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## CHARACTERIZATION OF DIFFRACTION GRATINGS SCATTERING IN UV AND IR FOR SPACE APPLICATIONS

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### ABSTRACT

The use of Bidirectional Scatter Distribution Function (BSDF) in space industry and especially when designing telescopes is a key feature. Indeed when speaking about space industry, one can immediately think about stray light issues. Those important phenomena are directly linked to light scattering.

Standard BSDF measurement goniophotometers often have a resolution of about  $0.1^\circ$  and are mainly working in or close to the visible spectrum. This resolution is far too loose to characterize ultra-polished surfaces. Besides, wavelength range of BSDF measurements for space projects needs to be done far from visible range. How can we measure BSDF of ultra-polished surfaces and diffraction gratings in the UV and IR range with high resolution?

We worked on developing a new goniophotometer bench in order to be able to characterize scattering of ultra-polished surfaces and diffraction gratings used in everyday space applications. This ten meters long bench was developed using a collimated beam approach as opposed to goniophotometer using focused beam. Sources used for IR characterization were CO<sub>2</sub> (10.6 $\mu$ m) and Helium Neon (3.39 $\mu$ m) lasers. Regarding UV sources, a collimated and spatially filtered UV LED was used. The detection was ensured by a photomultiplier coupled with synchronous detection as well as a MCT InSb detector.

The so-built BSDF measurement instrument allowed us to measure BSDF of ultra-polished surfaces as well as diffraction gratings with an angular resolution of  $0.02^\circ$  and a dynamic of  $10^{13}$  in the visible range. In IR as well as in UV we manage to get  $10^9$  with same angular resolution of  $0.02^\circ$ . The 1m arm and translation stages allows us to measure samples up to 200mm.

Thanks to such a device allowing ultra-polished materials as well as diffraction gratings scattering characterization, it is possible to implement those BSDF measurements into simulation software and predict stray light issues. This is a big help for space industry engineers to apprehend stray light due to surface finishes and to delete those effects before the whole project is done.

We are now thinking of possible improvement on our optical bench to try to get dynamic in IR and UV similar to what we have in visible range (e.g.  $10^{13}$ ).

**Keywords:** scattering, BSDF, diffraction grating

### I. INTRODUCTION

#### A. BSDF

The distribution of the scattered light from optical components depends on several parameters: the wavelength, the angle of incidence, the sample's reflectance, transmittance and absorption, the refractive index of the sample, the cleanliness, etc. The Bidirectional Scattering Distribution Function is commonly used to describe scattered light patterns. In other words, the way that the light is scattered by the sample is described by the BSDF.

Actually, the BSDF is a general term of the BRDF, BTDF, or BVDF for Bidirectional Reflective, Transmittance and Volume Distribution function.

Even if the mathematic expression of the BSDF is simple, it is not always obvious to interpret it if we are not familiar with, that is why the BSDF is not used extensively. Yet, the BSDF could be useful to qualify and understand how an optical sample scatters the light.

#### B. TIS

The Total Integrated Scatter (TIS) is the integration of the scattered signal into a hemisphere: the scattered light from the sample is integrated into a reflective hemisphere then normalized by the total reflected power of the incident beam. The ratio is defined as the TIS.

Without closer looking, the TIS could be considered as a single number for sample's scatter characterization. Indeed, for smooth and clean surfaces, with low absorption, the TIS approaches 1 and reciprocally. Today, the TIS is used as an important scatter specification.

### C. ARS

With the Specular Bench developed by Light Tec, we measure the Angle Solved Scatter (ARS) and not the BSDF directly. Then, from the measured ARS, we deduce the BSDF. Indeed, the ARS is the BSDF function multiplied by the cosine of the scattering angle.

## II. ARS MEASUREMENTS AND INSTRUMENTATION

Light Tec has developed a ten-meter-long goniophotometer to measure the Bidirectional Specular Distribution Function (BSDF) of specular samples and gratings for different angles of incidence and different wavelengths: from UV to IR.

### A. Goniophotometer

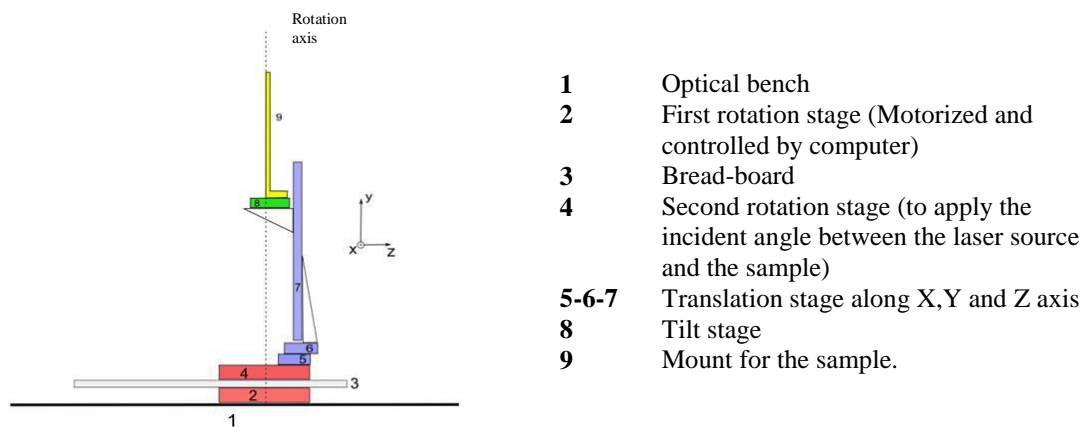
The Goniophotometer Bench dedicated to the high specular measurements contains most of components typically found in more-sophisticated systems. These may be grouped in four categories: light source, sample mount, detection system, and computer package.

In IR, the light source is a collimated laser: CO<sub>2</sub> laser (10.6μm) or Helium Neon laser (3.39μm). A Reflective Beam expander (×2 or ×4) is also used in order to decrease the Beam divergence and so increasing the Bench Resolution.

In UV range, the illumination is provided by a spatially filtered laser UV LED: the light source (e.g. UV LED) is coupled into an optical fiber by imaging the light emitting area onto the core of the optical fiber using a lens. The second end of the fiber is placed at the focus of the second lens to obtain a collimated beam.

A complex mount was developed to allow the micro-metric positioning of the sample. Indeed, 6 degrees of freedom are required to fully adjust the sample: 3 translational degrees (X, Y and Z) and 3 rotational degrees ( $\alpha$ ,  $\beta$  and  $\gamma$ ). The developed mount allows to play only on 5 degrees of freedom (X, Y, Z,  $\alpha$  and  $\beta$ ). However, we check that the reflected and transmitted beam are in the same horizontal plane or that the different diffraction orders of the grating are coplanar (e.g. it is an adjustment of  $\gamma$  tilt).

A manual rotation stage allows to apply an angle of incidence between the sample and the incident beam (refer to Fig.1).



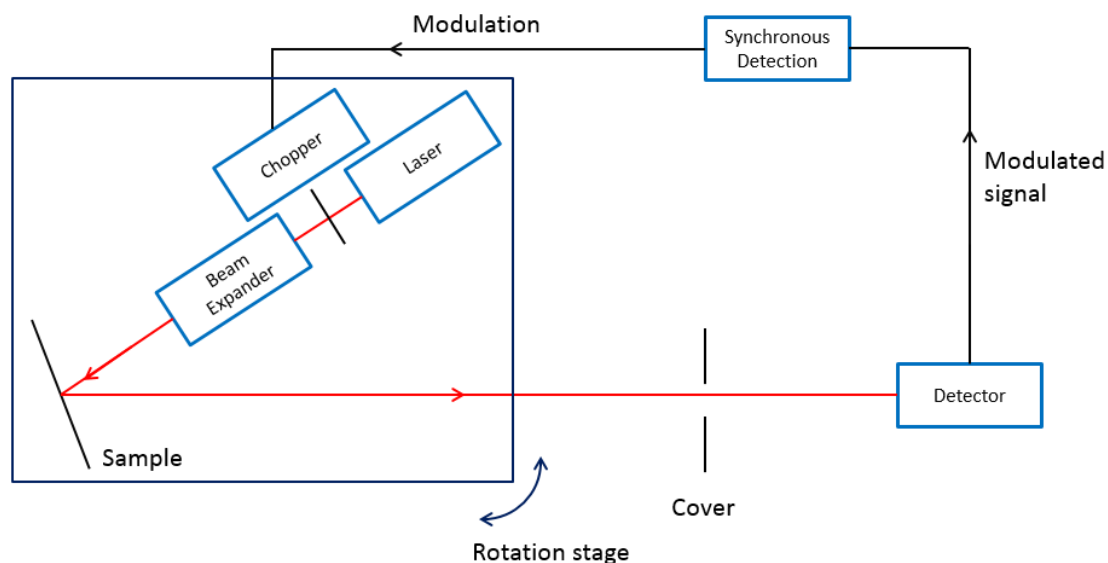
**Fig. 1.** Schematic of the sample holder

The laser source, the beam expander and the sample holder are placed on a breadboard, which turns on a motorized rotation stage controlled by computer. All the stage rotates to analyse the reflected or transmitted intensity over an angular range defined by the user.

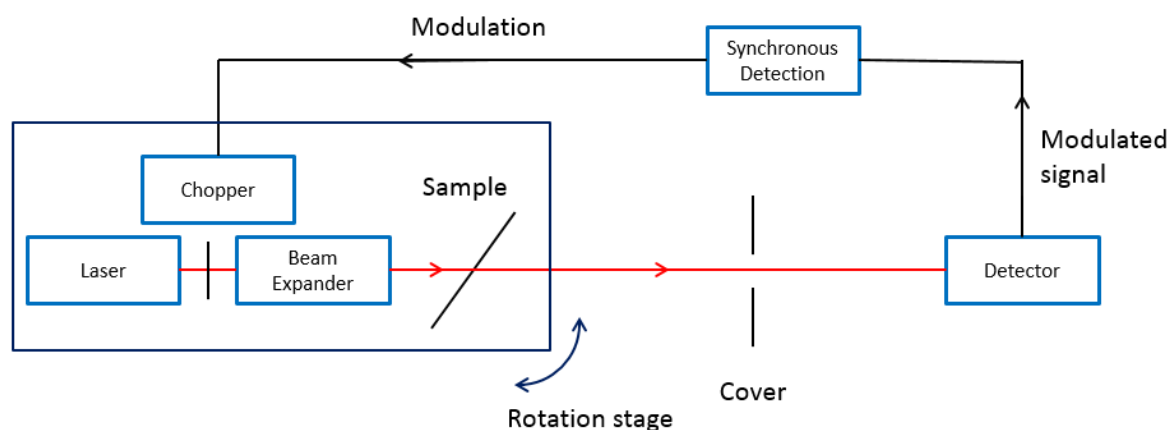
The detector is placed at 9 meters from the rotating stage. In order to increase the dynamic of the Bench, we play on the power of the source and on the numerical aperture of the detector: we add a density filter in front of the detector near the Specular Peak and a lens for the largest scattering angles.

To make sure the optical bench is isolated from stray light, a baffling system has been made and the bench also uses a chopper coupled to a synchronous detection.

Below, a schematic set-up of the Bench in BRDF and BTDF configurations:



**Fig. 2.** Schematic of the Bench in BRDF configuration



**Fig. 3.** Schematic of the Bench in BRDF configuration

The goniophotometer has a fixed detector and a rotating source and sample holder. Another configuration is possible, the source and the sample holder can be fixed and the detector rotates around them.

### B. Measurements Procedure

First of all the laser source and the beam expander are placed at the center of the rotating stage and a full measurement of the angular emission of the source is done. The obtained profile is called the Bench's signature.

The signature profile is not an ideal diffraction-limited spot because it contains aberrations caused by the reflective beam expander and stray light from source. It gives information about the dynamic range of the Bench, its resolution and its stability.

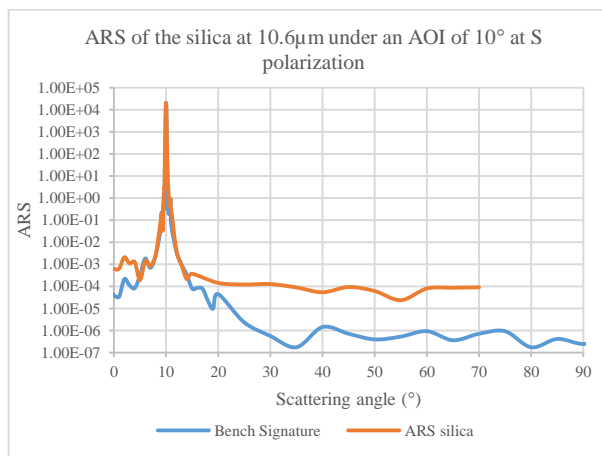
The ARS profiles measured with the Bench are always ultimately compared to its signature.

Once the Bench's signature is measured, the sample is placed at the center of the rotating stage and illuminated by the source which is at 30cm typically from the sample holder. Thereafter, the incident angle required is applied using a manual rotating stage. Finally, a scan over the angular range is done.

Near to the specular direction, the measured intensity can saturate the detector. If so, a density is then used. This density is placed in front of the detector as close as possible of it. Thus, the scattered light introduced

by the density is collected by the detector and does not affect the detected signal. Then, a second measure is done for low intensity angles near to the specular. Finally, for scattering angles over 1 degree, we can add a lens in front of the detector in order to increase its numerical aperture and collect more flux.

Overlaps between these "three detectors" allows the combination of the three obtained profiles. The obtained curb is the ARS of the sample.



**Fig. 4.**ARS of the Silica at 10.6µm under an angle of incidence of 10 degrees at S polarization

### III. FROM THE ARS TO THE BSDF

#### A. Data Processing

The measured profile (ARS) is proportional to the diffused angular intensity. That is why it is necessary to convert this initial data to BSDF data rescaling by the cosine of scattered angle. The obtained profile is proportional to the BSDF of the sample and needs to be calibrated.

Two different procedures can be applied for the normalization by the TIS value:

- The first one is based on the BRDF measurement of a well-known (reference) sample: these data are then used to rescale the measured data of the sample.
- The second method consists in the normalization by using the TIS value :

$$BSDF_{final} = ARS \frac{TIS_{measured}}{2\pi \int_{\alpha}^{90} ARS \cdot \cos(\theta) \cdot \sin(\theta) \cdot d\theta} \quad (1)$$

Where

$$TIS = \frac{E_{scattered}(\alpha - 90^\circ)}{E_{incident} R_{Sphere}} \quad (2)$$

Where:  $E_{scattered}(\alpha - 90^\circ)$  is the power of the scattered integrated from  $\alpha$  to  $90^\circ$ ,  $E_{incident}$  is the power of incident light and  $R_{sphere}$  the radius of the integrating sphere.

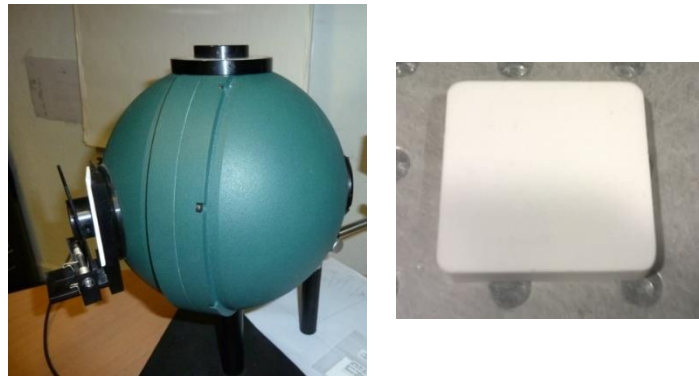
Integral limits depend on TIS measurement (taking into account the specular reflectance or not).

The first method has the inconvenience to be limited by the accuracy of the measurement on the reference sample. In consequence, we prefer the second one.

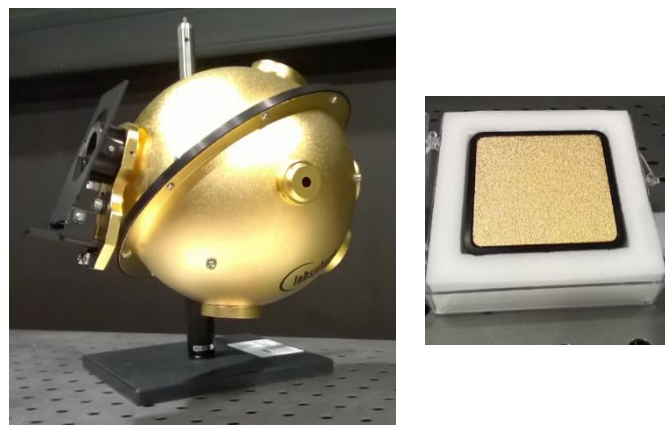
*B. TIS measurement*

The measurement of Total Integrated Scatter (TIS) of a sample is done compared to the TIS of a reference: a white Lambertian *spectralon* with a calibrated reflection coefficient for UV, visible wavelengths, and at 1550nm or a golden Lambertian *spectralon* at 3.39 $\mu$ m and 10.6 $\mu$ m.

The sample is placed in an integrating sphere or on the exit port and lighted up by a laser source. Then, the lambertian spectralon sample is placed in the same conditions than the sample and the measured intensities are compared. Knowing the calibrated reference reflectance, we calculate the TIS of the sample.

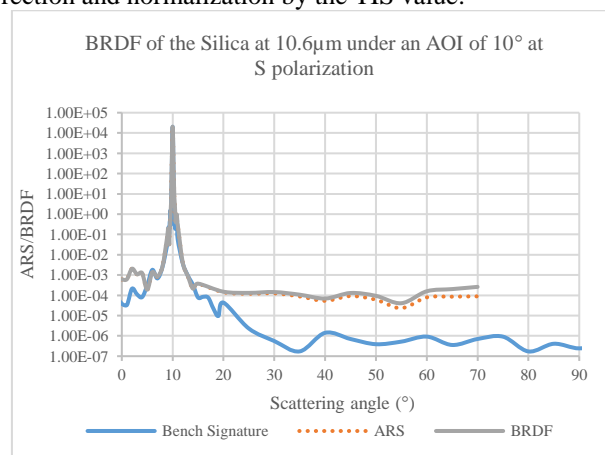


**Fig. 5.** Integrating Sphere and White Lambertian Spectralon



**Fig. 6.** Golden Integrating Sphere and Golden Lambertian Spectralon

The Graph below represents the BRDF of the Silica at 10.6 $\mu$ m under an angle of incidence of 10 degrees at S-polarization after cosine correction and normalization by the TIS value:



**Fig. 8.** BRDF of the Silica at 10.6 $\mu$ m under an angle of incidence of 10 degrees at S polarization

IV. SPECULAR BENCH'S PERFORMANCES

The Specular Bench was developed in first time for use in visible range. Then, it was enhanced to be used in UV and IR range. The dynamic range of the Bench is  $10^{13}$  for visible wavelengths and more than  $10^9$  in UV and IR. Its resolution is less than  $0.02^\circ$ .

A. Technical Characteristics

Tab. 1. BRDF Specular Bench's technical characteristics

Type of measurement	ARS/BRDF/BTDF
Dynamic range	More than $10^9$
Wavelengths	UV : 280nm, 375nm Visible : 445nm, 532nm, 635nm, 638nm IR : 808nm, 850nm, 1550nm, 3.39 $\mu$ m, 10.6 $\mu$ m
Mechanical sensitivity	$0.002^\circ$
Reading resolution	$0.001^\circ$
Angular resolution	$\leq 0.02^\circ$
Weight	500 kg

The dark room, where the Specular Bench is, is controlled in temperature and humidity and classified Class5 recently.

B. Bench's signatures and some examples of measured ARS/BSDF

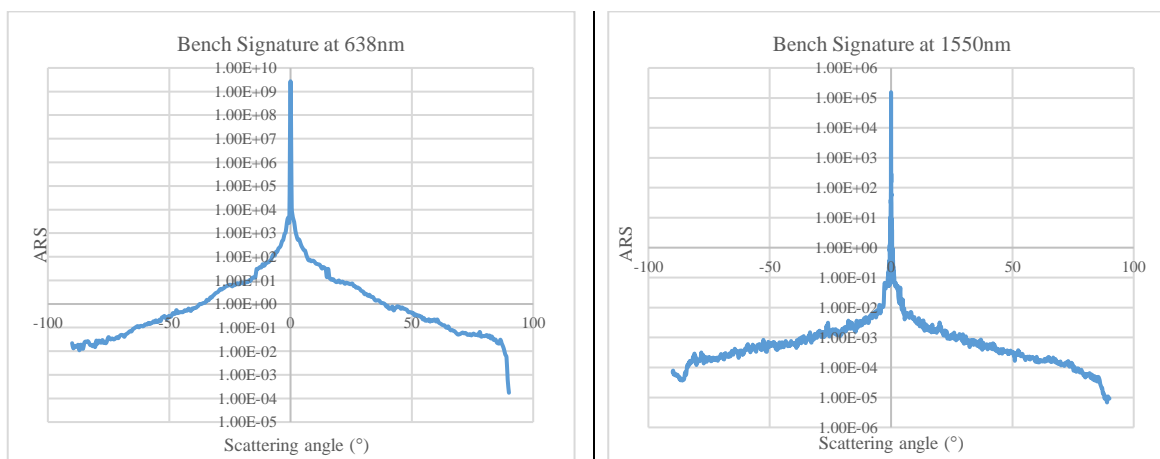


Fig. 9. Bench signatures at 638 and 1550nm

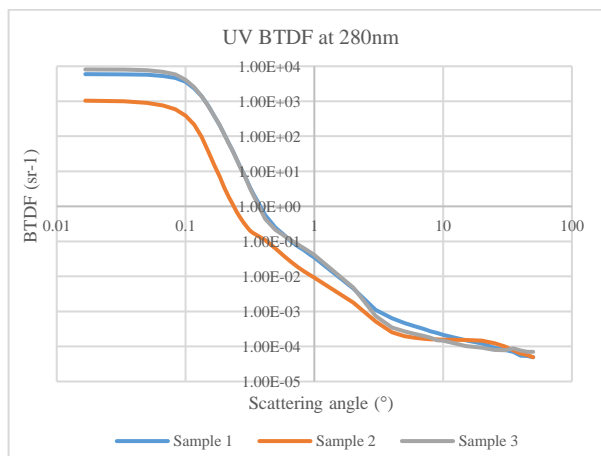


Fig. 10. UV BTDF at 280nm  
Proc. of SPIE Vol. 10562 1056205-7

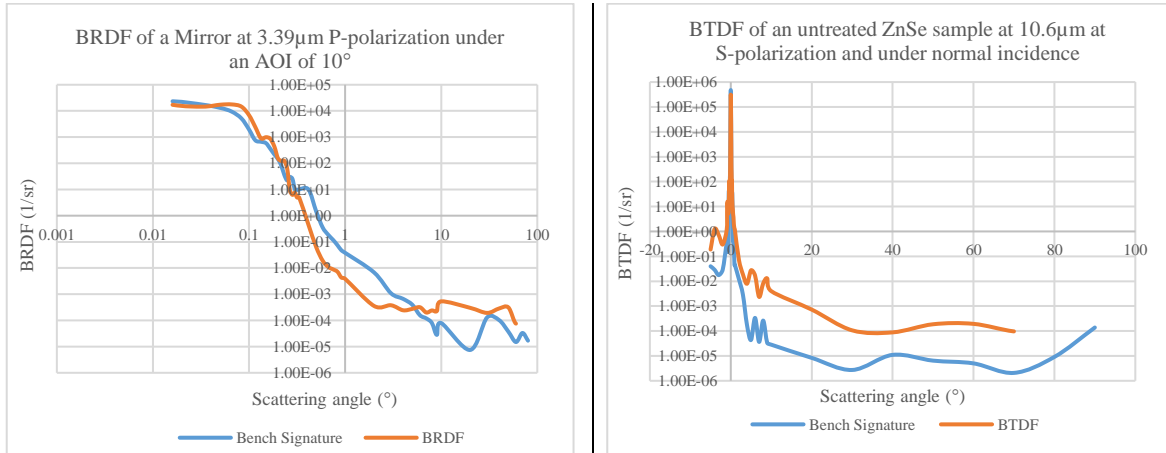


Fig. 11. Infrared BPDF at 3.39µm and 10.6µm

C. Diffraction Gratings ARS

The Specular Bench was used to characterize Diffraction gratings in transmission and reflection.

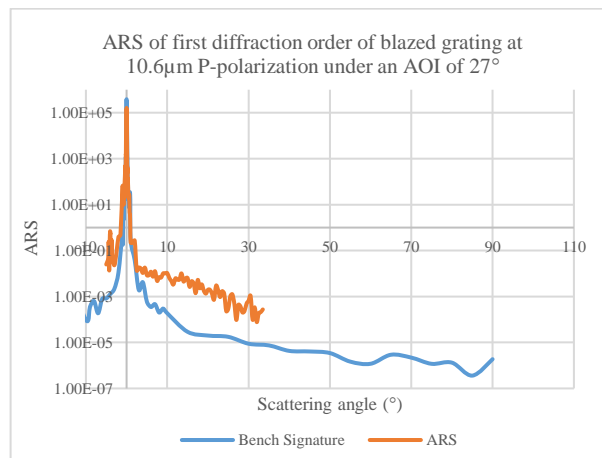
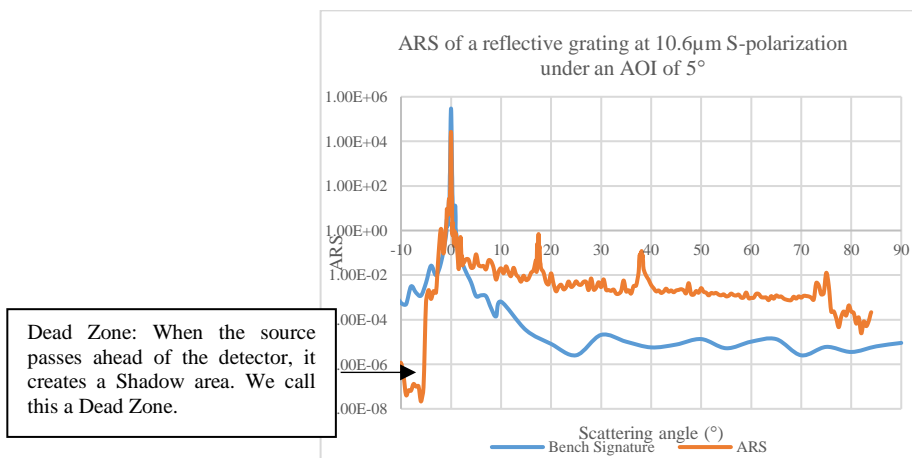


Fig. 12. ARS of first diffraction order of blazed grating at 10.6µm P-polarization under an AOI of 27°



Dead Zone: When the source passes ahead of the detector, it creates a Shadow area. We call this a Dead Zone.

Fig. 13. ARS of a reflective grating at 10.6µm S-polarization under an AOI of 5°

Grating's ARS gives information on:

- Diffraction orders,
- Line space's irregularity: the enlargement of the specular peak (compared to the Bench's signature) is due to the irregularity of the grating's line space.
- Secondary peaks (and not diffractions orders) are due to the surface defects (scratches, digs, etc.)



## V. CONCLUSION

BSDF is the most common form of scatter characterization. It is aimed to be used in optical designs. In space industry, it allows to get information on stray light which is one of the major problem's faced by the Telescope's designers.

Light Tec has developed a ten-meter specular Bench dedicated to BSDF measurements. First, the Bench was developed for visible wavelength range and was used to characterize optics as windows and mirrors. Then, the Bench has been improved to work in the UV and the IR range.

Thanks to its 10 meters long, the resolution of the Bench is  $0.02^\circ$  at all wavelength. However, the dynamic range in the visible range still better than in the IR and UV range: a dynamic of 13 decades was achieved for visible wavelengths, but for UV and IR wavelengths, its dynamic is between  $10^9$  and  $10^{10}$ . We are now thinking of possible improvements on our optical Bench to try to get dynamic in IR and UV similar to what we have in visible range (e.g.  $10^{13}$ ). Nonetheless, these 10 decades of dynamic were sufficient to characterize reflective and transmitting gratings at  $3.39\mu\text{m}$  and  $10.6\mu\text{m}$ .

We are now working to improve the Bench even more and so characterize curved optics and gratings in Littrow configuration.

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