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## LIGHT SCATTERING CHARACTERIZATION OF OPTICAL COMPONENTS FOR SPACE APPLICATIONS

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### I. INTRODUCTION

Light scattering can critically affect the performance of high-end optical systems. For instance, unavoidable but small residual imperfections of optical components such as surface or coating roughness, bulk inhomogeneities, and defects as well as the interaction of light with apertures and baffles give rise to light scattering propagating through the optical system which degrades the imaging quality and leads to a loss of the optical throughput.

Measurements of the Bidirectional Reflectance and Transmittance Distribution Function (BRDF / BTDF) provide essential information on the suitability of optical components for the desired application. Especially in complex optical systems and for high-end applications, knowledge about the scattering properties of the optical elements is fundamental in order to assess their impact onto the optical performance of the system.

Thus, characterizing the light scattering properties of optical system components is an important step during the development of sophisticated optical systems. Light scattering measurements help identifying and improving critical components and materials. This, in particular, holds true for the aerospace industry because of the cutting edge optical components as well as unique sample types with just a handful of specimen fabricated. The development of high-end optical systems with such optics is a driving area of application for the manufacturing processes and the characterization of these components. Light scattering techniques can be advantageously applied to specify and monitor the compliance of the requirements and the optical performance.

### II. DEFINITIONS AND MEASUREMENT SYSTEMS

The preferred term for describing off-specular scattering is the BRDF which is defined as the ratio of the power  $\Delta P_s$  scattered into the solid angle  $\Delta\Omega_s$  normalized to this solid angle and the incident power  $P_i$  [1-3]:

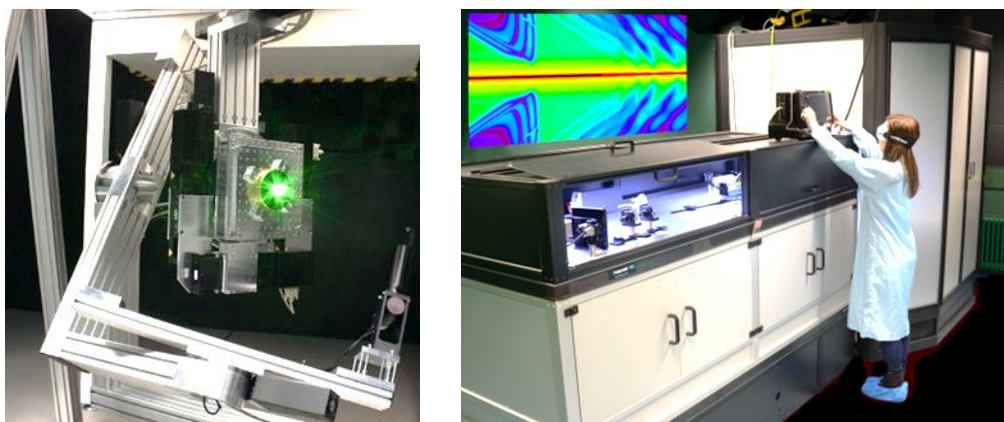
$$BRDF(\theta_s, \varphi_s) = \frac{\Delta P_s(\theta_s, \varphi_s)}{\Delta\Omega_s P_i \cos(\theta_s)} = \frac{ARS(\theta_s, \varphi_s)}{\cos(\theta_s)} \quad (1)$$

$\theta_s$  and  $\varphi_s$  are the polar scatter and azimuthal scatter angles, respectively. The cosine factor is sometimes omitted; in this case, the resulting function is called Angle Resolved Scattering (ARS). When referring to the transmissive rather than the reflective scattering hemisphere, the term BTDF (Bidirectional Transmittance Distribution Function) is used instead of BRDF.

Various instruments for angle resolved scatter measurements were developed at Fraunhofer IOF together with analysis techniques to link the measured light scattering distributions to the corresponding surface or thin film properties [4-9]. This includes systems for different spectral regions, such as extreme ultraviolet, ultraviolet, visible, near-infrared, and infrared, applying different measurement principles. Thus, the optimal tool for numerous measurement tasks can be chosen from the instruments available.

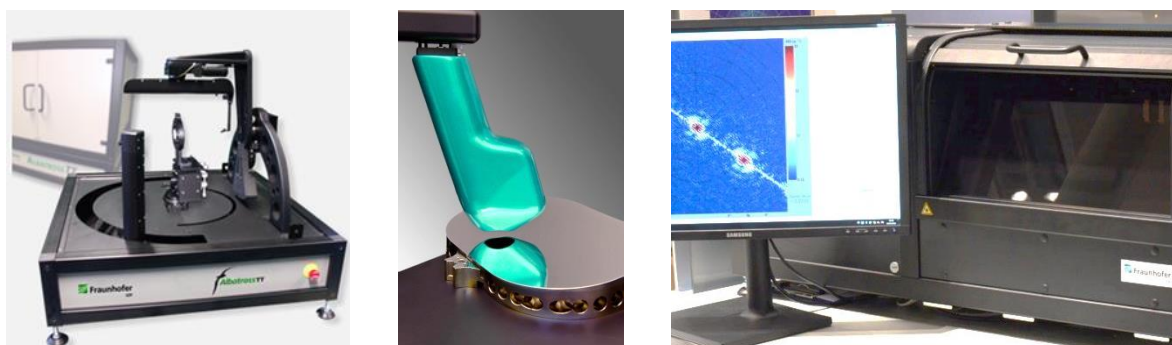
Fig.1 shows the goniometer-based measurement systems *ALBATROSS* (left) and *MLS-1600* (right) which are designated for the UV, VIS and IR spectral range. The main difference between both systems is that *MLS-1600* has a tunable laser source, based on an optical parametric oscillator, which offers the selection of arbitrary wavelengths between 250 nm and 1.5  $\mu\text{m}$  [6]. *ALBATROSS*, in contrast, uses a pool of single laser sources with discrete wavelengths between 325 nm and 10.6  $\mu\text{m}$  [5]. Both systems offer highest flexibility and sensitivity while simultaneously meeting the requirements for highly resolved light scattering measurements. This is, however, not always required and sometimes the main requirements on the systems are not the highest

flexibility but sensor size and measurements speed, in particular for manufacturing processes, such as polishing and coating.



**Fig.1.** Light Scatter Measurement Systems *ALBATROSS* (left) and *MLS-1600* (right)

More compact tools which can be used for in-process characterization (or at least for close to process inspection) are the table top measurement system *AlbatrossTT*, the light scattering sensor *horos*, and the *BTDF sensor*, all illustrated in Fig. 2. The system *AlbatrossTT* was developed with the goal of maintaining detection in the full 3D sphere and to keep the sensitivity but having a compact housing. This compact design causes limitations regarding the size of samples, the level of motorization and the number of wavelengths but offers the same measurement capabilities as the large laboratory systems. [7]



**Fig.2.** Left: Table Top System *AlbatrossTT*, Center: Light Scattering Sensor *horos*, Right: *BTDF Sensor*

The light scattering sensor *horos* is a compact instrument which can be used for a fast scattering characterization of reflective optical components. The sensor with its advantageous size and the camera-based data acquisition offers the possibility to measure 3D ARS or BRDF in just a few seconds in a scattering range of  $\pm 8^\circ$  with a sensitivity of approx.  $10^{-3} \text{ sr}^{-1}$ . [8]

A similar approach was realized in the *BTDF Sensor* which was designed for the investigation of the light scattering of transparent optical components and optical systems. It is also equipped with a matrix detector for fast data acquisition. There is space to integrate more than one laser to have a high flexibility. The measurement chamber is large enough to mount even complete optical systems, e.g. objectives. The system offers highly resolved 3D light scattering measurements in transmission direction with a very small near-angle limit.

### III. MEASUREMENT EXAMPLES

The benefit of light scatter measurements for the characterization of high-end optical components, performed with the equipment developed at Fraunhofer IOF, will be demonstrated in this section. The selected examples are focussed on optics for application in space.

### A. Grism for Euclid NISP

The near infrared spectroscopic photometer (NISP) for the ESA Euclid mission is designed to explore the universe and its dark matter. The NISP is observing near infrared radiation from a very large number of galaxies in the whole universe. One important and critical component of the spectro-photometer is a grism (see Fig. 3). It combines the functionality of a grating, a prism, and a band pass filter. [10]

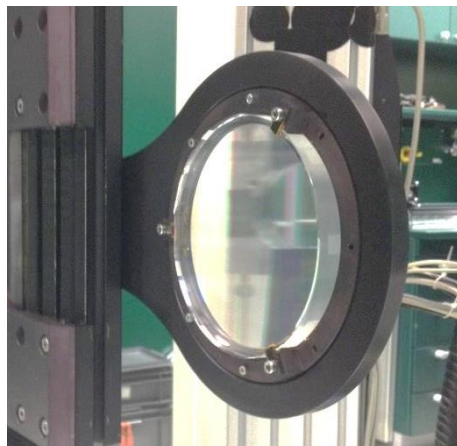


Fig.3. Photograph of the Euclid NISP grism

One part of the test procedure was dedicated to light scattering measurements on the grism. The measurements were performed at Fraunhofer IOF with the *MLS-1600* instrument at a wavelength of  $1.4\ \mu\text{m}$  and with the *ALBATROSS* system at  $1064\ \text{nm}$ . The light scattering was analysed in reflection and transmission direction, for different polarization configurations, and on different positions on the surface. The light scattering distribution at the center of the grism and horizontally polarized light is shown in Fig. 4. The blue line is the light scattering distribution perpendicular to the diffraction plane. The light scattering in the diffraction plane is visualized in red and it shows the diffraction peaks which can be observed in reflection and transmission direction. The grey curve represents the instrument signature at  $1.4\ \mu\text{m}$  which is a scattering measurement without a sample.

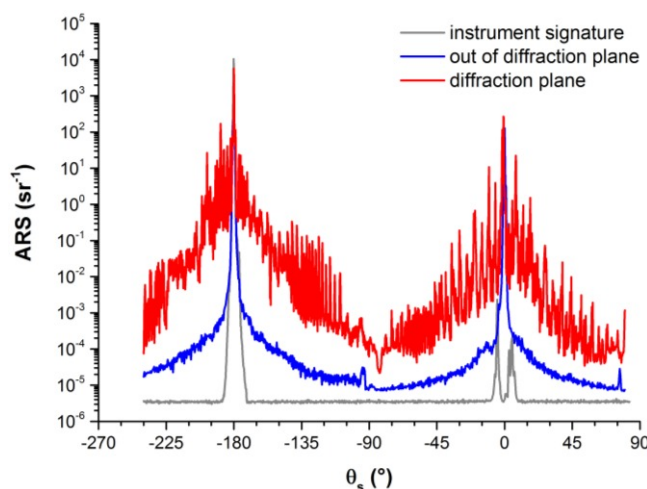


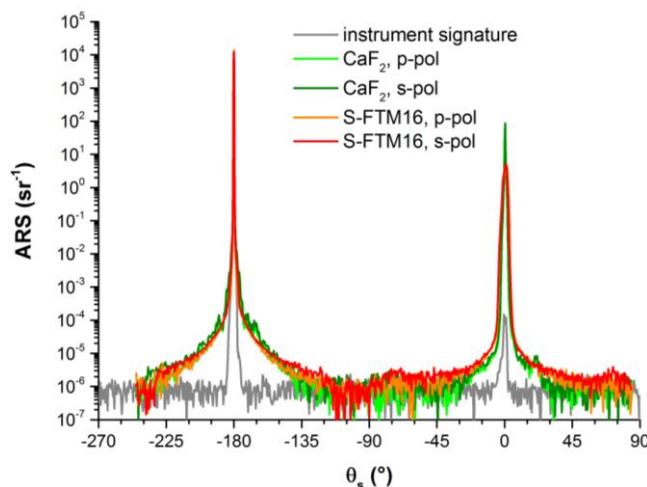
Fig.4. Scattering distribution of Euclid NISP grism for normal incidence at  $1.4\ \mu\text{m}$  (horizontal polarization)

The light scattering data was not only used to compare the assumed and real scattering performance but also served as input for the straylight modelling of the entire system.

### B. Camera Lenses for Euclid NISP

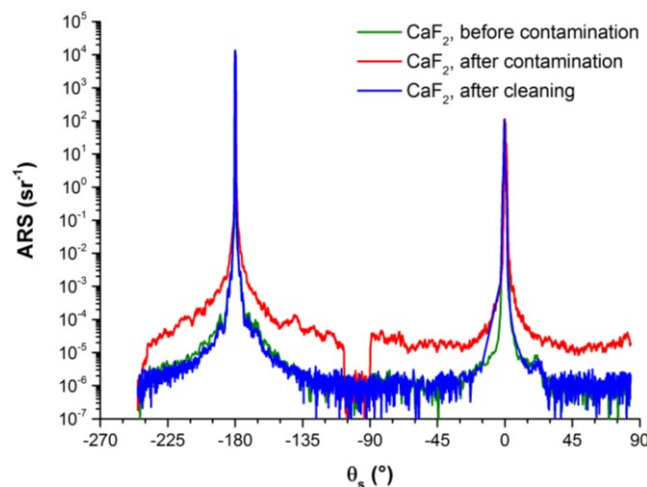
Further components of the Euclid NISP instrument which were characterized at Fraunhofer IOF are lenses of the camera lens assembly of the photometer. [11] In a first light scattering measurement campaign, two of the lenses (both spherical-aspherical meniscus lenses) were investigated at different wavelengths ( $1064\ \text{nm}$ ,  $1.4\ \mu\text{m}$ ) and for different polarizations. The results for the measurements at  $1064\ \text{nm}$  are shown in Fig. 5. In both

polarization configurations, both lenses have a very low scatter level. There is no significant difference in the scattering distributions of the lenses which are made from different materials.



**Fig.5.** Scattering distribution of Euclid NISP camera lenses made from different materials measured at 1064 nm

A second investigation was dedicated to the light scattering performance of the CaF<sub>2</sub> camera lens after a period of systematic and monitored contamination which was followed by a cleaning process. The intended level of contamination should simulate the end of life condition of the system and the results of the light scattering measurements served to study the optical performance of the lens in this state.



**Fig.6.** Scattering distribution of Euclid NISP CaF<sub>2</sub> camera lens with different levels of contamination measured at 1064 nm

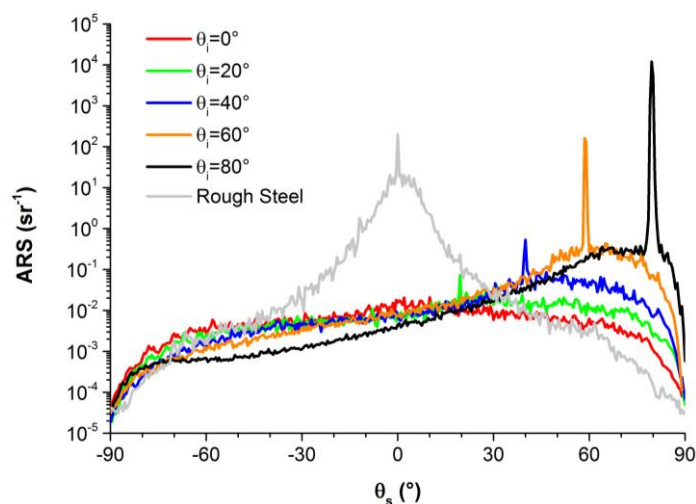
The light scattering before contamination and after cleaning is comparable (see Fig. 6), indicating a successful cleaning procedure even for these delicate optics and materials. In contrast, the contaminated lens shows an increased scattering level. The average level is approx. one order of magnitude higher compared to the uncontaminated state. These measurement data can be advantageously used as input for the simulation of the performance of the NISP at the end of life and allows calculating a more reliable estimation than just assuming a scattering distribution for this situation.

### C. Black Surfaces

In order to suppress stray light in complex optical systems, baffles and black diffusing absorber coatings are used. One example are Acktar black coatings which were designed to exhibit particularly low residual reflectance and have been implemented in various instruments [12]. These coatings exhibit almost perfect absorbing properties over the entire visible spectral range. However, in particular for application in the mid-infrared, it is extremely challenging to find good absorbers. Even though the scattering distribution of any

material is perfectly diffuse in the visible range and at near normal incident angles, this cannot automatically be presumed for longer wavelengths and oblique angles of incidence.

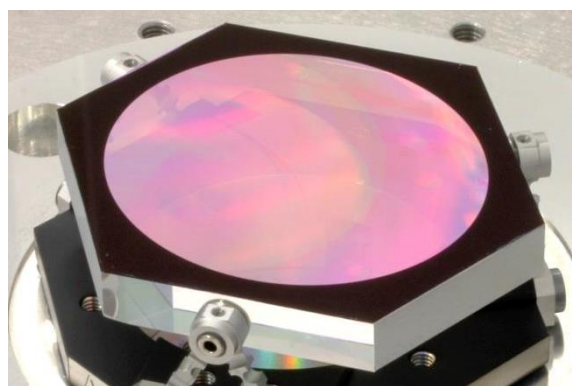
The results of scatter measurements of Acktar UltraBlack™ foil at a wavelength of 4.6 μm are shown in Fig. 7 together with the scattering distribution of an uncoated rough steel surface. The results reveal that a nearly perfectly diffuse scattering behavior at a tremendously reduced level (3 orders of magnitude) is achieved at moderate angles of incidence. At larger angles of incidence, a distinct specular component can be observed, which is, however, confined to a small region around the specular direction. The BRDF data provides valuable information that can be used to model and suppress stray light in optical systems for IR applications. In addition, the BRDF data can also be analysed to optimize the scattering behaviour of the black coatings and adapt their fabrication processes. [13]



**Fig.7.** Scattering distribution of Acktar black coating for different angles of incidence at 4.6 μm

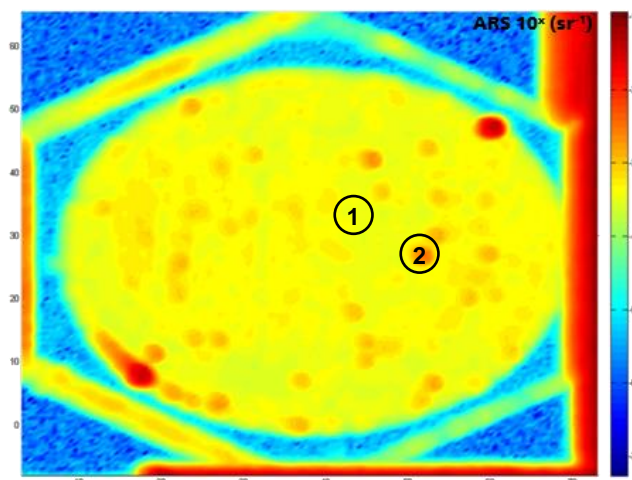
#### D. NIR diffraction grating for Sentinel 4

One future ESA mission is Sentinel 4, an earth observation mission. Its main instrument is a high resolution spectrometer system operating between the ultraviolet and near-infrared band. One of the essential components of the spectrometer is a dielectric reflection grating for the near-infrared (NIR) channel. The grating (see Fig. 8) was manufactured at Fraunhofer IOF using electron beam lithography in combination with reactive ion etching. [14]



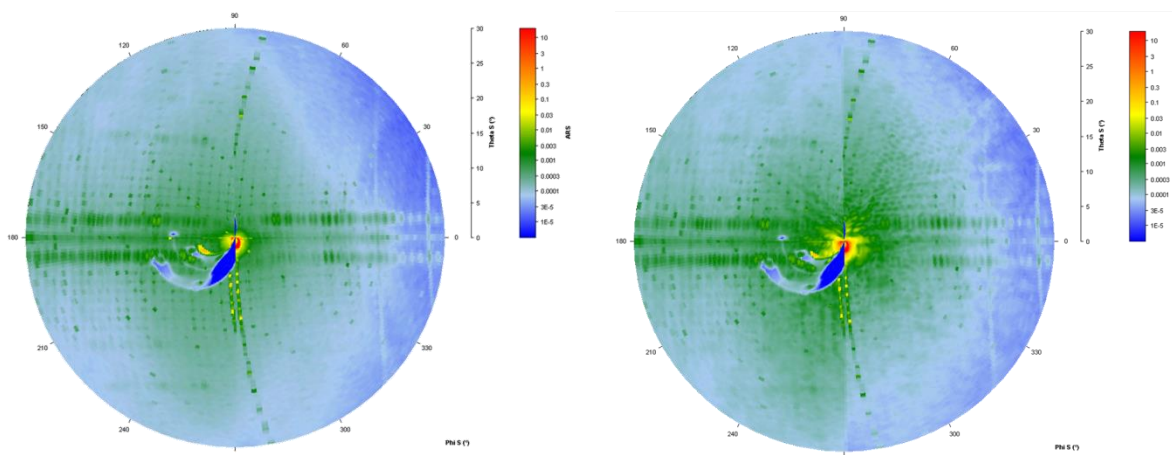
**Fig.8.** Photograph of Sentinel 4 NIR grating

The light scattering of the grating was characterized in order to investigate the diffraction efficiency and the scattering performance. The illumination conditions for the measurements, such as the angle of incidence or the wavelength, were equal to the design parameters of the grating and its final application scenario during the scattering measurements. At first, the entire surface was scanned at a fixed detector angle to get a quick impression of the homogeneity of the grating surface (see Fig. 9). This data was then used to select measurement positions for the following 3D light scattering measurements.



**Fig.9.** Scatter map of Sentinel 4 NIR grating

The 3D light scattering distribution (see Fig. 10) was measured in a cone of 30° around the -1<sup>st</sup> diffraction order for selected positions. Besides the pure scattering information, it is possible to analyse the diffraction efficiency in the different diffraction orders, the scattering level perpendicular to the diffraction plane and additional unwanted diffraction peaks caused by the manufacturing process.



**Fig.10.** 3D light scattering distribution of Sentinel 4 NIR grating (left: position 1; right: position 2)

#### IV. CONCLUSION

Optical instruments used in space missions are sophisticated systems which consist of high-end optical components fabricated and often operated at the current technological limits. The test, characterization, and verification of these optical elements thus require sensitive and ideally non-destructive measurement techniques. As demonstrated by several different application examples, light scattering is a convenient and effective method to characterize a wide range of optical components for the application in space. It delivers direct information about optical performance parameters, such as the diffraction efficiency or the BRDF, at the relevant wavelengths.

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