different diffusers

Diffuser	Roughness (R_q in µm)
Transmission, 1 rough surface	0.5, 1.0, 1.5, 2.0, 2.5, 3.2
Transmission, 2 rough surfaces	0.5, 1.0, 1.5, 2.0, 2.5, 3.2
Reflection, 1 rough surface	0.5, 1.0, 1.5, 2.0, 2.5, 3.2
Reflection, 2 rough surfaces	0.5, 1.0, 1.5, 2.0, 2.5, 3.2

Table 2-1 Set of QVD's with different properties

3. BSDF MEASUREMENTS

The present chapter describes the performed BSDF measurements. Before the results are presented a description of the used experimental setup is given.

3.1 Experimental Setup: Absolute Radiometric Calibration Facility ARCF

The characterization of optical components, such as diffusers with regards to their BSDF properties is executed in TNO's "Absolute Radiometric Calibration Facility ARCF".

The ARCF is a test setup located in a dedicated class 100 clean room that is capable of accurate measurements of the BSDF. The facility has been used in the past for analyzing components and during calibration campaigns of several earth observation instruments such as the Medium Resolution Imaging Spectrometer (MERIS), SCHIAMACHY, the Ozone Monitoring Instrument (OMI) and GOME-2. The figure below shows a schematic description of the ARCF measurement set-up.

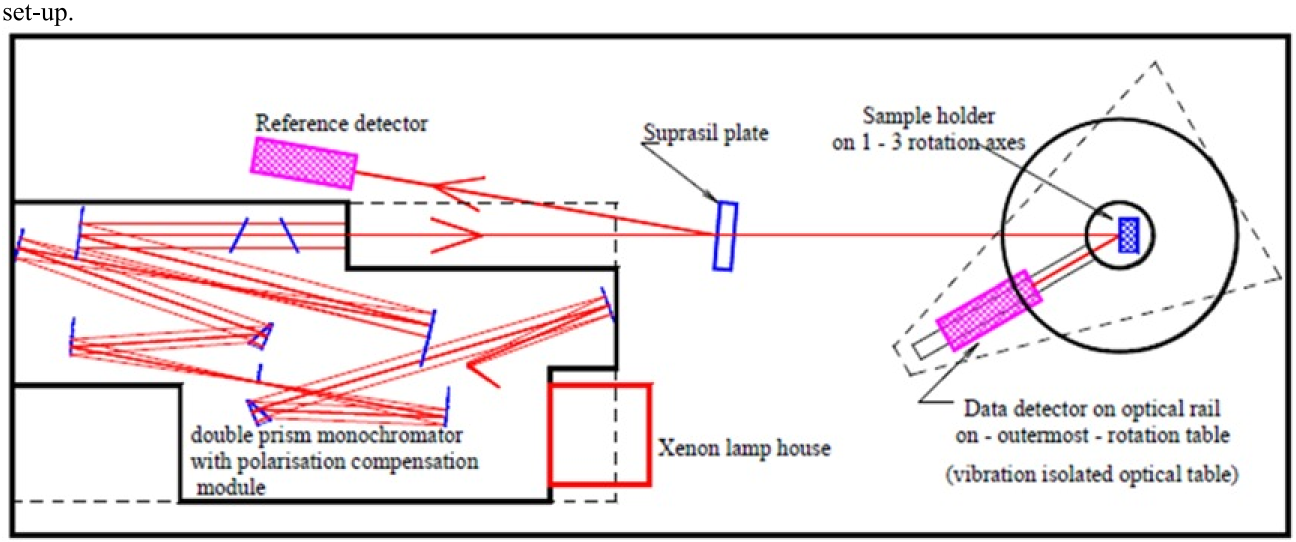

Figure 3-1 Schematic description of the ARCF setup

A wavelength tunable light beam is created by a Xe lamp and an in-house developed monochromator. The beam enters a computer controlled double prism monochromator that is capable to transmit spectral bands in the range of 240 to 2400 nm. The light exits then the monochromator as a collimated beam with a maximum diameter of 40 mm.

The transmitted light is directed towards the optical rail with the data detector and sample. Both the reference and data detector assemblies contain the same components including telescope, detectors from the same manufacturing batch, and synchronous readout. The data detector assembly is positioned on an arm capable of a 360° rotation in a horizontal plane around the diffuser under test.

Two different detectors assure measurements in the full mentioned wavelength regime. A silicon detector for the UV/VIS/NIR domain between 200nm and 1100nm and an Indium-Gallium- Arsenide detector for the SWIR range up to 2400nm. A particular feature of this set is furthermore the possibility of out-of-plane measurements. However, for this study all measurements have been executed in-plane.

Measurements have been performed in three wavelength ranges, i.e. at 325nm, 650nm and 1000nm at varying angles of incidence of illumination. For transmission diffusers this angle was varied between 0° and 20°, for reflective diffusers measurements were performed at 25° and 45° angle of incidence.

3.2 Results BSDF Measurements

In this section we present first results of the performed measurements. Please note that a full analysis is not completed yet and results are presented exemplary. The purpose of this study is to generate an empirical model, for now however we present first results and indicate further intended approaches and investigations.

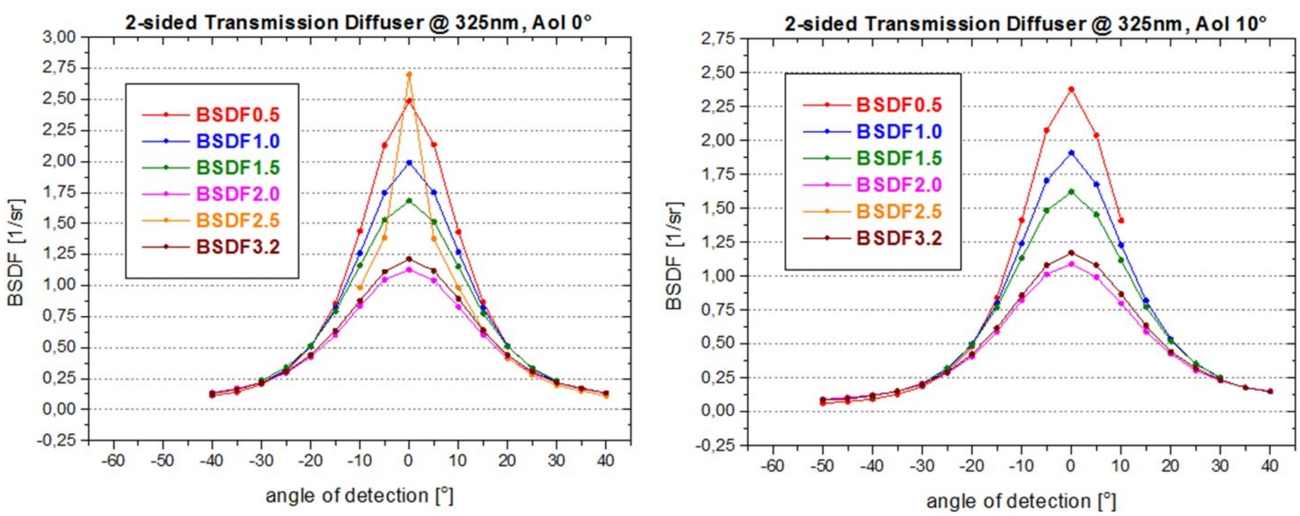

Figure 3-2 BSDF of a transmission QVD with two rough surfaces

Figure 3-2 displays the BSDF of a transmission diffuser with two rough surfaces at an angle of incidence of 0° (left figure) and 10°. As can be seen the max of the BSDF at the specular angle decreases with increasing surface roughness up to 2µm. This is not unexpected, however part of further analysis and studies will be to quantify this pattern. At the same time however irregularities appear. The BSDF curve at 3.2µm surface roughness is above the 2µm one. In particular the 2.5µm results show a very strong specular peak, thus indicating the effect of surface defects. A first conclusion out of these results therefore is that high attention must be paid to the finishing and verification of the surface properties.

3.3 1-sided Reflection Diffuser @ 650nm, AOI=45°

The results in this section display the measurements on a 1-sided transmission QVD at 650nm. As mentioned above 1-sided means that one surface is roughened, while one side is polished. The roughness in µm rms is indicated by the numbers in the graphics.

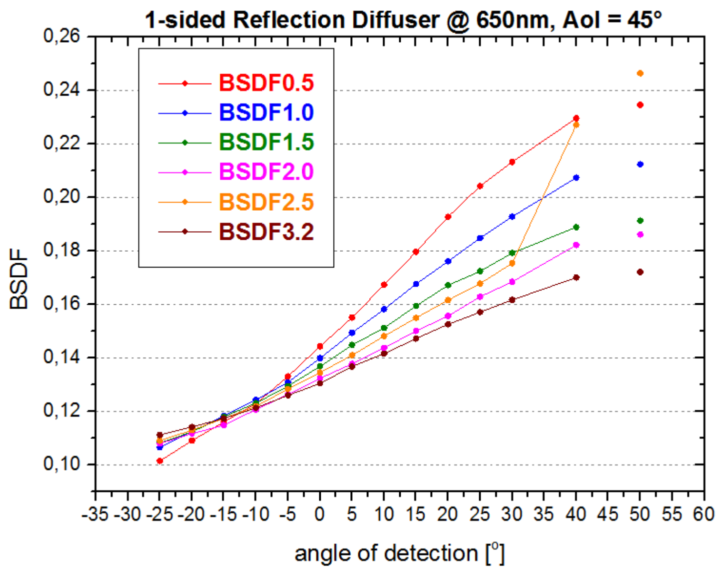

Figure 3-3 Measured BSDF on a 1-sided reflection QVD @ 650nm

It can be seen that the BSDF increases as expected towards the specular angle of 45°. Furthermore a general tendency is visible, showing a flattening BSDF curve with increasing roughness. It can be seen as well though that the diffuser with 2.5µm roughness does not follow this pattern, in particular the strong slope at 35° indicates that the quality of the surface finish is a critical factor, as also seen in Figure 3-2.

To investigate systematic patterns we have a closer look at one fixed angle of detection. This is displayed in more detail in the following graphics.

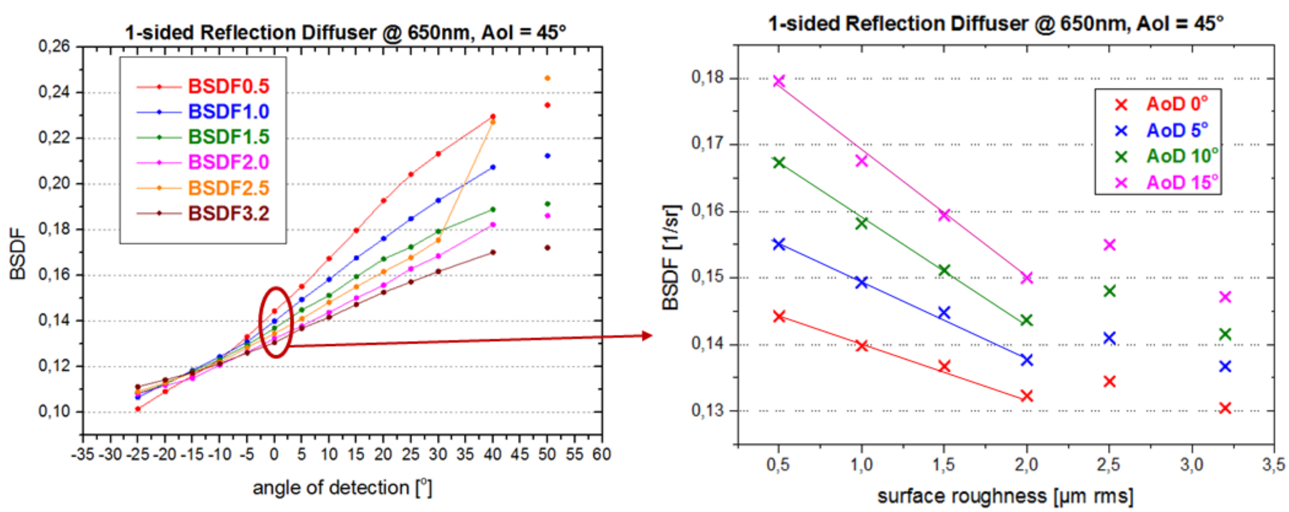

Figure 3-4 BSDF at a fixed angle of detection at different surface roughness

The left graphics is identical with Figure 3-2, the red circle indicates, how the right graphics is generated. In the right graphics the BSDF is drawn over the surface roughness at several angles of detection. The crosses are the values the lines are linear interpolations. It can be seen that the BSDF follows a linear pattern up to a surface roughness of 2.0µm. The values at 2.5µm seem to be too high, it is to be assumed that the sample at this roughness has incomplete surface finish and thus these values are not to be used. There are shown here nevertheless to indicate the criticality of the surface quality of the diffuser. Besides that the pattern seems to "flatten" out for surface roughness above 2µm. One of further investigations and goals will be to quantify this pattern and to compare it with existing theoretical models. Figure 3-4 contains data of several fixed angles of detection. The slope for the linear pattern appears larger at higher angle of detection. In the following graphics the slope for the linear interpolations as shown in Figure 3-4 is printed over the different angles of detection. Here as well a linear pattern can be observed, a linear change of the slope with increasing angle of detection. This information can be used for further investigation and possible modelling.

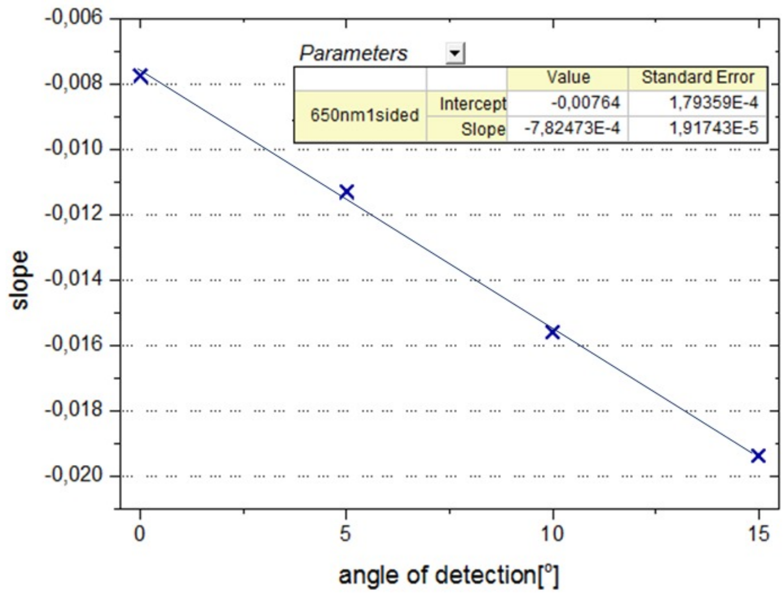

Figure 3-5 Slope value of the linear interpolations over the angles of detection.

4. SPECKLE MEASUREMENTS

In this section we present the experimental setup and results of the speckle measurements. As mentioned above the cause of spectral features in recorded spectra lies in the generation of speckle patterns in the entrance slit by the diffuser. The setup is designed to investigate this pattern and is schemed in the following figure:

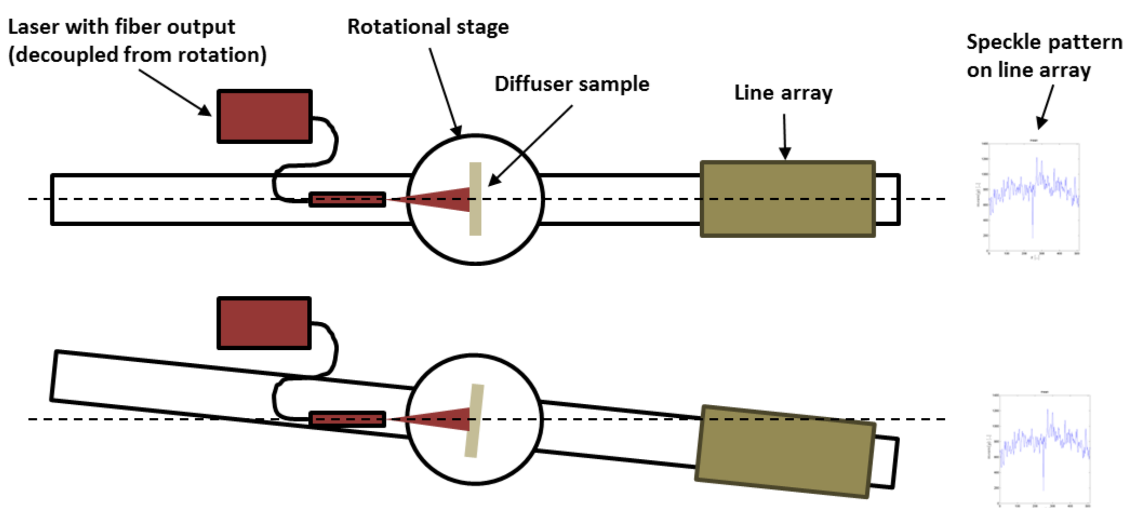

Figure 4-1 Simplified setup scheme for speckle measurements

A rail with a line array is mounted on a rotational stage, on the rail the diffuser sample can be implemented. A diode laser with fiber output (λ = 2330nm) is placed before the sample. The source output is not coupled to the rotational stage, as can be seen in the lower graphics. The angle of illumination is varied by rotating the stage and thus rotating the diffuser sample and line array. Please note that the constellation between diffuser and detector remains constant during rotation.

The purpose of the measurements is as follows. As mentioned above the diffuser generates a speckle pattern on the detector. When the spacecraft moves during a calibration mode around earth, the angle of illumination of the sun on the diffuser changes. This variation of illumination angle results in a shift and change of the speckle pattern, as exemplary displayed in the following figure:

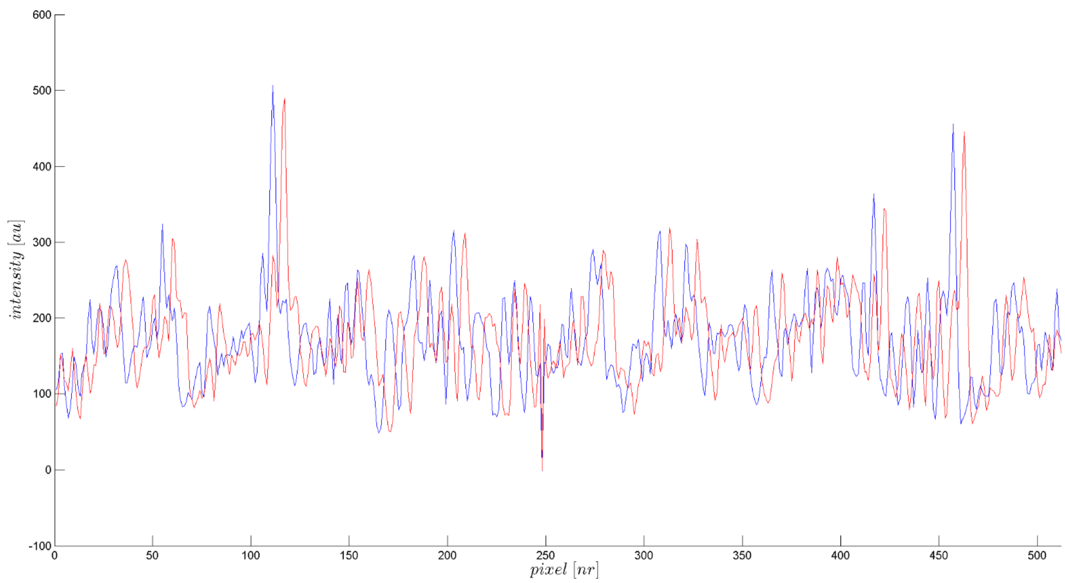

Figure 4-2 Two speckle patterns with slightly different angle of illumination

Basically the rotation of the diffuser simulates the movement of the spacecraft .The shift and change of speckle patterns results in an "averaging-out" effect influencing the amplitude of the spectral features. Thus it has a significant impact on the achievable accuracy of scientific observations. The main question of interest is as follows: How fast does an initial speckle pattern de-correlate so that a minimum of spectral features can be achieved? May Θ_1 and Θ_2 be two different angles of illumination and the according speckle patterns be described by their intensity profile. The correlation coefficient between to patterns at two angles can then be described as

$$\mathrm{Corr}_{\mathrm{coeff}}(\theta_1, \theta_2) = \frac{\sum_{i=1}^{n}\left(I_{\theta_1}\ (x_i) - \overline{I_{\theta_1}}\right)\sum_{j=1}^{n}\left(I_{\theta_2}(x_j) - \overline{I_{\theta_2}}\right)}{\sqrt{\sum_{i=1}^{n}\left(I_{\theta_1}\ (x_i) - \overline{I_{\theta_1}}\right)^2} \times \sqrt{\sum_{j=1}^{n}\left(I_{\theta_2}\ (x_j) - \overline{I_{\theta_2}}\right)^2}}$$

Two patterns are considered de-correlated, when the coefficient reaches the value 0.5. The according decorrelation angle is the angle is the value twice as the one at 0.5.

4.1 Results Speckle Measurements

This chapter contains first results of the performed speckle measurements. As described above one speckle pattern is recorded at an angle of incidence of 0°. Then the rotational stage is rotated by 0.005°, another speckle pattern is recorded and the correlation coefficient determined. Preliminary exemplary results for a transmission are shown in Figure 4-3:

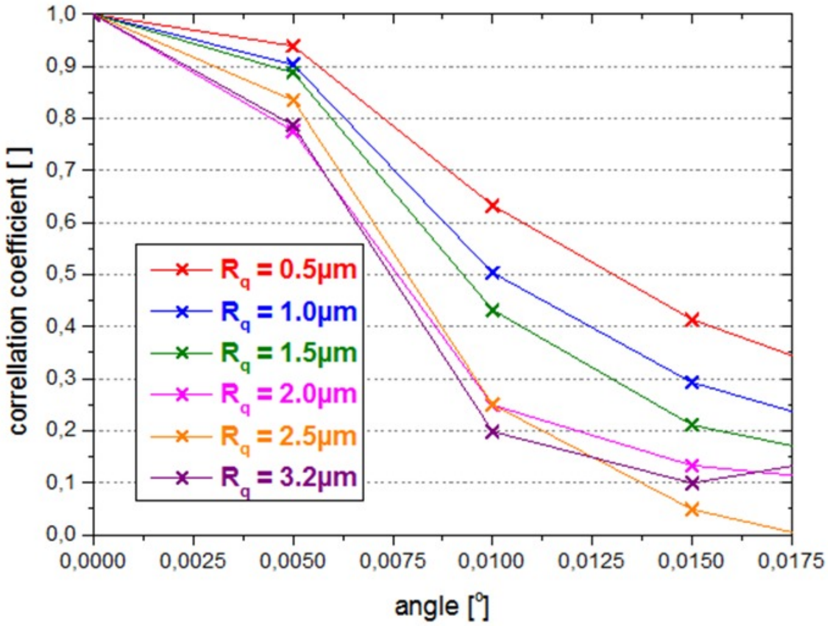

Figure 4-3 Correlation coefficients for QVD samples with different surface roughness

It can be seen that the speckle pattern decorrelates faster with increasing surface roughness, which is not unexpected. As mentioned above the decorrelation angle is twice the angle, where the graphics intersects the value at 0.5. However it is still to be investigated, if this pattern can be quantified. In the following graphics this angle is drawn over the surface roughness:

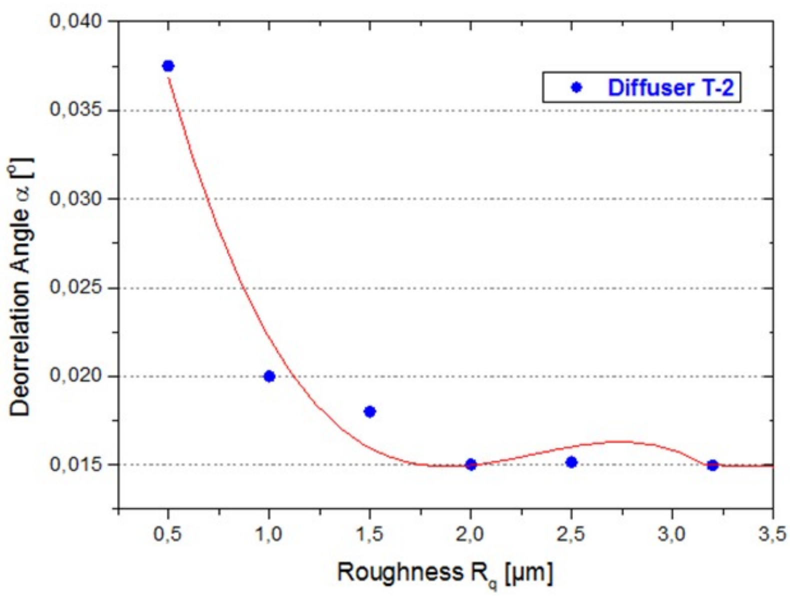

Figure 4-4 Decorrelation angle over surface roughness

Similar to the BSDF results shown in Figure 3-4 we see a strong slope and pattern up to a surface roughness of 2µm, before the curve flattens out. This as well has to be investigated, whether this pattern can be explained with existing models.

5. SUMMARY AND CONCLUSIONS

In the recent past TNO has introduced so called quasi volume diffusers (QVD's) as components in on-board calibration units. In comparison to spectralon or Al-diffusers the choice of QVD's showed different advantages, one having a less degradation in orbit and two, showing smaller spectral features in the L2 data product. The connection however between diffuser properties, such as for instance observational conditions or surface properties and the diffuser performance in terms of BSDF or spectral features are not well known. The motivation of this paper was to systematically investigate this relation experimentally and to generate a large data base that can be used for possibly generating an empirical model. For this purpose a set of 24 QVD's has been manufactured with different properties, such as transmission, reflection, number of rough surfaces and surface roughness. One of the main goals in the data analysis besides the generation of a data set was to identify also possibly existing systematic patterns in the data. Measurements were done under varying conditions, such as different wavelength (325nm, 650nm, 1000nm) and different observational conditions (angle of incidence, angle of detection).

In this paper we have presented exemplary first results in terms of BSDF and spectral features. A first analysis of the data showed that accurate knowledge of the surface properties must be known and surface defects can lead to significantly incorrect results. This will be further investigated.

A systematic pattern could be identified, when observing the BSDF behavior at a fixed angle of detection. The data showed linear behavior with changing surface roughness up to 2µm. In further activities it will be attempted to quantify this effect and to compare it with existing theoretical models.

A similar observation was made for speckle measurements. First, the decorrelation of two speckle patterns occurred faster with increasing surface roughness. Second, similar as to the BSDF the data showed a rapid change of the relation between decorrelation angle and surface roughness was stronger for a roughness up to 2µm.

Further data analysis and the investigation of systematic patterns is in progress. Additional activities will include the evaluation of methods for a proper surface evaluation and the comparison with theoretical models.

REFERENCES

[1] Courrèges-Lacoste, G. B., van Brug, H., Groote Schaarsberg, J., Otter, G. del Bello, U. "Spectral features effect on reference diffusers : diffuser trade-off study", Proc. SPIE 5978 (2005)
[2] Otter, G., van Brug, H., Groote Schaarsberg, J., Delwart, S., del Bello, U., "Enhancement of Diffuser BRDF Accuracy" Proc. 6th International conference on Space Optics, ESA SP-621 (2006)
[3] Otter, G., "Spectral_features" Spectral Features Workshop 4, Astrium Toulouse (2005)