Solar diffusers in earth observation instruments with an illumination angle of up to 70°: Design and verification of performance in BRDF

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ABSTRACT

The present paper describes the challenging diffuser design and verification activities of TNO under contract of a customer for an earth observation instrument with observation conditions that require feasible BRDF under large angles of incidence of up to 70° with respect to the surface normal. Not only the design though but also the verification of the diffuser performance under such angles including "out-of-plane", i.e. angle theta detection of the scattered light, was an essential activity to be executed. In this paper we will summarize the R&D activities with respect to diffuser design and verification that were recently carried out at TNO and present its applicability to current and future earth observation missions with challenging observation conditions and thus challenging diffuser requirements under high illumination angles.

Keywords: BSDF, BRDF, Diffuser, Radiometric Calibration

1. INTRODUCTION

Onboard calibration units are highly important elements of an earth observation instrument. This unit ensures through its calibrating and monitoring functionality accurate performances and thus accurate scientific observations of an instrument during its lifetime in orbit. One critical optical element in this unit is the so-called solar diffuser, which is illuminated by the sun as an irradiance source. The diffusers performance is expressed through its scattering properties, the Bi-Directional Scattering Function BSDF (or BTDF in transmission mode or BRDF in reflection mode) and depends on several parameters, such as surface properties, angle of incidence and detection and further. Thus its adequate definition in these terms of variables and parameters are of significant importance for the quality and accuracy of L2 data products. The present paper describes the challenging diffuser design in reflection mode and verification activities of TNO in cooperation with BISME for an earth observation instrument with observation conditions that require feasible BRDF under large angles of incidence of up to 70° with respect to the surface normal. Besides the design the according verification of the diffuser performance under such angular conditions, including "out-of-plane", i.e. angle theta detection of the scattered light, was an essential activity to be executed. This was carried out using the "Absolute Radiometric Calibration Facility ARCF" at TNO Delft in the Netherlands, a unique facility for the characterization and calibration of optical components for space applications.

2. EO INSTRUMENT

The calibration unit under consideration was designed for the earth observation instrument called *"Atmospheric Instrument (AI)"*. AI is a spectrometer designed for determination of atmospheric compositions in a sun synchronous orbit. AI will operate in a spectral range 0.75 to 2.4 microns and will measure atmospheric absorption spectra with high resolution. As mentioned above the on-board calibration activities, including on-ground characterization, for this instrument, are very crucial for the high accuracy retrievals of atmospheric compositions and are carried out, when the instrument is not in operational mode. For this purpose a *"Quasi Volume Diffuser (QVD)"* was selected due to its stable properties in particular with regards to degradation and further features [1]. Despite of that stability however two diffuser plates are mounted on the mechanism, one plate being exposed to sunlight every orbit for solar irradiance calibration, while the other plate is exposed less frequently for monitoring purposes of performance degradation.

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3. OBSERVATIONAL CONDITIONS

Once an earth observation instrument is in orbit regular calibration procedures have to be performed. Earth observation instruments 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 (in reflection mode) the "Bi-Directional Reflectance Function" BRDF of the earth (*BRDF = radiance_earth / irradiance_sun*) is determined. To mimic the scattering of the earth, so-called 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.

The right choice of a diffuser that meets mission requirements in terms of its scattering performance depends on a variety of variables, such as angle of incidence and detection, its required scattering behavior, spectral range and further. It is the ideal combination then of several parameters that suggests a design of a diffuser that will perform as required for the individual mission, such as type of diffuser (transmissive, reflective, Spectralon, aluminum, Quasi Volume Diffusers (QVD's), …), material, surface properties and further. For the present project a reflective QVD was selected, a (water-free) fused silica component with an aluminum coating. The following image illustrates exemplary the general process of a QVD design, in which based on customer and mission requirements TNO experts define according diffuser properties.

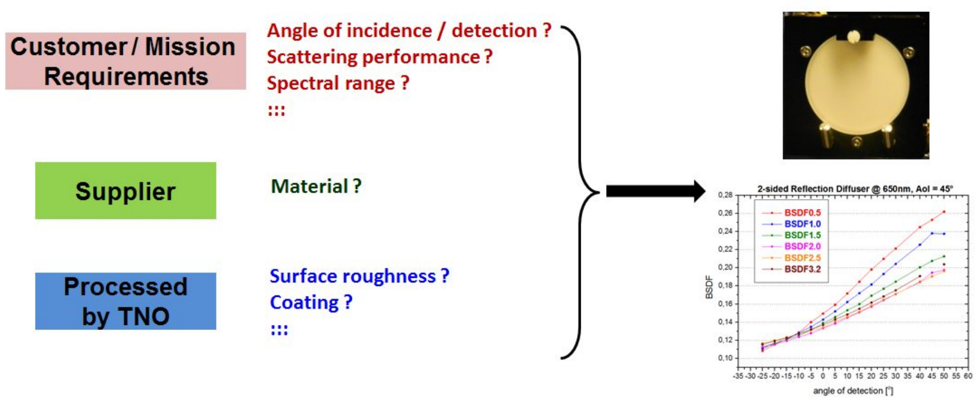

Figure 3-1 Combination of parameters for required diffuser performance

As mentioned above almost each earth observation mission has its unique tasks, goals and observational conditions. The project with regards to this paper contains requirements on the on-board diffuser, which differ to previous missions, such as for instance an angle of incidence of illumination of up to 70° to the diffuser surface normal. Please note that also angles out of plane, the so-called "theta" angle was given with 32.5°.
The sampling time of the instrument is much longer than most missions. To minimize the error induced by the variation of the sunlight incident angle during the solar calibration, the diffuser surface is designed to be parallel to the orbital plane (XZ plane) based on the feature of synchronous orbit. The largest incident angle of sunlight to the surface normal will be 70° which is determined by the local time of ascending node. The image below shows a very simplified illustration of the largest angle of incidence.

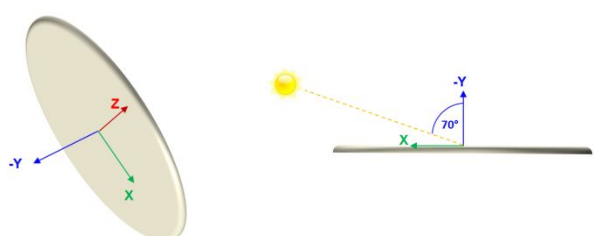

Figure 3-2 Simplified illustration of largest angle of incidence. The left image shows the diffuser as seen by the sun, the right image displays the X-Y plane with the maximum angle of incidence of 70° to the surface normal. The -Y direction indicates the angle of detection and has an angle of 32.5° with respect to the diffuser normal.

A full summary of all illumination conditions is listed in Table 3-1. The image on the side (Figure 3-3) shows the calibration unit as seen from the sun, indicating the large angle of incidence to the diffuser normal, while the scheme below (Figure 3-4) illustrates the full illumination conditions as listed in Table 3-1:

	CU Coordinate System		
Measurement No.	**Zenith**	**Phi (-β, X-Z plane)**	**Theta (Y-Z plane)**
1	70°	-27.0°	32.5°
2	70°	-18.5°	32.5°
3	70°	-10.0°	32.5°
4	55°	-27.0°	32.5°
5	55°	-18.5°	32.5°
6	55°	-10.0°	32.5°
9	65°	-27.0°	32.5°
8	65°	-10.0°	32.5°
10	60°	-27.0°	32.5°
7	60°	-10.0°	32.5°
11	60°	-18.5°	32.5°
12	65°	-18.5°	32.5°

Table 3-1 Listing of all angular illumination conditions

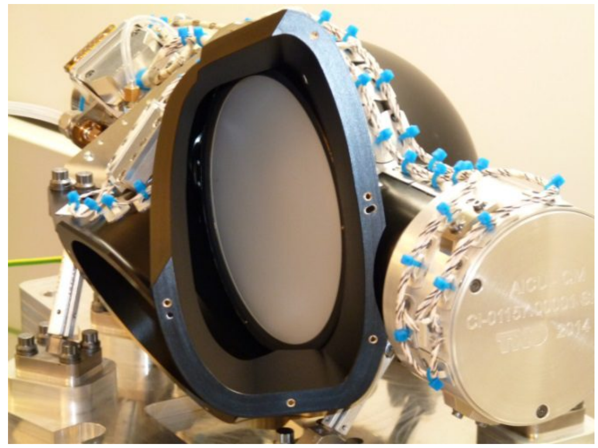

Figure 3-3 Calibration unit with diffuser as seen by the sun

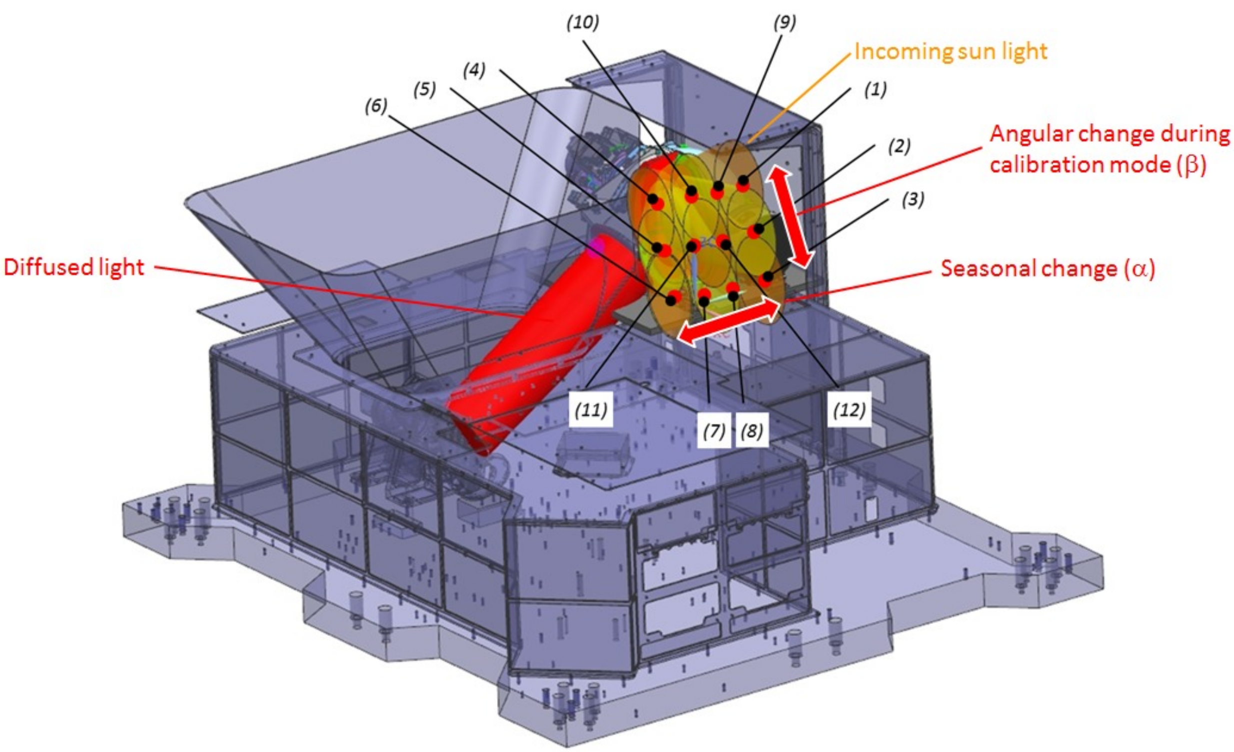

Figure 3-4 Illustration of all angular illumination conditions as listed in Table 3-1

For the full characterization of the diffuser it is necessary to cover the full illumination grid as shown above.

The spectral bands are listed in the following table:

	Channel 1	Channel 2	Channel 3	Channel 4
Wavelength range (µm)	0.75-0.77	1.56-1.72	1.92-2.08	2.20-2.38

Table 3-2 Requirements on spectral radiance scattered by the diffuser

4. EXPERIMENTAL SETUP

Before the results are presented a description of the used experimental setup is given.

The characterization of optical components, such as diffusers with regards to their BRDF 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 BRDF / BTDF. 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.

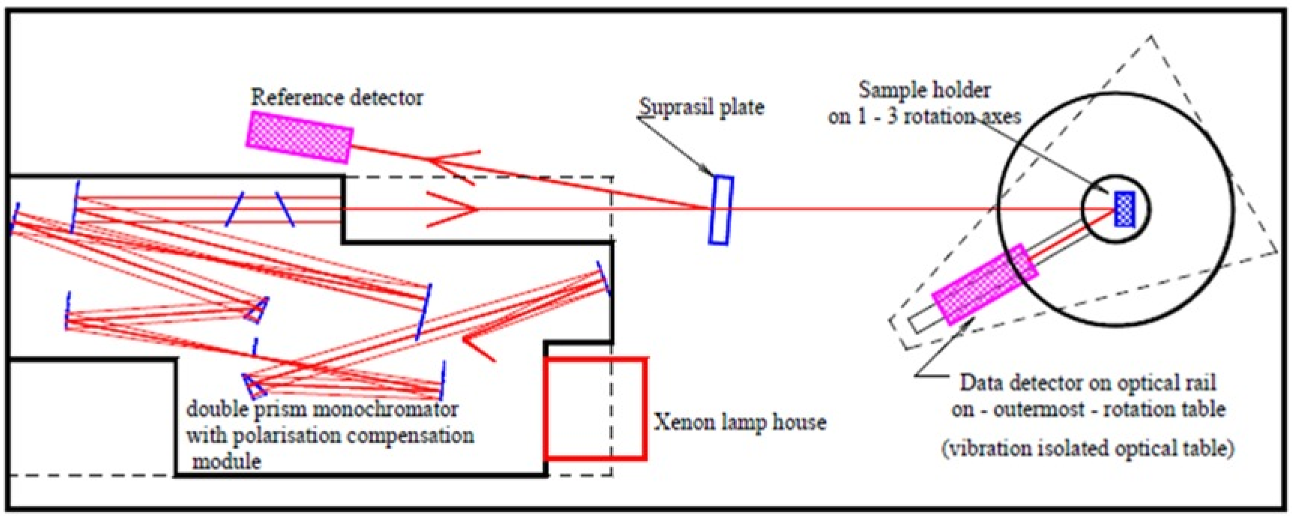

Figure 4-1 Schematic description of the ARCF setup

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. For this purpose the setup is extended with an additional device containing additional stages and thus allowing movement and rotation in further degrees of freedom.

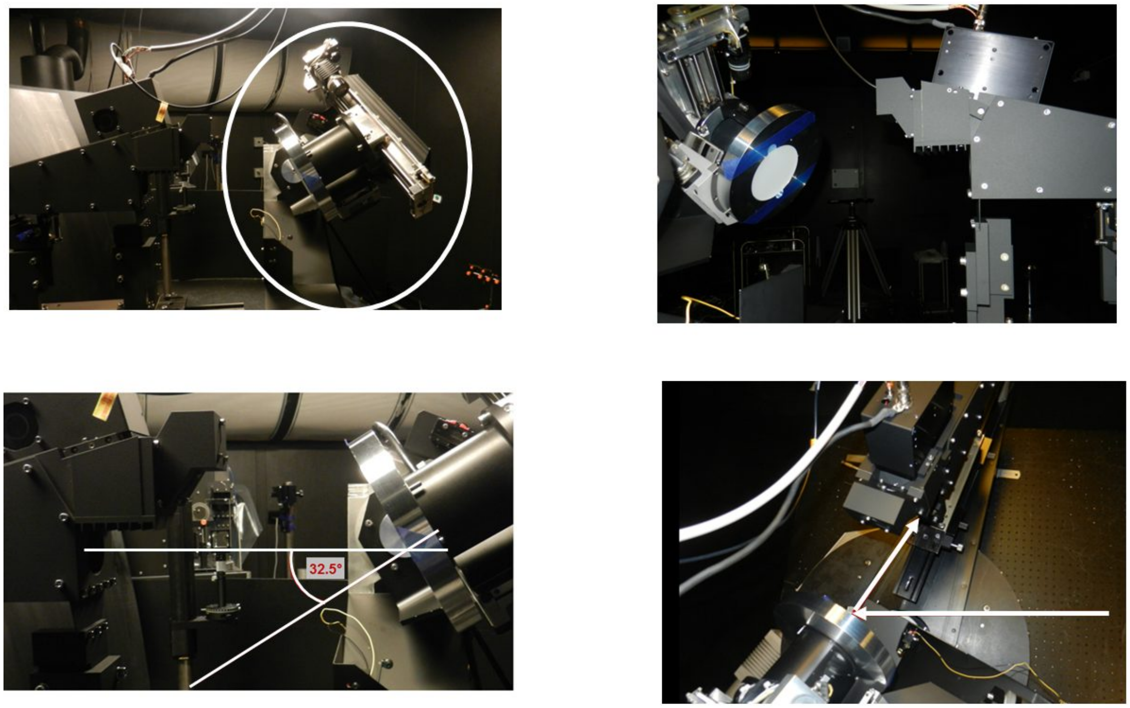

Figure 4-2 Out-of-plane measurements with the ARCF setup

5. RESULTS

In this section we describe the process as illustrated in Figure 3-1 and present according results of BRDF measurements.

In a first step we describe the surface finishing of the samples and evaluation of surface properties that influence the BRDF performance of the QVD. Secondly we present the results of the selected QVD design.

5.1 Surface Roughness

When considering a QVD as a diffuser, one of the main points to be evaluated is the surface property of the QVD. In particular the surface roughness influences the scattering behavior of the QVD significantly, as displayed in the following figure [1]:

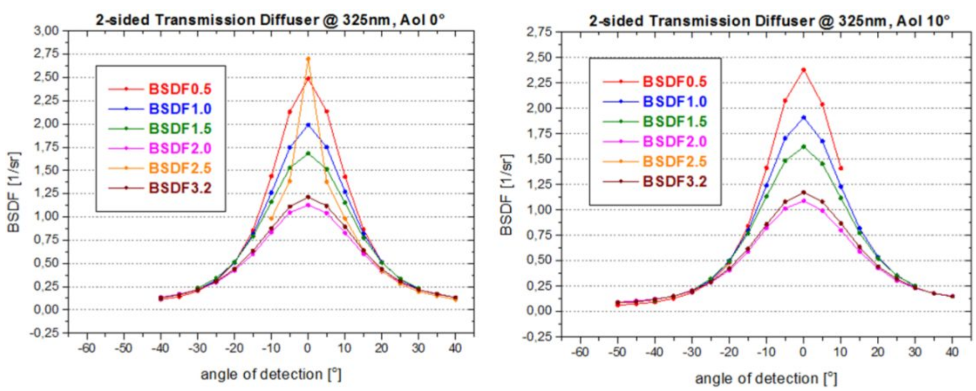

Figure 5-1 BSDF of a transmission QVD with two rough surfaces

Figure 5-1 displays the BRDF of a transmission diffuser with two rough surfaces at an angle of incidence of 0° (left image) and 10° and an angle of detection of 0°. The numbers in the legend indicate the surface roughness (on both surfaces of the diffuser plate) in terms of "root mean square" rms in µm. Thus *"BSDF0.5"* represents data related to measurements of a transmission diffuser with 2 rough surfaces of a roughness of 0.5µm rms. As can be seen the maximum of the BRDF at the specular angle decreases with increasing surface roughness up to 2µm. At the same time however irregularities appear, such as the results for the 2.5µm diffuser plate shows a very strong specular peak, indicating the effect of surface defects. A first conclusion out of these results therefore was that high attention must be paid to the finishing and verification of the surface properties. Please note that although a transmission diffuser is shown here (in order to display the shown surface defects) it applies as well to reflective diffusers. Further details can be found in [1].

At the same time previous investigation as reported in [1] indicate for single diffuser plate configurations a limit on needed surface roughness for a certain required BSDF performance. Meaning that above 2µm rms a further increase in surface roughness does not lead to stronger scattering properties and stronger BSDF performance. Thus for further scattering not a higher surface roughness, but rather additional rough surfaces would be needed. The following figure supports this finding.

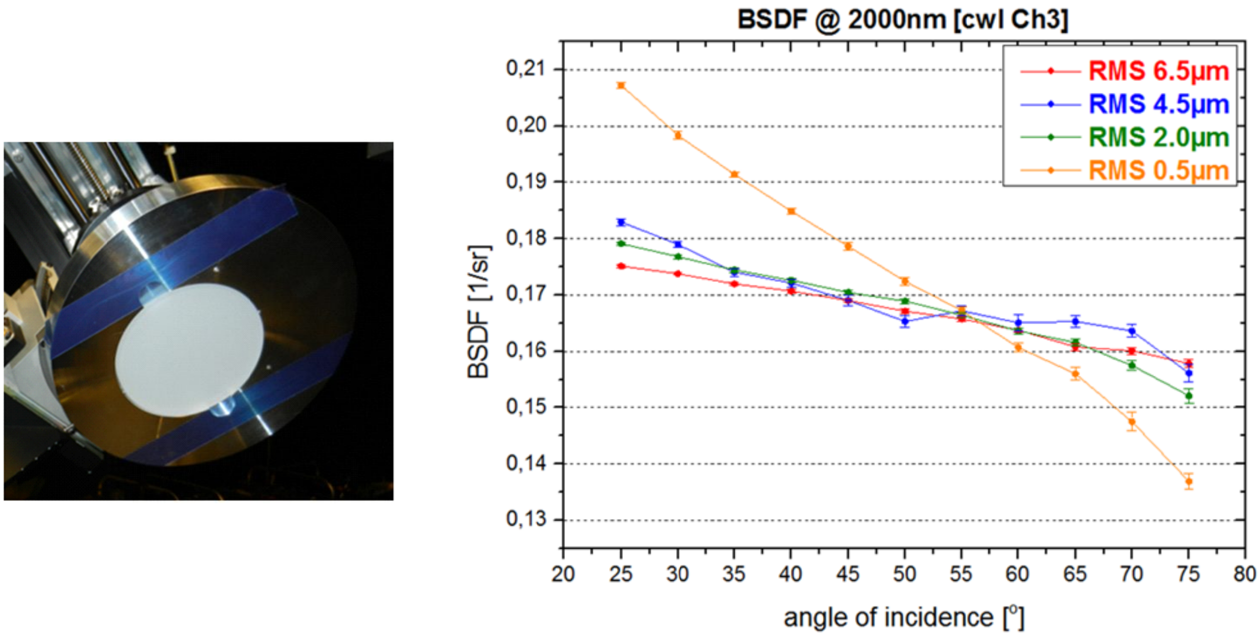

Figure 5-2 BSDF measurements with different test samples and varying surface roughness @ 2000nm. The angle of detection is 0°

Figure 5-2 displays BSDF measurements of diffusers (Ø 125mm, thickness 5mm, fused silica with Al-coating) with different surface properties and varying angle of incidence in the SWIR range. As can be seen the BSDF for the QVD's with 2µm to 6.5µm surface roughness rms are very similar (within 5-7%) in value and trend, while the diffuser with a rather low roughness of 0.5µm rms differs significantly and shows a strong slope. Beside the rather weak scattering properties this would be more sensitive to roughness variations and also require more stringent mechanical accuracy requirements for the diffuser mechanism in an EO instrument.

Although above 2µm rms the BSDF performance seems not to change significantly, homogeneous surface properties are desired. In an internal TNO project the surface properties of fused silica material was investigated for different surface roughness' in particular to ensure homogeneous surface properties. Differences can be seen in the following figure. The left two figures had a target roughness of 2µm rms, the right images 6µm rms. Both samples were treated with abrasive grinding. The upper figures display images taken with a confocal microscope, while the lower figures show one line measured with a chromatic sensor. It can be seen that the sample with 2µm roughness shows a more homogeneous surface profile and thus would be more preferable for the final design of the QVD in the present project.

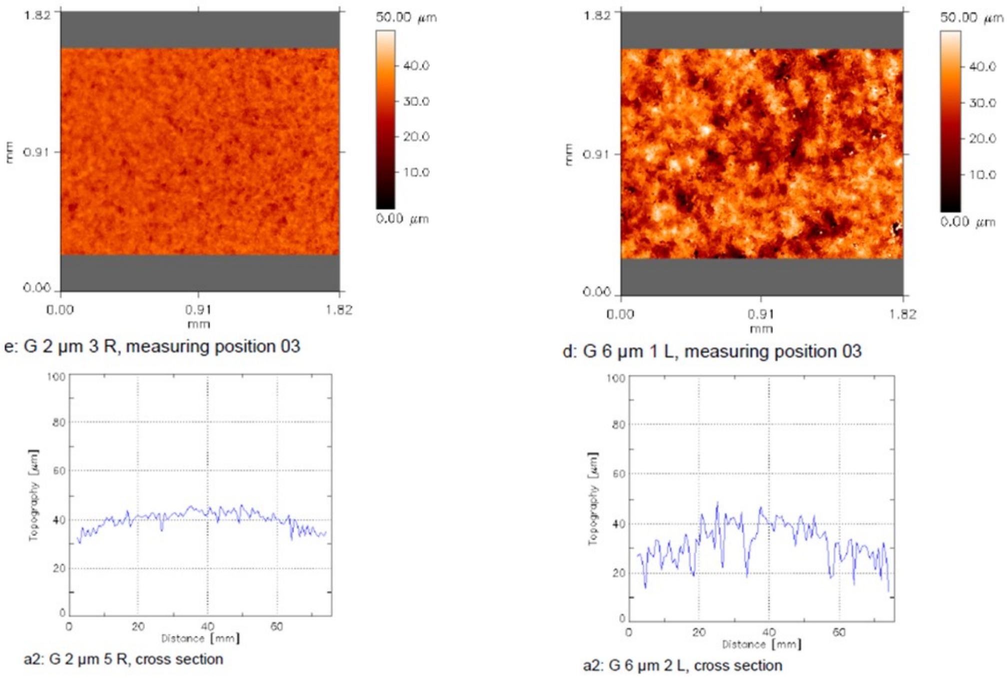

Figure 5-3 Optical surface measurements of fused silica components with a confocal microscope (upper images) and a chromatic white-light sensor (lower images). The better surface homogeneity at 2µm surface roughness makes this surface roughness more preferable for the final design of the QVD.

5.2 BRDF Measurements – Different Spatial positions

After the optimizing process had been completed BRDF measurements were performed on several samples within the spectral bands and angular configurations as described in chapter 3. In chapter 5.1we underlined the criticality on the surface homogeneity. Thus, for verification purposes of the accordance BRDF performance some of the samples have been measured on different spatial positions, as illustrated in Figure 5-4:

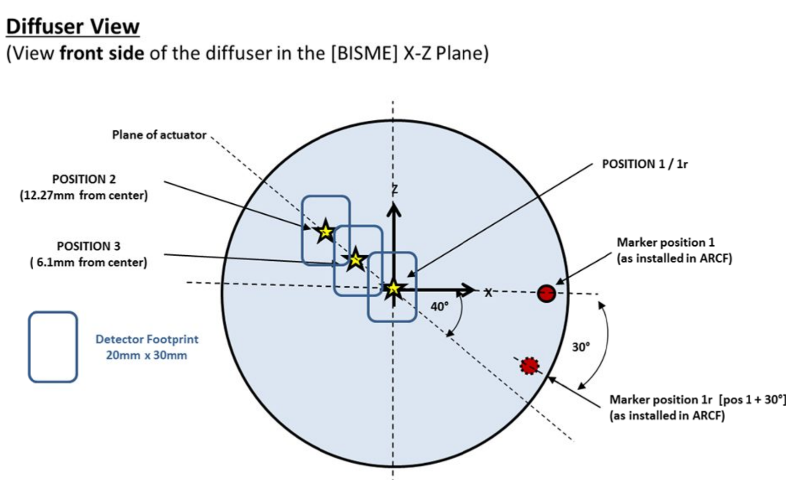

Figure 5-4 Position and areas, where BRDF has been measured

In Figure 5-4 the footprint of the detector is indicated along with the spatial positions, where the BRDF has been measured. In addition the central position has been measured under a different orientation of the diffuser, i.e. rotated by 30° and marked as position "*1r*". In Figure 5-5 exemplary results are shown for one diffuser sample at different angular configurations. Analysis shows a variation of less than 1% (1σ), indicating well manufactured and homogeneous surface properties.

Please note that the legends of the x-axis in Figure **5-5** to Figure **5-9** refer (due to project related reasons) to the diffuser surface plane, not to the diffuser normal. Thus e.g. 20° refers to an angle of 90° - 20° = 70° to the diffuser normal

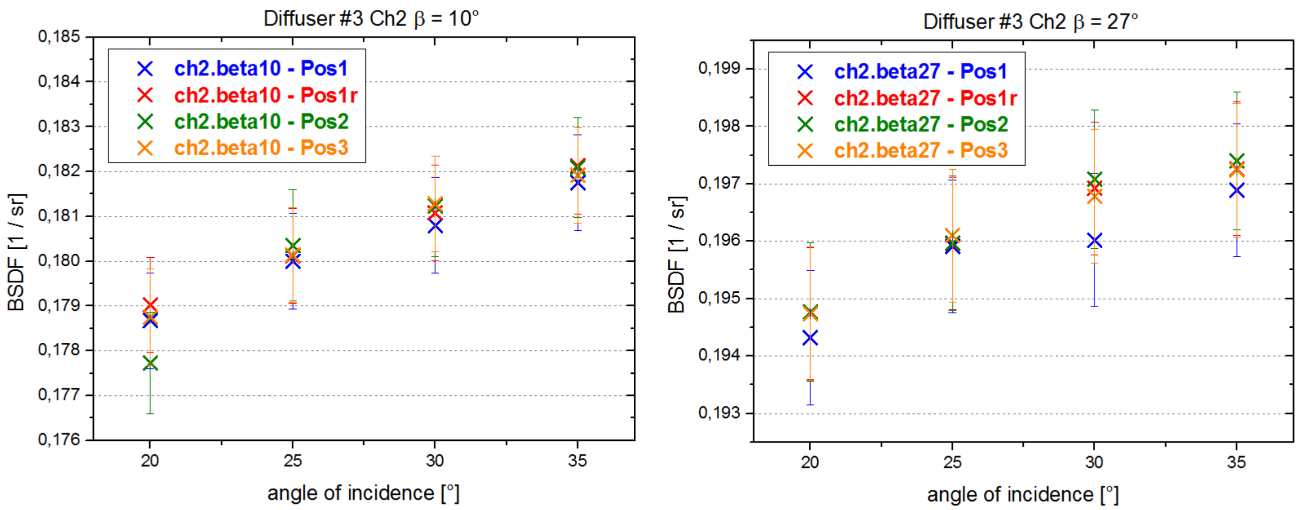

Figure 5-5 BSDF measurements at different spatial positions

5.3 BRDF Measurements – Results

In this section we present the results from the aforementioned measurements. Please note that due to the large data set that was generated during this project, some graphics are exemplary. Overall a set of 9 samples were manufactured, however not all of them underwent the same measurement program. On two samples different spatial positions were measured as discussed in section 5.2. Seven samples (in the following labelled as diffuser# or sample#) were evaluated with the full measurement program incl. all angular configurations as listed in Table 3-1.

Figure 5-6 to Figure 5-9 show exemplary the BSDF results in all spectral regions from 4 different diffuser samples.

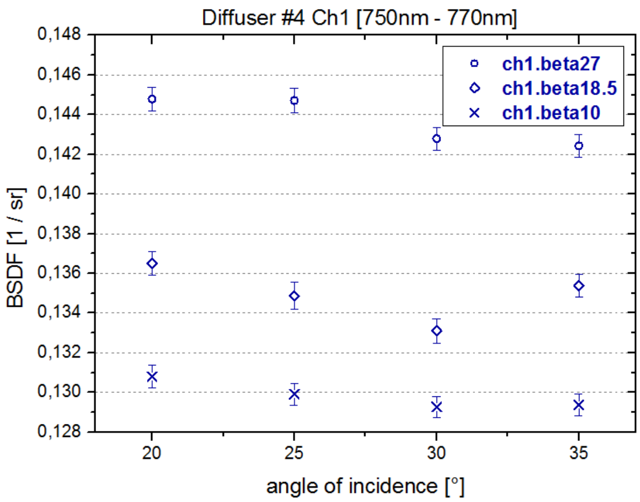

Figure 5-6 BSDF for diffuser #4 in channel 1

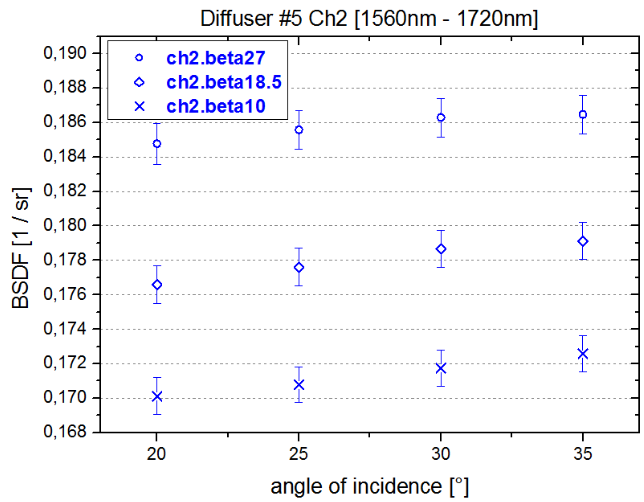

Figure 5-7 BSDF for diffuser #5 in channel 2

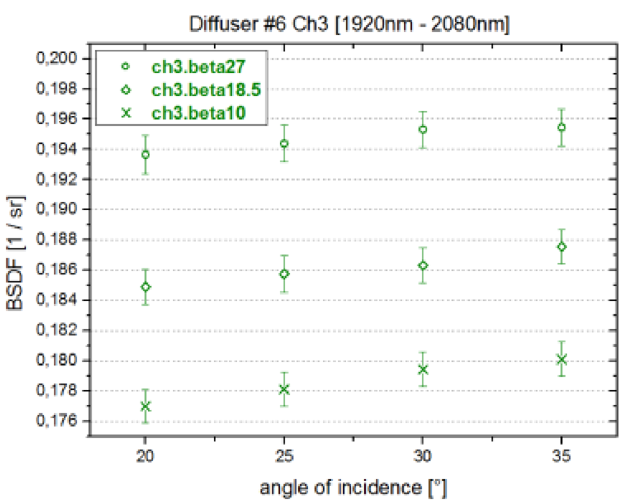

Figure 5-8 BSDF for diffuser #6 in channel 3

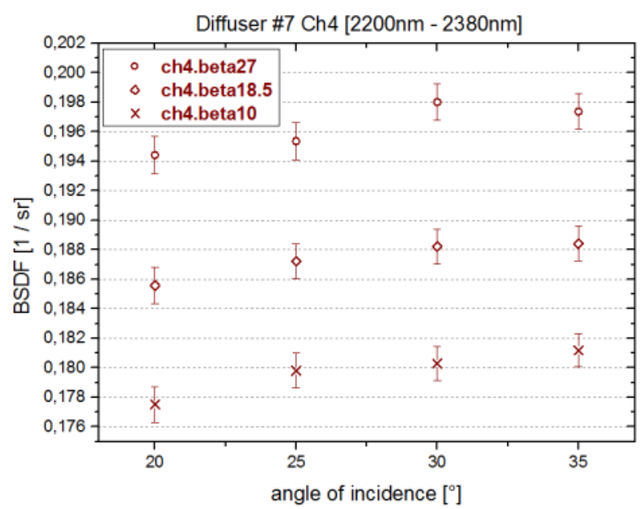

Figure 5-9 BSDF for diffuser #7 in channel 4

Figure 5-10 display all results that were determined during this project additionally in radiance units. The upper values correspond to an angle of incidence of 55°, while the lower ones to the maximum angle of incidence of 70°.

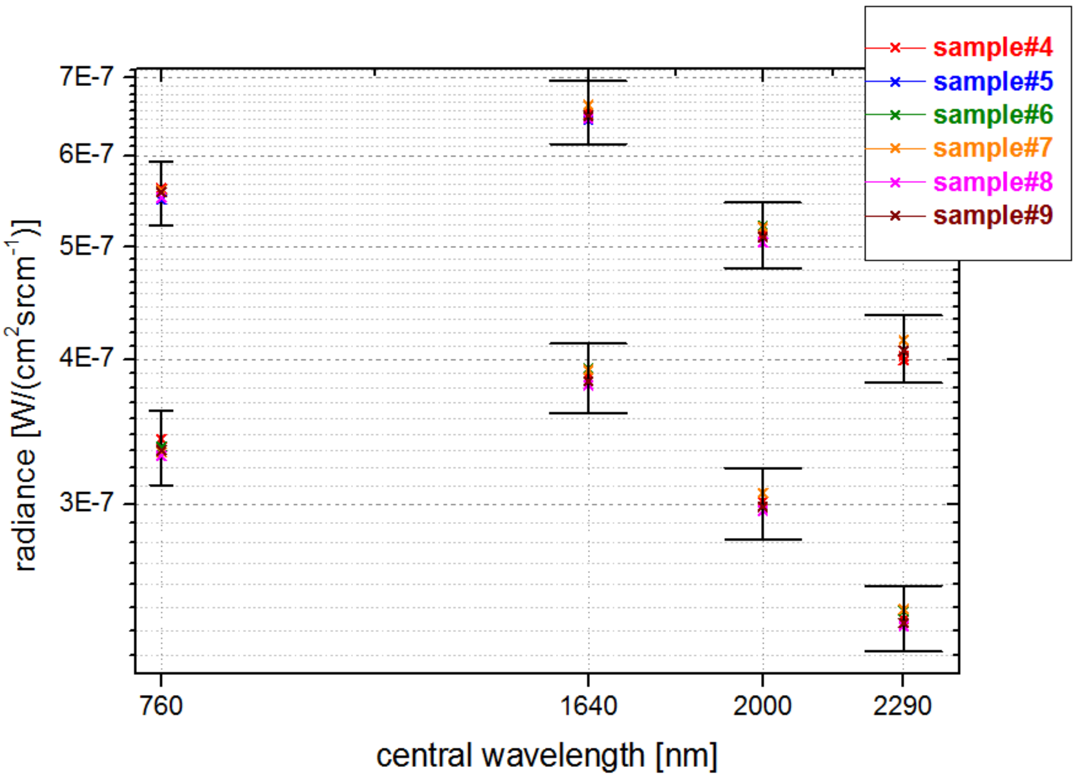

Figure 5-10 All determined values in radiance values.

Detailed statistical analysis (which would be out of the scope of this manuscript) show a variation of 2.4% to 2.9% between the different samples. This underlines additionally the stable manufacturing procedure of the samples.

6. SUMMARY AND CONCLUSIONS

This paper describes the challenging diffuser design for the on-board calibration unit of the "*Atmospheric Instrument*" under the leadership of the Beijing Institute of Space Mechanics & Electricity BISME. In order to meet the requirements under difficult illumination conditions, such as high angle of incidence of up to 70°, many aspects in terms of surface roughness, homogeneity and further in the QVD design had to be considered. It was demonstrated that a water-free fused silica QVD with two rough surfaces and an aluminum coating is a suitable component for the desired task. BSDF measurements were performed on 9 samples in TNO's "*Absolute Radiometric Calibration Facility ARCF*", a dedicated setup for BSDF measurements in a class 100 (ISO 5) clean room environment. All results are well within the required specifications.

REFERENCES

[1] Gür, B., van Brug, H., Xu, M., Vela, E., "*Diffusers, properties, and performance in BRDF*", Proc. SPIE 9205-10 (2014)