Light scattering techniques for the characterization of optical components


Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Jena

ICSO 2014
International Conference on Space Optics
7 - 10 October 2014
Tenerife, Spain
Motivation

- Developments in optical technologies → new demands on quality of optical components:
  - Reduction of surface defects
  - Minimization of roughness and other scatter-relevant irregularities

- Quality monitoring by light scattering methods:
  - Non-contact, rapid, efficient, sensitive

- Origins of scattering:
  - Roughness, defects, bulk inhomogeneities, internal scatter in coatings, contaminations

→ Specifications based on roughness parameters are not always sufficient
  → Direct specification and measurement of light scattering
Light scattering measurements

![Diagram of light scattering measurement system](image)

**Angle Resolved Scattering**

\[
ARS(\theta_s) = \frac{\Delta P_s(\theta_s)}{P_i \Delta \Omega_s}
\]

**BRDF**

\[
BRDF(\theta_s) = \frac{ARS(\theta_s)}{\cos \theta_s}
\]

**Total Scattering**

\[
TS = \frac{P_s}{P_i} = 2\pi \int ARS(\theta_s) \sin \theta_s d\theta_s
\]

(ISO13696: 2° - 85°)

---


© Fraunhofer
Requirements on scatter metrology for space optics

- Measurements at wavelengths relevant for the application
- High dynamic range (at least 11 orders of magnitude for VIS optics) and good linearity
- High sensitivity / low noise (noise equivalent BSDF < $10^{-6}$ for VIS optics)
- Small near angle limit ($< 0.5^\circ$ for imaging applications)
- 3D capability for anisotropic structures
- Large and complex components or entire systems
- Operation in clean room environment, high-vacuum, purge gas, environmental monitoring / particle counting
Measurement system ALBATROSS

- Various wavelengths in UV-VIS-IR spectral range (325 nm, 442 nm, 532 nm, 1064 nm, 10.6 µm, …)

- Highly sensitive system:
  - Noise equivalent ARS: < $10^{-8}$ sr$^{-1}$
  - Roughness equivalent sensitivity: $\sigma < 0.1$ nm

- Full spherical ARS capability for characterization of anisotropic samples

- Handling of large samples

- Characterization of entire sample surfaces

- Operation in clean room environment (class ISO5)
Scatter map of polished surface

- Measurement at 532 nm; fixed scatter angle of 25°
- Homogeneous overall level and areas of slightly enhanced scattering
- ARS data → residual turning marks, not removed by polishing process
- Localized spots with substantially enhanced scattering caused by defects and particle contaminations

→ Area-covering, direct information of scatter properties
BRDF of black surfaces at 4.6 µm

- Visible range → almost perfect absorbing properties
- Mid-infrared → perfectly diffuse scattering for longer wavelengths and oblique incidence extremely challenging
- Acktar UltraBlack™ foil:
  - Diffuse scattering distribution for moderate angles of incidence and low overall scattering level
  - Larger angles of incidence → distinct specular component observable, confined to a small region in specular direction
  - Behavior not according to Harvey-Shack scattering model

→ Measurement data essential
→ Simple models can be misleading or completely wrong
Low scatter transmission gratings at 633 nm

3D scatter measurement (BTDF) around 1st order

Scatter maps at fixed scatter angle...

- Within diffraction plane (DP)
- Out of DP
- Perpendicular to DP

→ Direct feedback for process optimization
→ Choice of parameters with lowest scattering

Telescope mirrors

- Mirrors used in laser beam expander used as flight hardware component in space
- S4: small angle between incoming and outgoing direction → critical near angle scattering
- S3: intermediate image close to mirror surface → large view factor to detector → minimization of scattering only by superior surface finish and coating

Measurements with identical geometrical and optical configuration as in final application in telescope
Measurement system SpectroScat

- Light source: high power OPO, 50 mJ, 20 Hz, 3 ns
- Wavelength range 225 nm – 1750 nm, spectral bandwidth < 0.05 nm
- 3D angle resolved scatterometer, multichannel detector head (PMTs + photodiode)

Rugate filters

Sample: HR 532 nm Rugate (Fraunhofer FEP)

→ Scatter loss increases from 0.1% at 532 nm to 2.2% at 505 nm!
→ Critical effect for spectral filters, spectral shifts, …
Summary & Outlook

- Light scattering can be critical for high-end optical applications (image degradation, losses)
- Many potential reasons for light scattering (roughness, defects, SSD, coatings, …)
- Direct measurements required
- Special demands on scatter metrology for space applications
- Instruments developed at Fraunhofer IOF to meet these demands
- Examples of applications presented for mirrors, black surfaces, grating structures, and interference coatings
Thank you!

Acknowledgements:

Thanks to A. Gebhardt, R. Steinkopf, U. Zeitner (Fraunhofer IOF), K. Täschner (Fraunhofer FEP), D. Katsir (Acktar Ltd.), and T. Weigel (RUAG Space) for providing samples and to M. Garrick, L. Mejnertsen, M. Opel, and D. Unglaub (Fraunhofer IOF) for their contributions to measurements and discussions.
Measurement systems TTS and horos

- Single-shot angle resolved scattering sensor based on detector matrix
- Comprehensive assessment of scatter, roughness, defects, ...
- High sensitivity, $\sigma_{\text{rms}} < 0.5$ nm
- Short measurement time < 1 s
- Compact system
- Weight < 0.5 kg

- Table top system, size of housing: $0.8 \times 0.8 \times 0.8$ m$^3$
- Full 3D-spherical measurement capability (ARS, BRDF, ...)
- Wavelengths: 405 / 532 / 640 nm
- Dynamic range: 13 orders of magnitude
- Noise equivalent ARS: $< 10^{-8}$ sr$^{-1}$
- Roughness equivalent sensitivity: $< 0.1$ nm
Angle Resolved Scattering (ARS) is related to the Power Spectral Density (PSD) of the surface roughness through the equation:

\[ ARS(\theta_s) = C \ PSD(f) \]

(total surface, \( \sigma \ll \lambda \))

Total Scattering (TS) is given by:

\[ TS = R \left( \frac{4\pi \sigma}{\lambda} \right)^2 \]

→ Prediction of light scattering from roughness data

→ Roughness analysis through light scattering measurements

E. L. Church et al., Appl. Opt. (1975); J. C. Stover, Optical Scattering: Measurement and Analysis (SPIE, 1995);
A. Duparré, In Encyclopedia of Modern Optics (Elsevier, Oxford, 2004);
Instrument signatures (ARS measurement without sample)

Example: ALBATROSS

- Incident beam $= 1/\Omega_s = \text{max. signal}$
- Dynamic range $> 11$ orders of magnitude
- Background ARS $= \text{min. signal}$
  (electronic noise, Rayleigh scatter from air molecules)

Instrument signatures (ARS measurement without sample)
Same as before but log-log scale

Relationship Scattering – Surface roughness:

Bidirectional Reflectance Distribution Function: 
\[ BRDF(\theta_s) = \frac{\Delta P_s(\theta_s)}{P_i \Delta \Omega_s \cos \theta_s} \]

For metal mirror (single surface, \( \sigma << \lambda \), small angles):

\[ BRDF(\theta_s) \sim \frac{16\pi^2}{\lambda^4} \text{PSD}(f) \]

\[ f = \frac{\sin \theta_s - \sin \theta_i}{\lambda} \]

Surface power spectral density (roughness spectrum)

- Basis for scatter prediction from surface roughness (or vice versa)
- But! Relationships much more complicated for other sources of scattering: defects, contaminations, SSD, coatings, deep structures

\[ \rightarrow \text{Specify and measure scatter directly!} \]

