International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 1056347 · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304146

LIGHT SCATTERING TECHNIQUES FOR THE CHARACTERIZATION OF OPTICAL COMPONENTS

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I. INTRODUCTION

The rapid developments in optical technologies generate increasingly higher and sometimes completely new demands on the quality of materials, surfaces, components, and systems. Examples for such driving applications are the steadily shrinking feature sizes in semiconductor lithography, nanostructured functional surfaces for consumer optics, and advanced optical systems for astronomy and space applications. The reduction of surface defects as well as the minimization of roughness and other scatter-relevant irregularities are essential factors in all these areas of application. Quality-monitoring for analysing and improving those properties must ensure that even minimal defects and roughness values can be detected reliably. Light scattering methods have a high potential for a non-contact, rapid, efficient, and sensitive determination of roughness, surface structures, and defects. [1-3]

Very often, specifications are directly derived from computer-based predictions assuming idealized surface properties by using simple roughness models while ignoring defects. However, light scattering is usually affected not only by surface properties but also by various other effects. Apart from surface roughness, the BRDF (Bidirectional Reflectance Distribution Function) of optical components can be influenced by defects, bulk inhomogeneities, internal scatter in coatings, or contaminations. In order to take all of these effects into account, measured light scattering data are required rather than relying solely on predictions. This in particular holds for high-end applications such as optical instruments in space.

In the course of aiming for ever increasing resolution of optical devices and the need to analyze more and more sophisticated structural features, the requirements regarding highest performances and lowest scattering levels have become challenging. This has also led to extreme demands on highly resolved light scattering metrology. In this sense, “highly resolved” means: (i) measurements with high angular resolution, not just in one plane but within the entire scattering sphere, (ii) looking at optical, not just mechanical resolution, (iii) small near-angle limits, (iv) highest sensitivities close to or even below the Rayleigh scattering limit, and most recently (v) measurements not only at single wavelengths but over the entire range of relevant wavelengths.

In addition, the requirements on light scattering / BRDF measurement techniques for high-quality optical components in general and for space applications [4] in particular are:

- Measurements at wavelengths relevant for the specific application
- High dynamic range (at least 10 orders of magnitude for VIS/ IR optics) and linearity
- Low noise (noise equivalent BRDF $<10^{-6}$ sr^{-1} for VIS / IR optics)
- Operation in clean room environment with options for environmental monitoring using particle counters

II. DEFINITIONS / MEASUREMENT SYSTEMS

The term BRDF is defined as the ratio of the scattered radiance L divided by the irradiance E. In our devices with oversized detector field of view, this translates to the power ΔP_s scattered into the solid angle $\Delta\Omega_s$ normalized to this solid angle and the incident power P_i [5-7]:

$$BRDF(\theta_s,\varphi_s)=\frac{\Delta L(\theta_s,\varphi_s)}{E}=\frac{\Delta P_s(\theta_s,\varphi_s)}{\Delta\Omega_s \mathrm{P_i}\cos(\theta_s)}=\frac{ARS(\theta_s,\varphi_s)}{\cos(\theta_s)}\,. \tag{1}$$

θ_s and φ_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 [8-11]. This includes systems for different spectral regions using various detector elements and 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 *MARS* (right) which are designated for the UV, VIS and IR spectral range. The main difference between both systems is that *MARS* has a tunable laser source, based on an optical parametric oscillator (OPO), which offers the selection of arbitrary wavelengths between 250 nm and 1.5 µm [8]. *ALBATROSS*, in contrast, uses a pool of single laser sources with discrete wavelengths between 325 nm and 10.6 µm [9]. Both systems offer highest flexibility and sensitivity while simultaneously meeting the requirements for highly resolved light scattering measurements mentioned above. However, these rather large and complex measurement systems are limited to the application in laboratories. In order to fulfill the need for systems close to manufacturing processes, like polishing and coating, and the ability to obtain 3D scattering information in less than one second, compact light scattering systems have been developed.

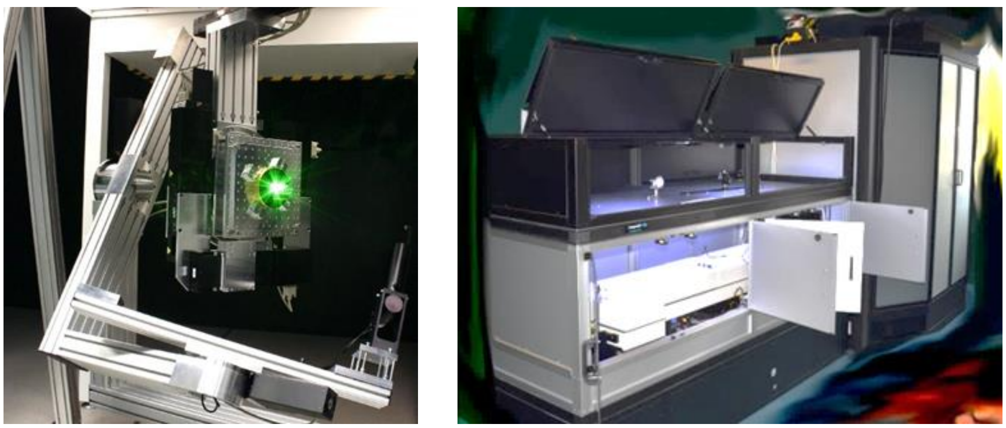

Fig. 1. Light Scatter Measurement Systems *ALBATROSS* (left) and *MARS* (right)

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* and the light scattering sensor *horos*, both illustrated in Fig. 2. The system *AlbatrossTT* was developed with the goal to maintain 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. [10]

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

The light scattering sensor *horos* is a compact instrument which can be used for a fast scattering characterization of reflective optical components. The advantageous size and the camera-based data acquisition lead to limitations compared to the laboratory systems regarding sensitivity (BRDF approx. 10^{-3} sr^{-1}), range of scattering angles covered (±10° around the specular reflection) and the operation at only one wavelength (convertible). [11]

Because the light scattering measurements on space optics require highest performance, flexibility, and clean room environment, the measurement examples presented in the next section were all performed with the laboratory systems *ALBATROSS* and *MARS*.

III. MEASUREMENT EXAMPLES

Surface roughness is often believed to be the main source of scattering from optical components. However, simple roughness specifications and roughness measurements do not adequately characterize the scatter-relevant surface properties for all applications. Therefore, direct scatter measurements are indispensable for the characterization of high-end optical components and systems. This is illustrated for various examples in the next paragraphs.

A. Polished Surfaces

In Fig. 3, the results of a scatter mapping of a diamond-turned and polished aluminum mirror measured at 532 nm at a fixed scatter angle of 25° is shown. The homogeneous background corresponds to a scatter level of 2×10^{-4} sr^{-1} related to an rms roughness of 1.9 nm. Areas of slightly enhanced scattering can be identified. This scatter level corresponds to a roughness of 3 nm. The angle resolved scatter data shown on the right reveals that these areas contain residual turning marks that had not been removed completely by the polishing process [12]. Moreover, localized spots with substantially enhanced scattering caused by defects and particle contaminations can be observed. It is obvious that detecting and localizing these effects using local techniques like white-light interferometry is extremely challenging. The example illustrates the advantage of light scattering measurements – they provide area covering direct information of the scatter properties even over larger areas.

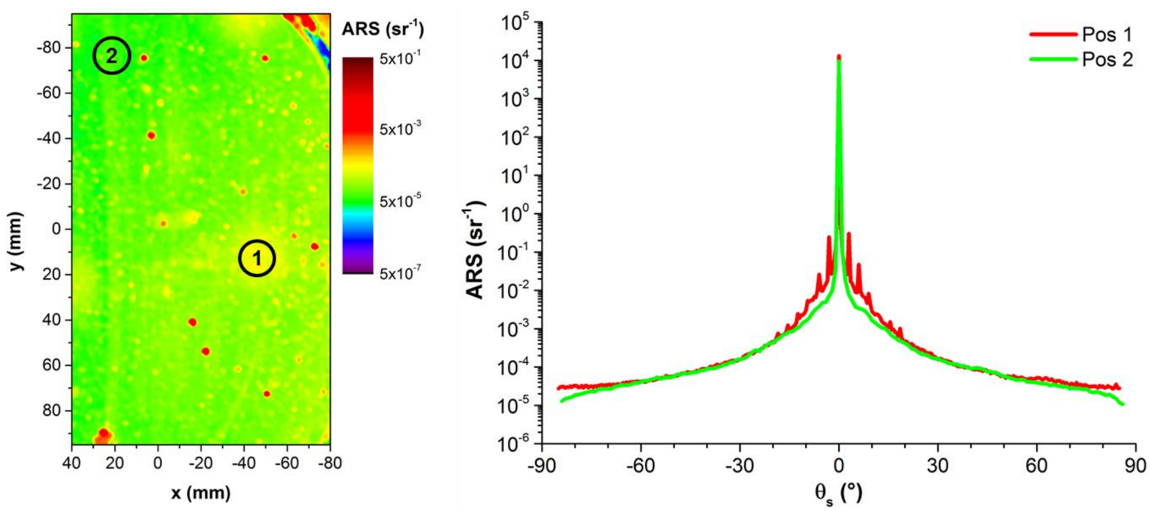

Fig. 3. Surface inspection of aluminum mirror using light scattering at 532 nm.
Left: Scatter map providing information on roughness, homogeneity, and defects.
Right: Angle resolved scatter revealing the origins of enhanced scattering

B. Black Surfaces

In order to suppress stray light in complex optical systems, baffles and black diffusing absorber coatings are used. Acktar black coatings were designed to exhibit particularly low residual reflectance and have been implemented in various instruments [13]. 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 incidence.

The results of scatter measurements of Acktar UltraBlack™ foil at 4.6 µm are shown in Fig. 4 together with the scattering distribution of an uncoated rough steel surface. The results reveal that a nearly perfectly diffuse scattering distribution 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 is observed, which is, however, confined to a small region around the specular directions. The BRDF data provides valuable information that can be used to model and suppress stray light in optical systems for IR applications.

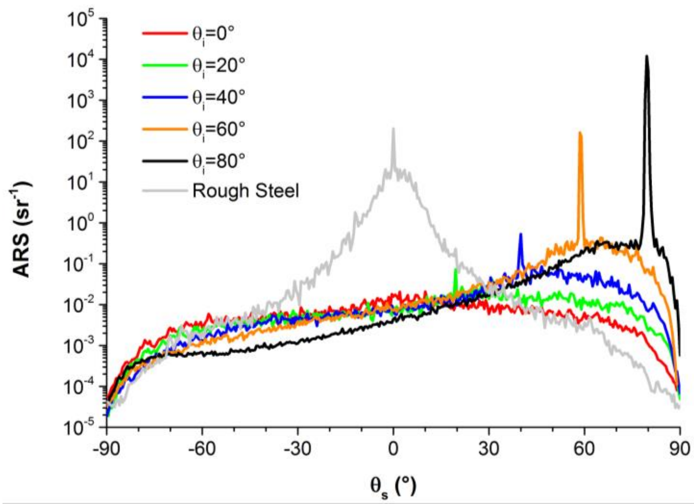

Fig. 4. Scattering of Acktar black coating for different angles of incidence at 4.6 µm

C. Diffraction Gratings

Space-based spectrometers are used in a variety of applications such as earth observation. Usually, extremely high spatial and spectral resolutions are required for those instruments and their elements. Transmissive diffraction gratings as dispersive elements are usually manufactured using ruling or lithography techniques [14]. Imperfections of the grating structure like surface roughness from etching, line edge roughness, or fluctuations of periodicity can induce anisotropic light scattering that degrades both the imaging properties and the spectral resolution.

In Fig. 5, the initial results of a 3D BTDF measurement around the 1st diffraction order of a grating at 633 nm manufactured using e-beam lithography are shown [15]. In addition to the diffracted order (peak in Fig. 5), parasitic diffraction effects can be observed. In order to optimize the structure with respect to scattering, a series of gratings with slightly varying grating parameters (line width) was generated on a 3x3 grid. The entire grid was then mapped and the scattering was measured at fixed scatter angles within the main plane of diffraction, perpendicular to the plane of diffraction, and out of plane. Based on these results, the process parameters offering lowest scattering into the critical directions could be identified.

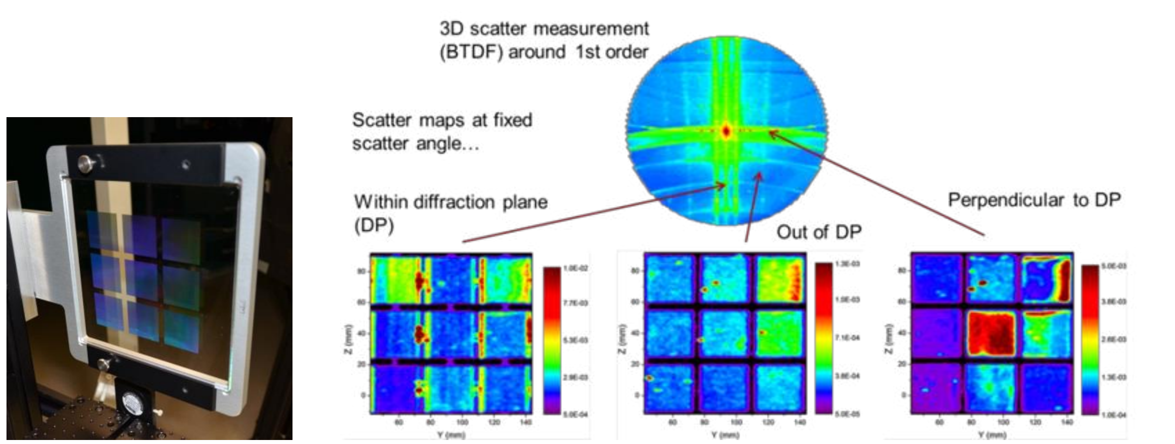

Fig. 5. Light scattering analysis of diffraction grating. Left: 3x3 grid of test structures.
Right: 3D scattering (BTDF) around 1st order and scatter maps at different locations on scattering hemisphere.

D. TMA Telescope Mirrors

Another example that demonstrates the benefit of BRDF measurements at the wavelength of application is a laser beam expander used as flight hardware component in space. In addition to the laser function, the system has an observation channel in the reversed direction which must be protected against back scatter from the laser in the telescope. This telescope, which was designed and assembled by RUAG Space, is an afocal TMA telescope with four mirrors. Due to the folded configuration, most mirrors have comfortable angles of incidence (Fig. 6).

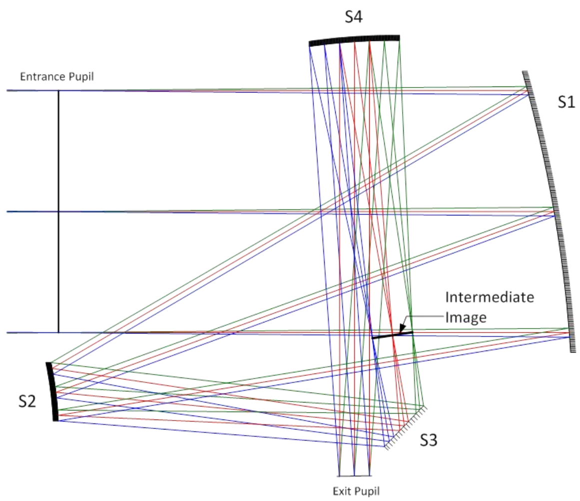

Fig. 6. Afocal Beam Expander (not to scale)

Nevertheless, there are two components in the telescope which are intrinsically critical to light scattering. The mirror S4 exhibits a small angle between incoming and outgoing direction. The laser side is thus particularly susceptible to near angle scattering of the mirror. Hence, extremely low surface roughness and a perfect coating is required. Options to increase this critical angle are limited by the required magnification of the system. Therefore, the BRDF of this mirror (S4) was checked thoroughly because it fully determines the backscatter performance of the entire telescope. The graphs in Fig. 7 show the scattering distributions of different samples of the mirror. The measurements were used to prove a low near angle scattering of the mirrors.

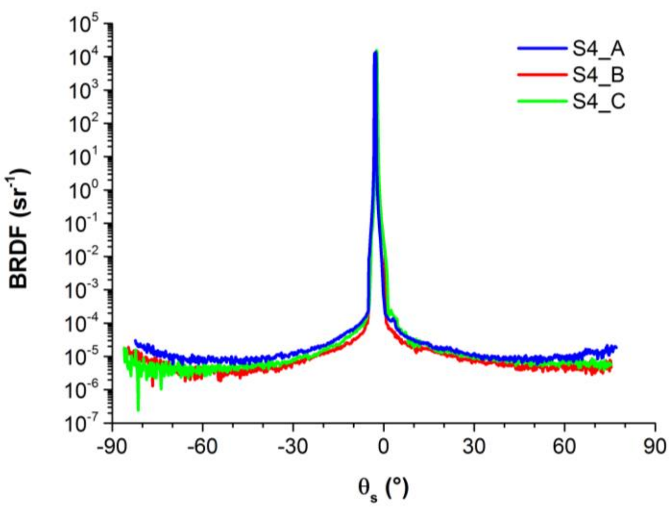

Fig. 7. Scattering of different samples of mirror S4

Another mirror (S3) has the potential to generate enhanced scatter because there is an intermediate image close to the mirror surface. Hence, there is a large view factor to the detector and the amount of scatter can only be mitigated by a superior surface finish and coating. In terms of the BDRF, the scattering had to be below 5×10^{-6} sr^{-1} in the retro-reflection direction. This performance was checked by light scattering measurements. The BRDF results for different mirrors of this type are shown in Fig. 8. Particular attention was paid to the scattering limit in the retro-reflection direction ($\theta_s \approx 43°$). As a result of the improvement of the production process, the mirror S3_D finally met the specifications.

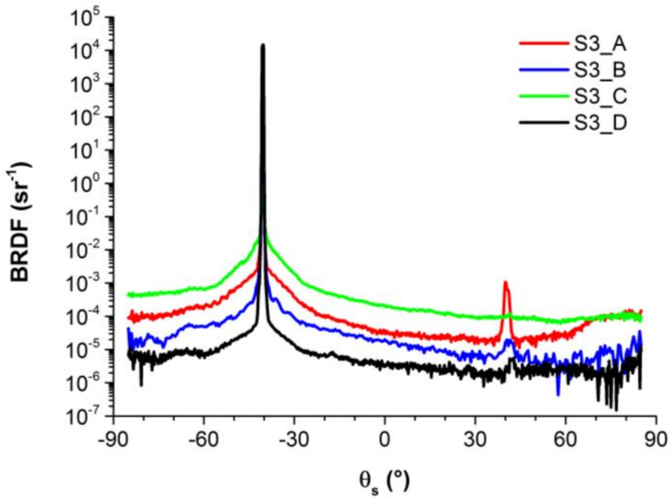

Fig. 8. Scattering of different samples of mirror S3

For the BRDF measurements, the same geometrical configuration as in the telescope was used because of the influence of the dielectric coating. Measurements directly into the retro-direction are particularly challenging as the detector is basically looking along the entire beam path. The scattering signal is thus prone to Rayleigh scattering of the air molecules. Therefore, the field of view of the BRDF detector has to be optimized, the scattering from the beam dump has to be minimized and the diameter of the laser beam should be kept as small as possible.

E. HR Rugate Coatings

Rugate filters are coated optical components which are characterized by a coating with a graded index profile. They exhibit high reflectivity at the design wavelength (see Fig. 9 left) and usually enhanced laser stability compared to standard multilayer systems with step-like index profiles [16]. Because of the unusual structure of the rugate filters, there had been no information about the scattering properties. Furthermore, enhanced scattering was predicted for standard stacks at the band edges but it was unknown if this would also be the case for rugate filters.

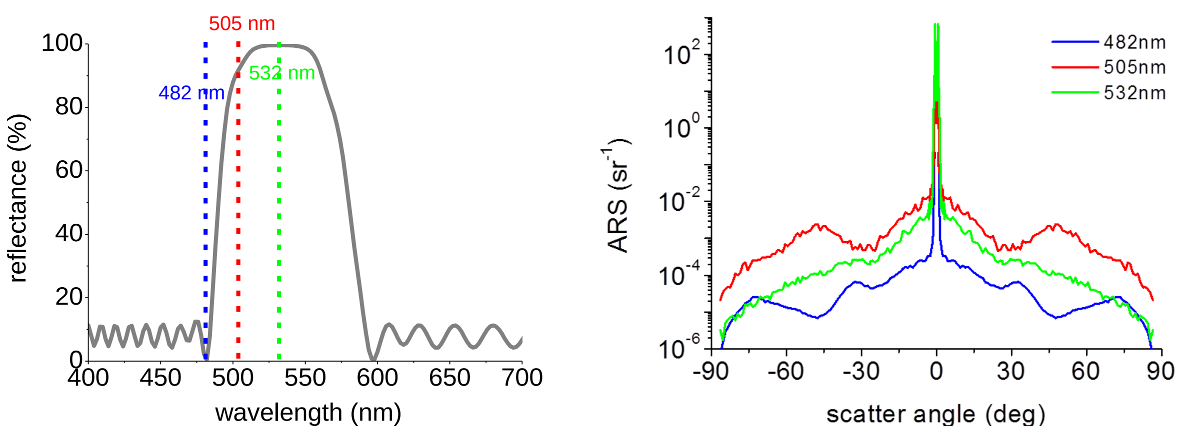

Fig. 9. Rugate filter. Left: Spectral properties. Right: Angle Resolved Scattering at different wavelengths.

Fig. 9 (right) shows the light scattering distributions for different wavelengths measured with the *MARS* system [8]. The focus of the investigations was on the scattering properties in the wavelength range of high reflection. It was shown that there is an increased scattering level near the band edge around 505 nm. There, the total scatter loss is up to 20 times higher compared to the central wavelength of 532 nm. This fact had been ignored in the design and characterization of dielectric filters, so far, and emphasizes the importance of light scattering measurements at all wavelengths relevant for the application.

IV. CONCLUSION

It was shown that light scattering measurements are a convenient and effective tool for the characterization of a wide range of optical components. Furthermore, there is the need to directly specify and measure the BRDF of optical components because, in addition to surface roughness, different mechanisms and sources of light scattering can influence the optical performance. However, offering highly resolved BRDF measurements is challenging, especially for measurements of optical components designed for application in space because additional optical and environmental conditions have to be considered. In addition, different measurement tasks can require focusing on totally different scattering parameters. The presented examples illustrate a selection from the spectrum of typical applications of light scattering techniques: area covering measurements for the detection of defects, measurements at extraordinary wavelengths, 3D scattering measurements, measurements close to the scattering limits, and spectral resolved measurements for the entire range of relevant wavelengths.

ACKNOWLEDGEMENTS

The authors would like to thank Lars Mejnertsen and David Unglaub for contributing to the measurements. Andreas Gebhardt, Uwe Zeitner, Martin Heusinger (Fraunhofer IOF), Dina Katsir (Acktar Ltd.), and Kerstin Täschner (Fraunhofer FEP) are gratefully acknowledged for providing high-quality samples.

REFERENCES

[1] J. M. Bennett, L. Mattsson, *Introduction to surface roughness and scattering*, 2^{nd} ed., Optical Society of America, Optical Society of America, 1989.
[2] M. Trost, S. Schröder, T. Feigl, A. Duparré, and A. Tünnermann "Influence of the substrate finish and thin film roughness on the optical performance of Mo/Si multilayers*," Appl. Opt.*, Vol. 50, No. 9, pp. C148-C153, December 2010.
[3] M. Trost, T. Herffurth, D. Schmitz, S. Schröder, A. Duparré, and A. Tünnermann "Evaluation of subsurface damage by light scattering techniques*," Appl. Opt.*, Vol. 52, No. 26, pp. 6579-6588, September 2013.
[4] H. E. Bennett, J. L. Stanford, J. M. Bennett "Scattering from Mirror Surfaces Used in Space Applications," in *Space Optics: Proc. of the Ninth International Congress of the International Commission for Optics*, pp. 717-738, October 1972
[5] J. C. Stover, *Optical Scattering: Measurement and Analysis*, 3^{rd} ed., SPIE, pp. 14-18, 2012.
[6] F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I. W. Ginsberg, and T. Limperis "Geometrical Considerations and Nomenclature for Reflectance*," U. S. Dept. of Commerce*, October 1977.
[7] C. Amra, C. Grezes-Besset, P. Roche, and E. Pelletier "Description of a scattering apparatus: application to the problems of characterization of opaque surfaces*," Appl. Opt.*, Vol. 28, No. 14, pp. 2723-2730, July 1989.
[8] S. Schröder, D. Unglaub, M. Trost, X. Cheng, J. Zhang, and A. Duparré "Spectral angle resolved scattering of thin film coatings*," Appl. Opt.*, Vol. 53, No. 4, pp. A35-A41, November 2013.
[9] S. Schröder, T. Herffurth, H. Blaschke, and A. Duparré "Angle-resolved scattering: an effective method for characterizing thin-film coatings*," Appl. Opt.*, Vol. 50, No. 9, pp. C164-C171, December 2010.
[10] A. von Finck, M. Hauptvogel, and A. Duparré "Instrument for close-to-process light scatter measurements of thin film coatings and substrates*," Appl. Opt.*, Vol. 50, No. 9, pp. C321-C328, January 2011.
[11] T. Herffurth, S. Schröder, M. Trost, A. Duparré, and A Tünnermann "Comprehensive nanostructure and defect analysis using a simple 3D light-scatter sensor*," Appl. Opt.*, Vol. 52, No. 14, pp. 3279-3287, May 2013.
[12] R. Steinkopf et al "Metal Mirrors with Excellent Figure and Roughness*," Proc. SPIE 7102*, Optical Fabrication, Testing, and Metrology III, 71020C, September 2008
[13] T. Kralik, D. Katsir, "Black surfaces for infrared, aerospace, and cryogenic applications", *Proc. SPIE 7298*, Infrared Technology and Applications XXXV, 729813, May 2009
[14] U. D. Zeitner, D. Michaelis, E.-B. Kley, and M. Erdmann "High performance gratings for space applications*," Proc. SPIE 7716*, Micro-Optics 2010, 77161K, May 2010
[15] S. Schröder, D. Katsir, U. Zeitner, and A. Duparré „Light Scattering of Optical Components for Space Applications,“ in *Classical Optics 2014*, OSA Technical Digest (online) (Optical Society of America, 2014), paper OM3C.3
[16] T. Herffurth, M. Trost, S. Schröder, K. Täschner, H. Bartzsch, P. Frach, A. Duparré, and A. Tünnermann "Roughness and optical losses of rugate coatings*," Appl. Opt.*, Vol. 53, No. 4, pp. A351-A359, January 2014.