BIDIRECTIONAL REFLECTANCE OF BLACK SILICON USED IN SPACE AND EARTH REMOTE SENSING APPLICATIONS

Georgi T. Georgiev, James J. Butler, Ron Shiri, Christine A. Jhabvala, Edward J. Wollack, Elena M. Georgieva

NASA Goddard Space Flight Center, Greenbelt, MD 20771

SPIE Remote sensing, 11 September, 2019, Strasbourg, France

OBJECTIVES

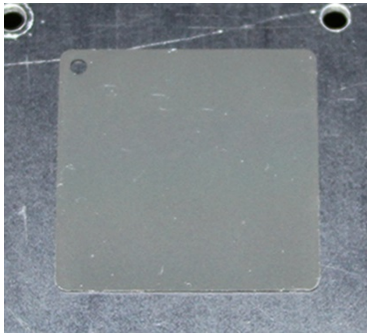
- Light which enters Earth observing satellite-based instruments is diffracted and scattered by internal instrument structures, adversely impacting remote sensing measurements;
- Scattered light is often controlled by the use of light tight enclosures equipped with strategically placed baffles and stops
- Space-based astrophysical observations often require the detection and measurement of light originating from small, distant, often faint objects;
- The direct imaging of exoplanets often require fabricated coronagraph masks to control scattering and diffraction of light;
- The ideal surface for control over of stray light and to fabricate coronagraph masks would be a Lambertian absorber achieving a uniform low reflectance independent of light incident angle and the wavelength.

Black Samples

The ideal surface for control over of stray light and to fabricate coronagraph masks would be a Lambertian absorber achieving a uniform low reflectance independent of light incident angle and the wavelength. We studied a Black Si, new and very promising black material for reducing stray light in space instruments also well known and used black materials as Z306 paint and Fractal Black

Black Silicon

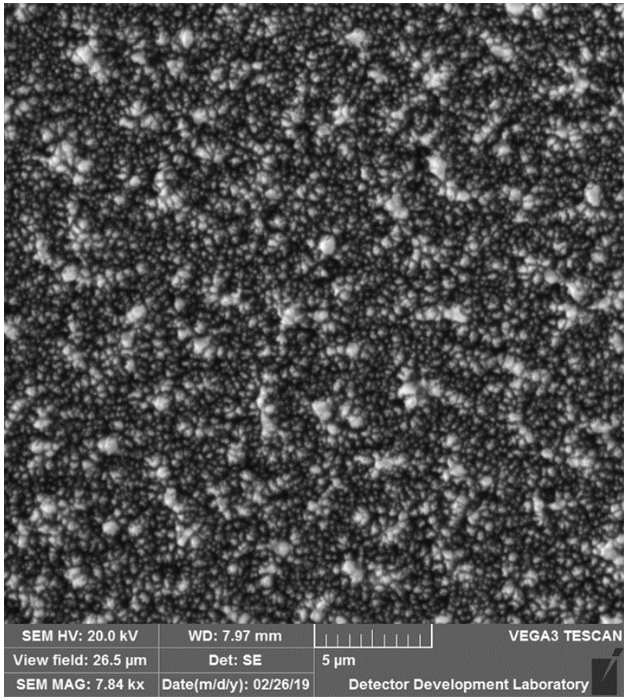
Z306

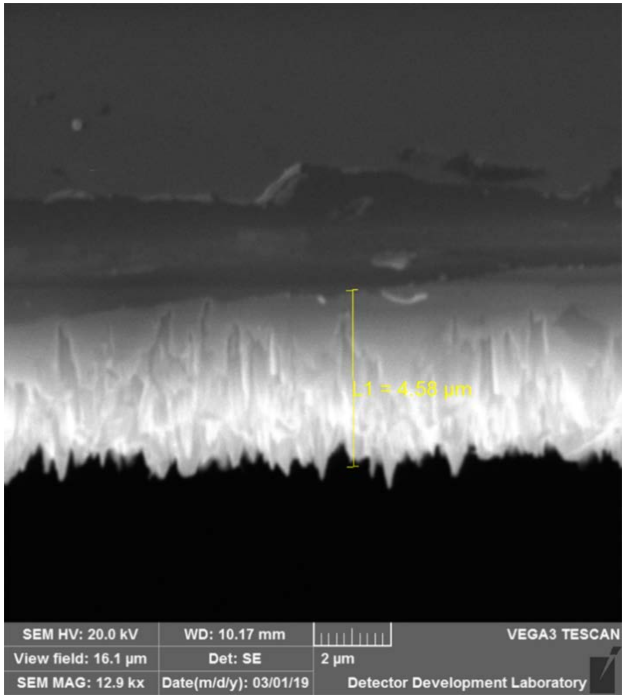


Fractal Black

Black Samples

Black Silicon





SEM images of cryogenic etching of Black Si on a flat Si wafer performed at the Detector Development Laboratory of Goddard Space Flight Center. (Left) Top view of the Black Si and (Right) Side view of the Black Si showing a 5-micron thickness height of the silicon grass or needle structures.

The Black Si reflectance can be lowered by introducing microstructures to lower the reflectance of the material surface and achieve extremely low broadband reflectance.

Optical Evaluation Techniques

8º directional/hemispherical reflectance

The darkness of the black samples was evaluated through measurements of their 8º directional/hemispherical reflectance from 250nm to 2500nm using Perkin Elmer 1050 spectrophotometer equipped with a 150mm Spectralon coated integrating sphere with a 25mm sample port.

Optical Evaluation Techniques

Bidirectional Reflectance Distribution Function (BRDF)

The bidirectional reflectance distribution function (BRDF) fully defines the directional reflection characteristics of a surface, providing the reflectance in a specific direction as a function of illumination, viewing geometry and wavelength.

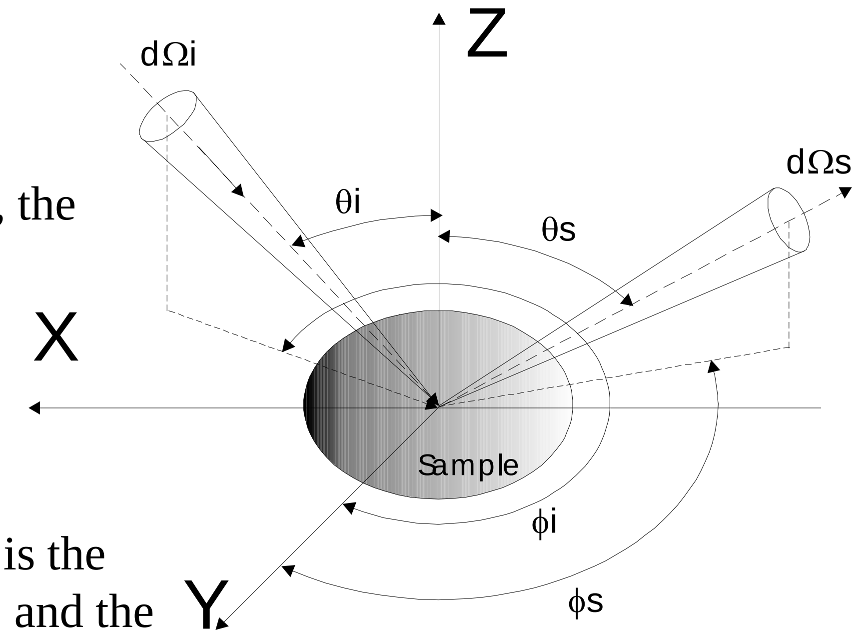
Following the NIST definition of BSDF, according to Nicodemus, the BSDF is referred to as the ratio of the scattered radiance, L_s, scattered by a surface into the direction (θ_s, ϕ_s) to the collimated irradiance, E_i, incident on a unit area of the surface:

$$BSDF = \frac{L_s(\theta_i, \phi_i, \theta_s, \phi_s, \lambda)}{E_i(\theta_i, \phi_i, \lambda)}$$

where θ is the zenith angle, ϕ is the azimuth angle, the subscripts *i* and *s* represent incident and scattered directions, respectively, and λ is the wavelength

$$BSDF = \frac{P_s / \Omega}{P_i \cos\theta_s}$$

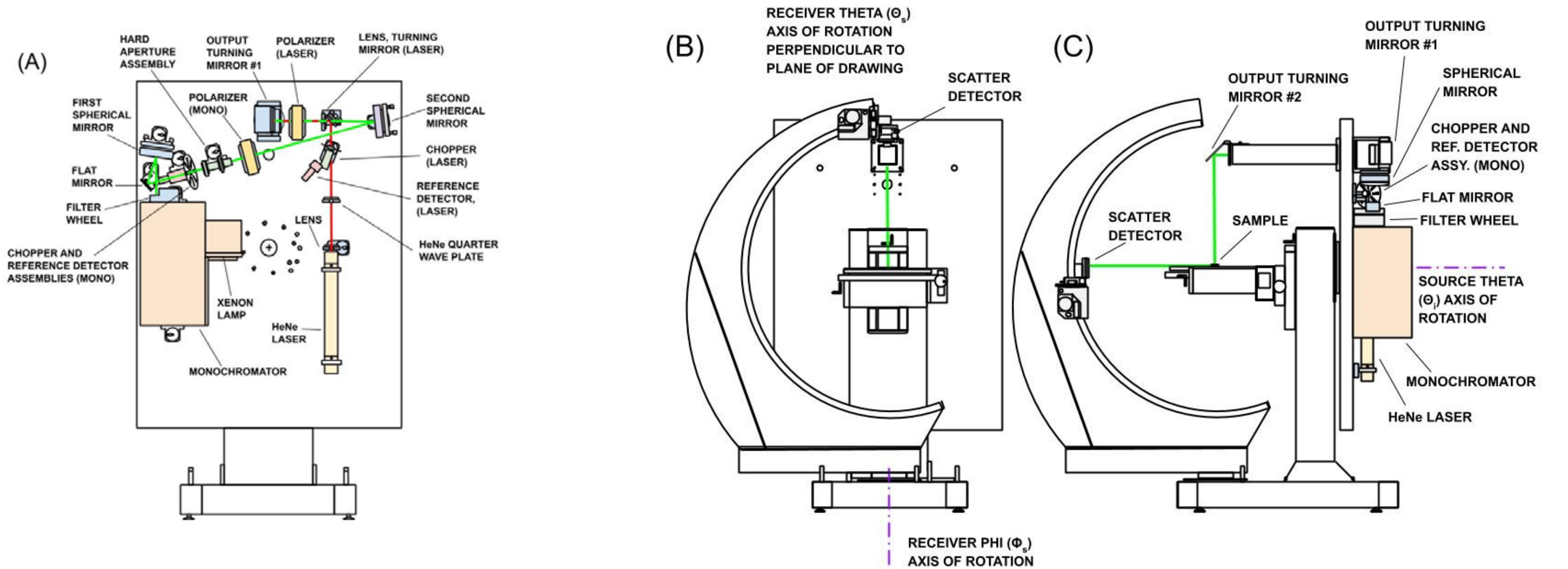
P_s is the scatter power, P_i is the incident power, Ω is the solid angle determined by the detector aperture, *A*, and the radius from the sample to the detector, *R*, or $\Omega = A/R^2$, and θ_s is the scatter angle



Angular convention

Optical Evaluation Techniques

Optical Scatterometer I.



The optical scatterometer in the BRDF measuring configuration. The optical source side of the scatterometer is shown in (A) and the sample side in (B). (C) is a side view showing the sample and optical source sides of the instrument with the receiver φ stage rotated to a position 90° from that shown in (B).

Optical Evaluation Techniques

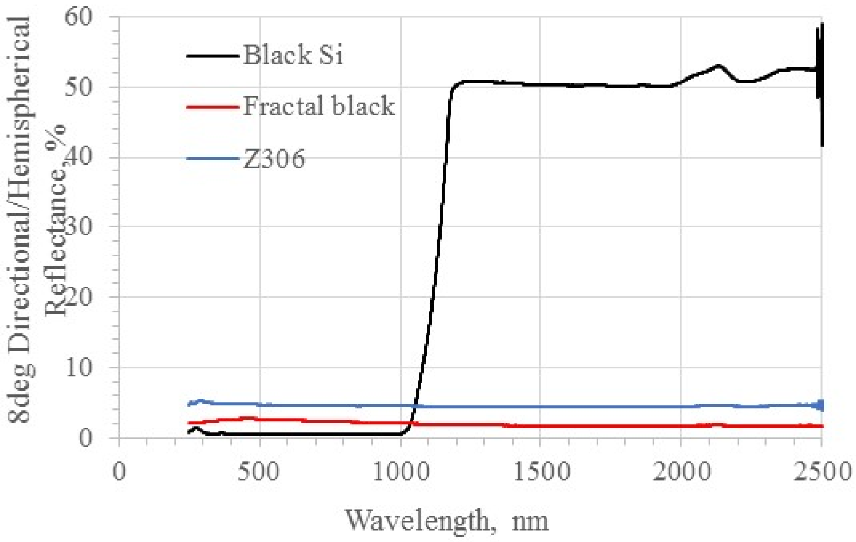
Optical Scatterometer II.

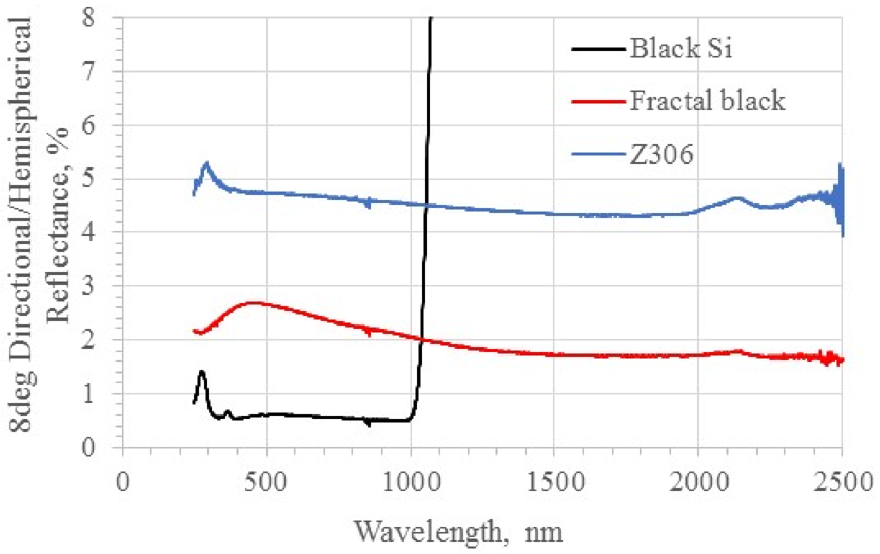
- Out-of-plane scatterometer capable of measuring bidirectional scatter distribution function (BSDF) of transmissive or reflective, specular or diffuse, optical elements
- Traceability of BRDF measurements to NIST is maintained using sets of Spectralon lab standards measured yearly by NIST and before all measurements by GSFC,

Optical Scatterometer sam

Results and Discussion

8º directional/hemispherical reflectance





Black Si, Fractal black and Z306

Black Si exhibit the lowest reflection from 250nm up to about 1000nm and then it increases to higher reflectance values

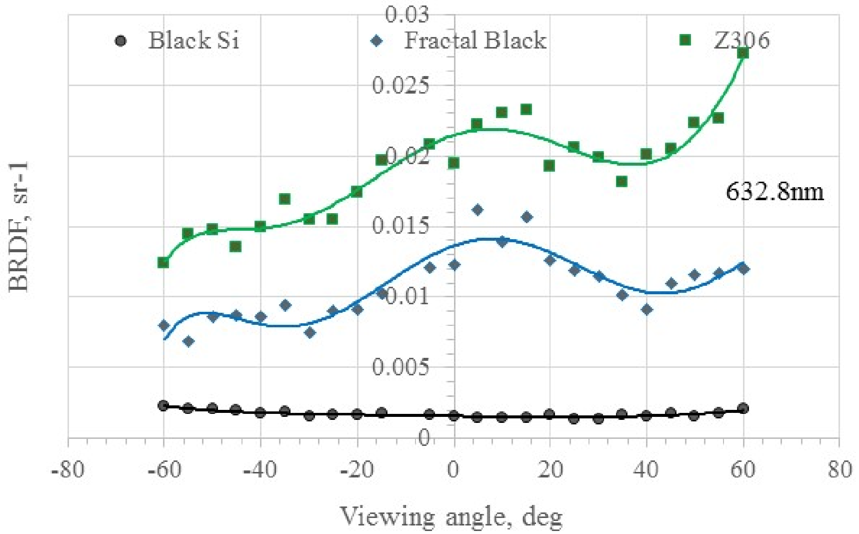
Results and Discussion

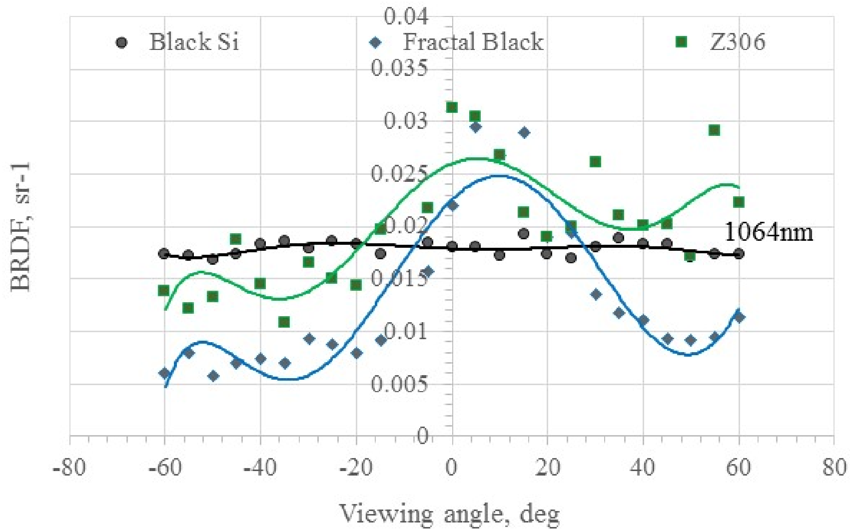
Bidirectional Reflectance I.

- The BRDF fully defines the directional reflection of a surface, reflects its structural and optical properties
- It provides the reflectance of a sample in a specific direction as a function of illumination and viewing geometry.
- It can be used to quantify the specularity and/or diffuseness of the Black Si and the other samples.
- The samples were measured at two orthogonal polarizations of the incident light, then averaged thus reporting the BRDF for unpolarized case of the incident light
- First set. The BRDF was measured at wavelengths of 632.8nm and 1064nm, incident angle of 10deg, and viewing angles from -60^{o} to 60^{o} in steps of 5^{o}
- Second set. Additional testing was done in order to quantify the samples at 10^{0} incident angle at 632.8nm and 1064nm with step of 0.5^{o}

Results and Discussion

Bidirectional Reflectance II.

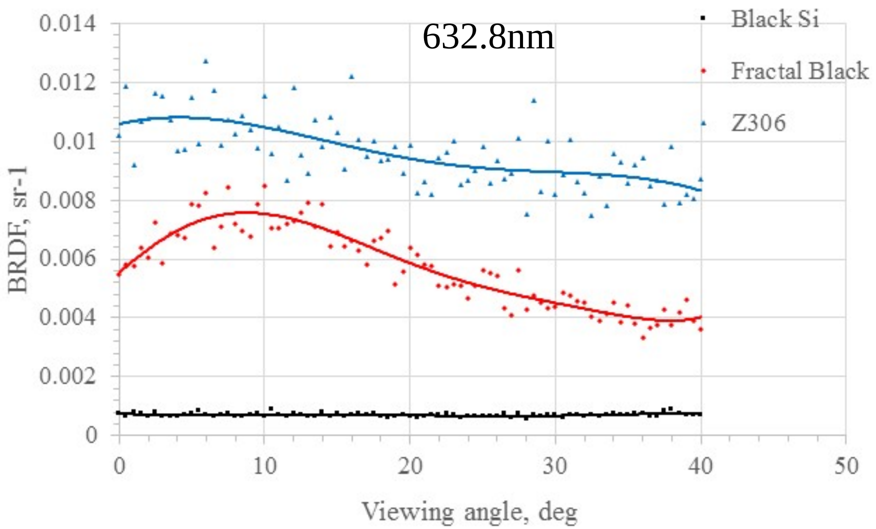


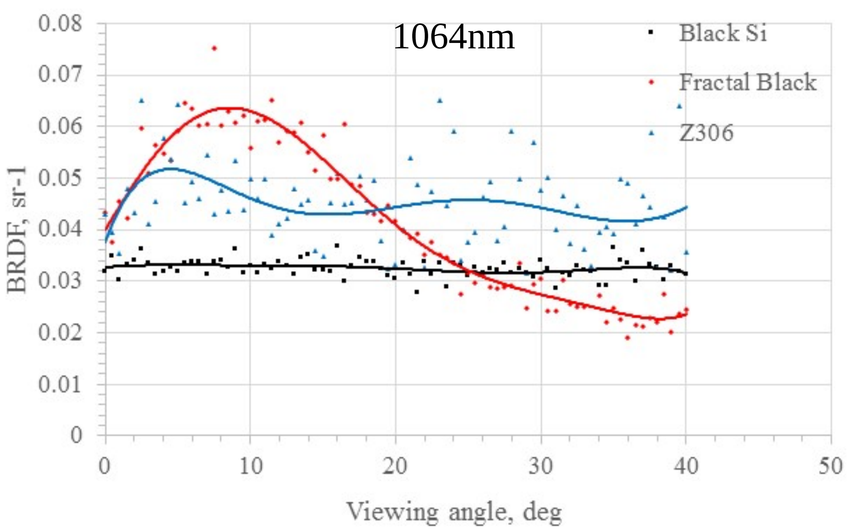


- The BRDF data follow the directional hemispherical reflectance data.
- The data predict the Black Si to be the darkest, followed by the Fractal black and Z306.
- Deviation from constant in the vicinity of the direction of specular reflection, i.e. 10^{o} viewing angle is an indication of non-Lambertian reflectance behavior.
- Z306 shows the largest and sharpest specular reflectance followed by the Fractal black. The Black Si sample has the lowest specular reflectance.
- Fractal black and Z306 demonstrate forward scattering properties
- Fractal black and Z306 exhibit decreasing reflectance at angles away from specular, then the reflectance increases due to forward scattering

Results and Discussion

Bidirectional Reflectance III.





Sources of specular reflection - coating itself and substrate

Z306 paint exhibits the highest BRDF at both 632.8nm and 1064 nm

Black Si exhibits virtually no forward scatter and retroscatter, characteristic of a near Lambertian scattering surface

Black Si sample does not show appreciable reflectance peaks. The specular reflectance most often originate from the top surface of the sample, as in the case with Z306. This is characteristic of a one-bounce surface scattering process.

Conclusions

- Initial studies of Black Si structures deposited on the substrates are presented in this paper,
- Black Si, created by etching on silicon substrate was found to be an order of magnitude darker in the spectral range from 250nm to 1000nm than Z306 also much darker than Fractal black,
- The Black Si sample exhibit practically none specular reflection at 632.8nm and 1064nm,
- There is no evidence of retroscatter in the Black Si sample. Retroscatter, if present, would originate from reflectance off the illuminated interior sides of the etched structure. The lack of retroscatter indicates that light illuminating inside of the coating structure is undergoing multiple internal reflections,
- The Black Si reflectance distribution is very close to Lambertian,
- Black Si performs as a very good volume diffuser with multiple reflections within the material,
- Black Si show potential for lowering stray and scattered light in optical instrumentation,
- Significant engineering and testing is required to optimize and qualify Black Si formulations for space use. Elements of this environmental validation effort are currently underway.

Measurement Uncertainty Budget (1 of 2)

- Equations:

$$\Delta_{BSDF}=(2(\Delta_{NS})^2 + 2(\Delta_{LIN})^2 + (\Delta_{SLD})^2 + (\Delta_{\theta S}\bullet\tan(\theta_S))^2) + (\Delta_{NIST})^2)^{1/2} \quad (1)$$

Δ_{BSDF} - BSDF measurement uncertainty

Δ_{NS} - Signal to noise uncertainty

Δ_{LIN} - Detector/electronics non-linearity

Δ_{SLD} - Receiver solid angle uncertainty

$\Delta_{\theta S}$ - Total scatter angle uncertainty

Δ_{NIST} – NIST lab standard measurement uncertainty

θ_S - Receiver scatter angle

$$\Delta_{SLD} = ((2\Delta_{RM})^2 + (2\Delta_{RZ})^2 + (2\Delta_{RA})^2)^{1/2} \quad (2)$$

Δ_{SLD} - Receiver solid angle uncertainty

Δ_{RM} - Goniometer arm radius uncertainty

Δ_{RZ} - Arm radius uncertainty due to sample z misalignment

Δ_{RA} - Detector aperture radius uncertainty

$$\Delta_{\theta S} = ((\Delta_{\theta M})^2 + (\Delta_{\theta Z})^2 + (\Delta_{\theta T})^2)^{1/2} \quad (3)$$

$\Delta_{\theta S}$ - Total scatter angle uncertainty

$\Delta_{\theta M}$ - Goniometer scatter angle uncertainty

$\Delta_{\theta Z}$ - Scatter angle uncertainty due to sample z misalignment

$\Delta_{\theta T}$ - Scatter angle uncertainty due to sample tilt error

Measurement Uncertainty Budget (2 of 2)

Uncertainty component	Equation Variable	Uncertainty
1/(Signal to Noise)	Δ_{NS}	0.001
Detector/electronics non-linearity	Δ_{LIN}	0.0035
Receiver solid angle	Δ_{SLD}	0.0032
•Goniometer arm radius	Δ_{RM}	0.0004
•Sample z misalignment	Δ_{RZ}	0.0004
•Detector aperture radius	Δ_{RA}	0.0015
Total scatter angle	$\Delta_{\theta S}$	0.0041
•Goniometer scatter angle	$\Delta_{\theta M}$	0.0023
•Sample z misalignment	$\Delta_{\theta Z}$	0.0005
•Sample tilt error	$\Delta_{\theta T}$	0.0033
NIST lab standard measurement	Δ_{NIST}	0.0056
Total measurement uncertainty (k=1)	Δ_{BSDF}	0.0083 or 0.83%

Questions