SCATTER LIGHT MEASUREMENTS IN SUPPORT OF OPTICAL INSTRUMENTS DEVELOPMENT

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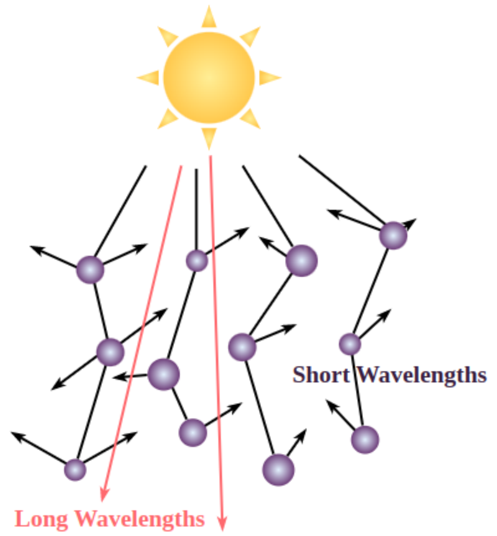
Scatter Light in General

We talk about *scatter light* when part of the light passing from one medium to another is absorbed or reflected in various directions.

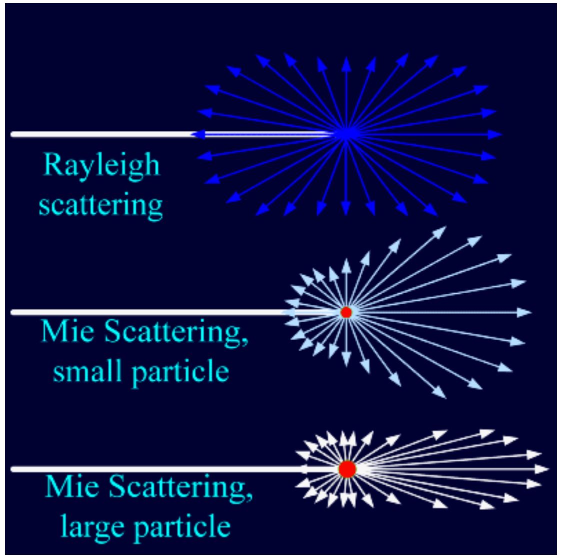
The light scattering can be described by the Maxwell's equations but since exact solutions to Maxwell's equations are only known for spherical particle geometries light scattering is studied by computational electromagnetics dealing with electromagnetic radiation and absorption by particles.

Scattering from any spherical particles with arbitrary size is explained by the Mie theory providing complete analytical solution of Maxwell's equations for the scattering of electromagnetic radiation by *spherical particles*. *Rayleigh scattering* regime is the scattering of light by particles *much smaller than the wavelength of the light.*

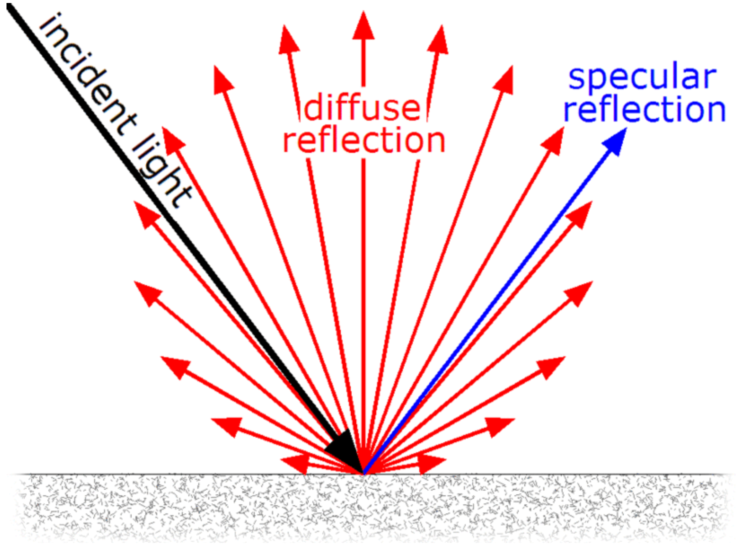
Geometric Optics Scattering or Ray-tracing techniques deal with particles of any shape much than the wavelength of light.

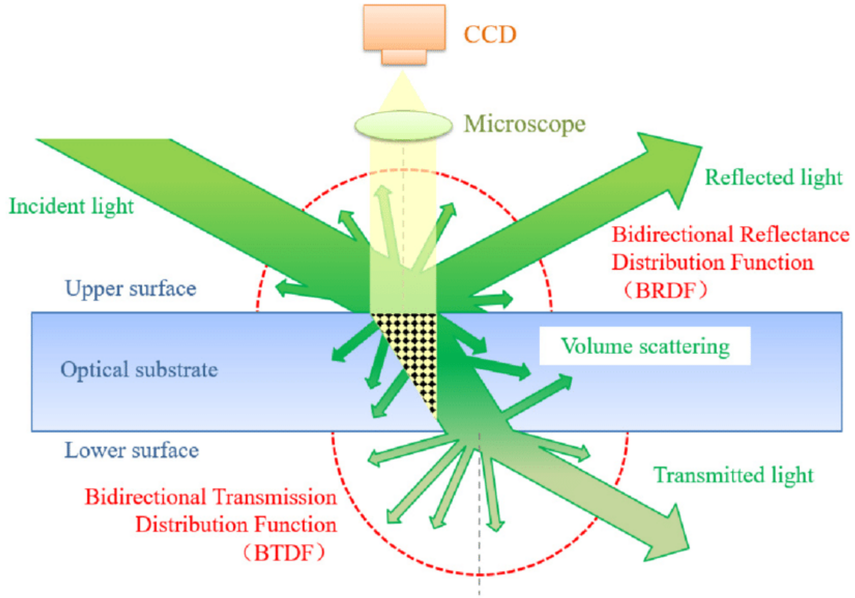


Scattering of Light



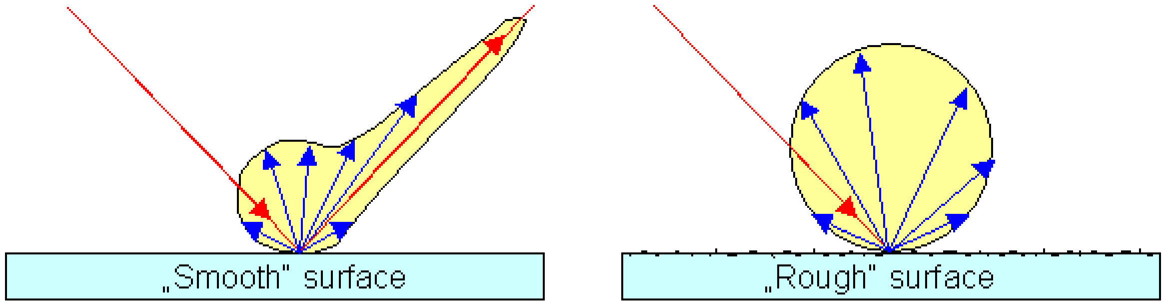
Specular and diffuse, Surface and Volume Scattering





Specular and Diffuse scattering
Specular scattering refers to a clear mirror-like reflection.
The diffuse scattering is observed when the light retains the energy but not the image

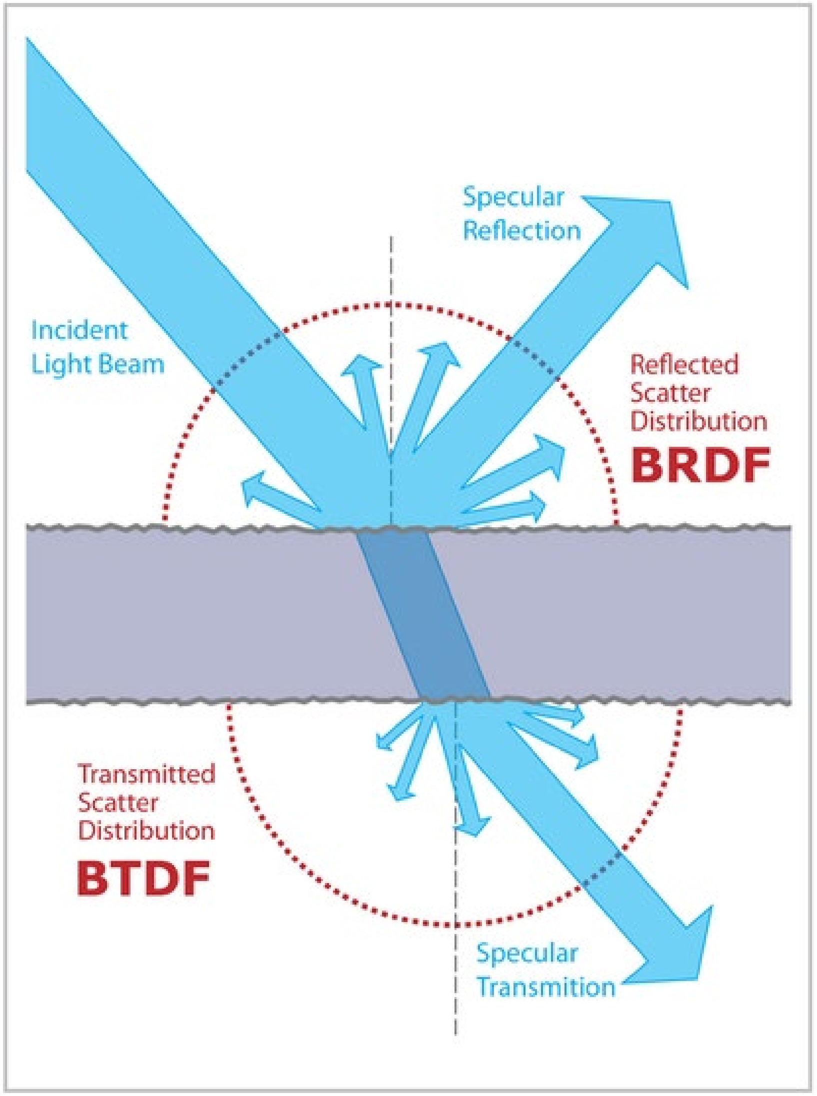
Optical scattering can be **surface scattering** and **volume scattering**.
When the scattered light comes only from the interaction with the surface it is surface scattering even when the optical material is completely clear.
Volume scattering occurs only in the bulk of the optical material.



Scatter Light Measurements at GSFC

Scatter light measurements characterize the materials surface by the Bidirectional Scatter Distribution Function (BSDF) as a function of illumination and viewing (scattering) geometry. BSDF is measured in sr^{-1} and can be defined as Bidirectional Reflectance Distribution Function (BRDF) or Bidirectional Transmittance Distribution Function (BTDF) depending on whether the incident to the sample light is reflected or transmitted. The BSDF quantifies the scattered radiation as a function of wavelength and scattering geometry - angles of incidence and scatter.

Incident light, Specular and diffuse reflection, Reflected scatter distribution (BRDF), Transmitted scatter distribution (BTDF), Surface and Volume scatter are presented



Optical Evaluation Techniques

Bidirectional Scatter Distribution Function (BRDF)

The bidirectional scatter distribution function (BSDF) 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.

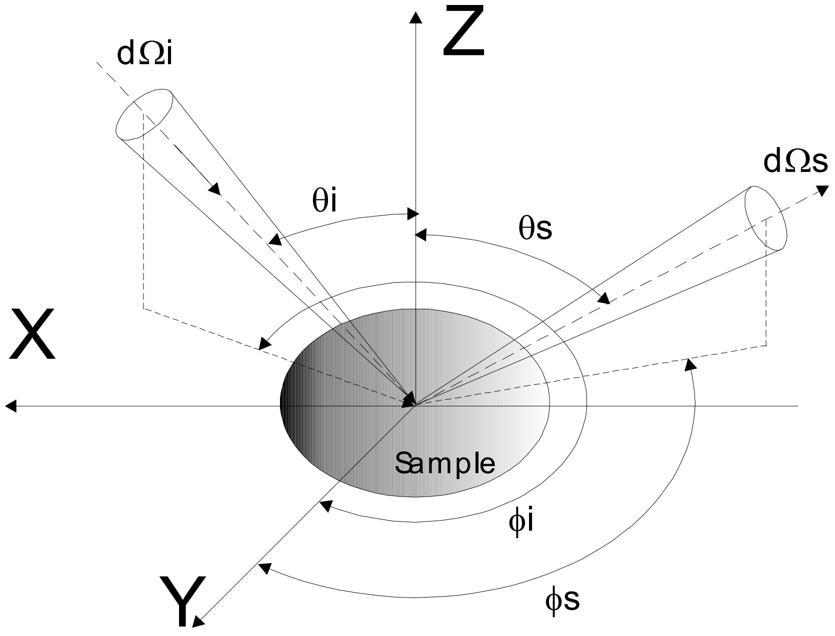
Following the NIST definition of BSDF, according to Nicodemus, (*F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I.W. Ginsburg, and T. Limperis, "Geometrical considerations and nomenclature for reflectance", National Bureau of Standards, NBS monograph 160, Oct. 1977*) the BSDF is referred to as the ratio of 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

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

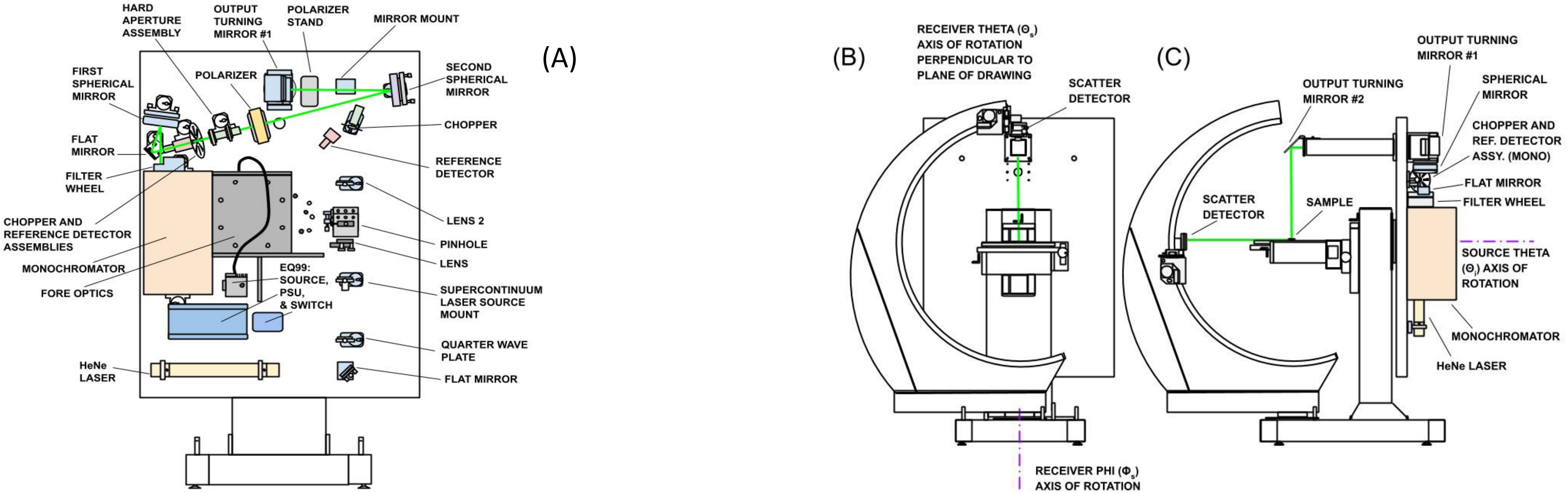
P_s is the scatter power, P_i is the incident power, Ω is the solid angle determined by the detector aperture, *A*, and the radius from the sample to the detector, *R*, or $\Omega = A/R^2$, and θ_s is the scatter angle



Angular convention

Optical Evaluation Techniques

GSFC Optical Scatterometer I.

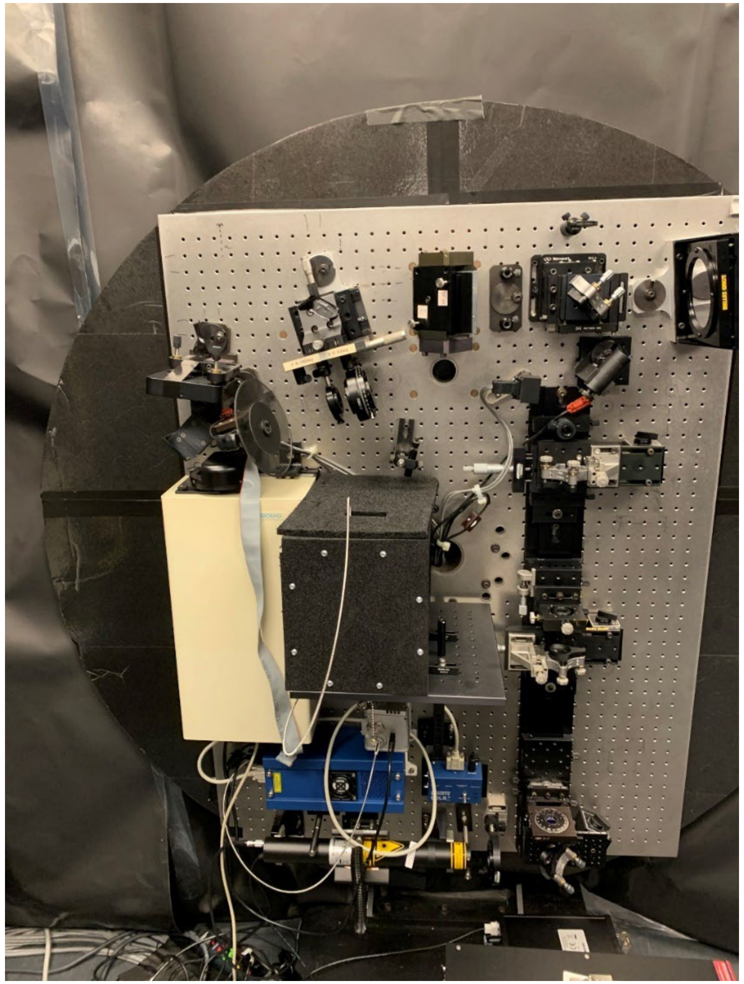


The instruments used for BSDF measurements are called Optical scatterometers.
They employs ultraviolet, visible, and infrared light sources and highly sensitive detectors.
There is a wide variety of scatterometers on the market. They differ by source and detector spectral range, incident angular range and scatter angular range, sample size, positioning and movement in X-Y-Z directions, etc.

The GSFC 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).

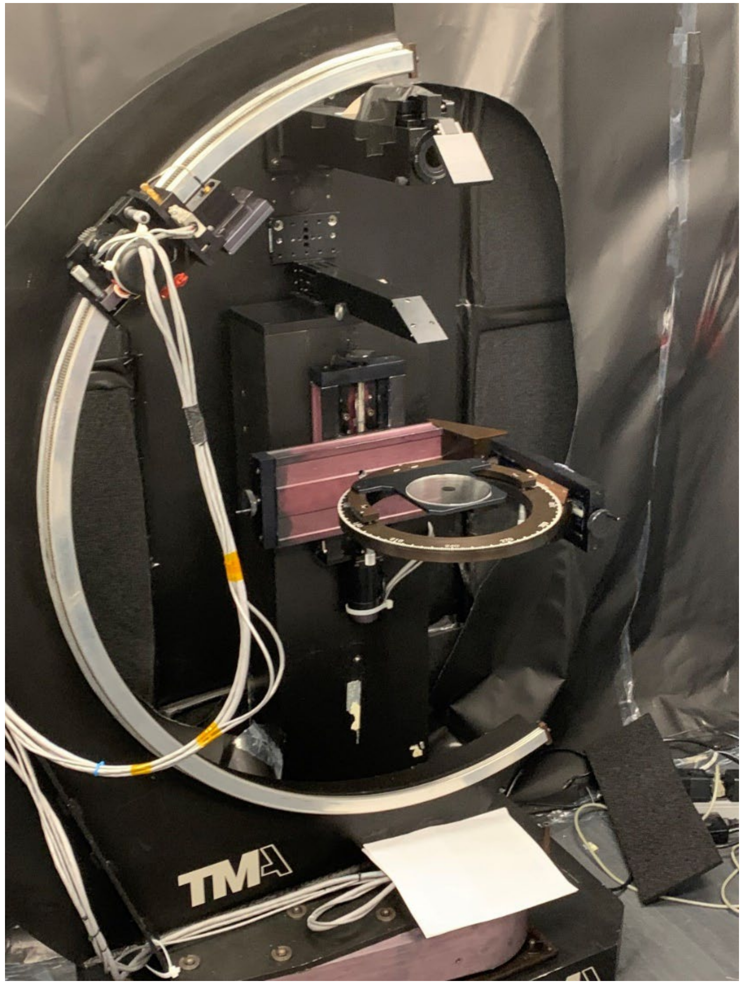
Optical Evaluation Techniques

GSFC Optical Scatterometer II.



Optical Table with different light sources, Energetiq - Monochromator, Fixed wavelength Lasers, Supercontinuum source, SIRCUS –like OPO system

The scatterometer is located in a ISO 7 laminar flow cleanroom, measuring the BRDF and BTDF in-plane and out-of-plane.



Goniometer, Angle of incidence zenith and azimuth, Scatter angles zenith and azimuth, Sample positioning in X-Y-Z directions and rotation.

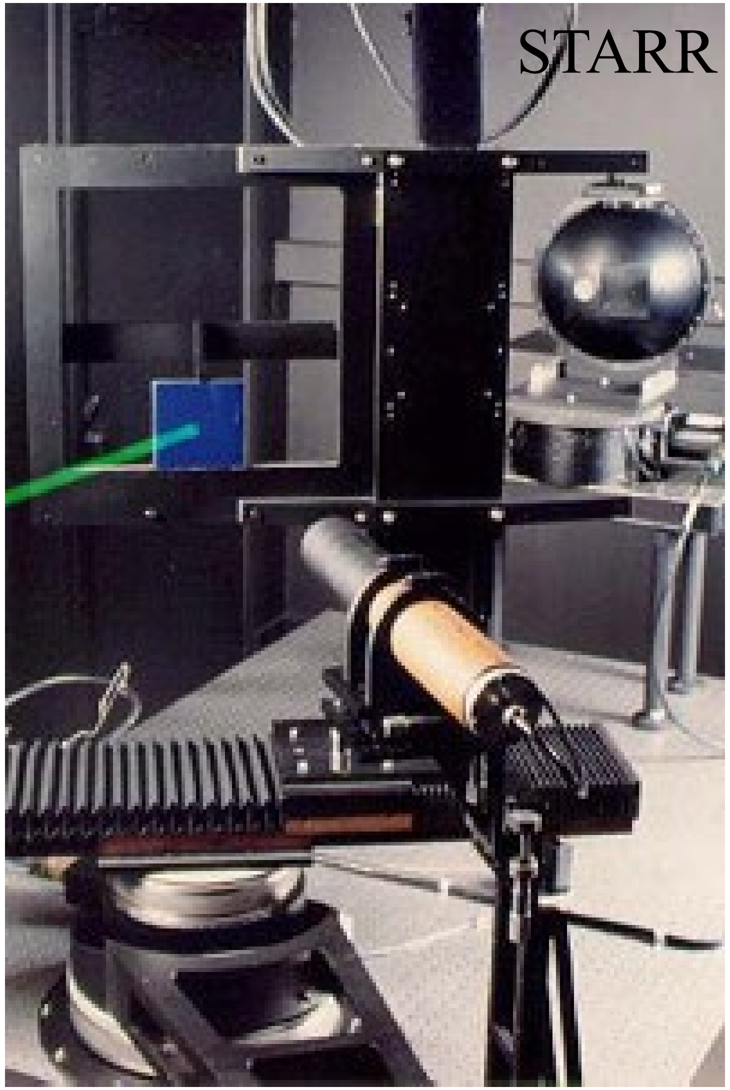
Optical Evaluation Techniques

8º directional/hemispherical reflectance

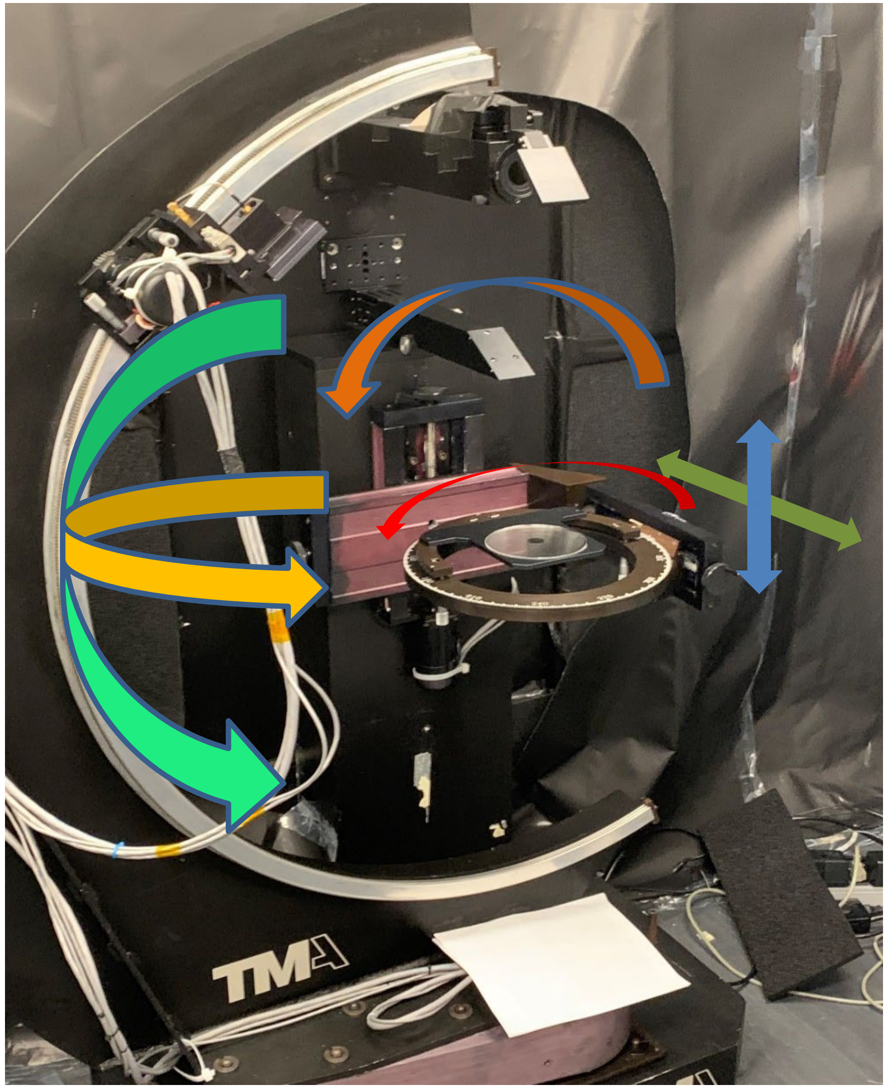
The samples reflection is evaluated through measurements of their 8º directional/hemispherical reflectance from 250nm to 2500nm using Perkin Elmer 1050 spectrophotometer equipped with a 150mm Spectralon coated integrating sphere with a 25mm sample port.

NIST Traceability

The scatterometer is regularly calibrated, and the results are traceable to measurements made on the National Institute of Standards and Technology's (NIST's) Special Tri-function Automated Reference Reflectometer (STARR) and Robotic Optical Scattering Instrument (ROSI). Traceability of optical scatter measurements to NIST is maintained using sets of Spectralon lab standards measured yearly by NIST and before all measurements by GSFC



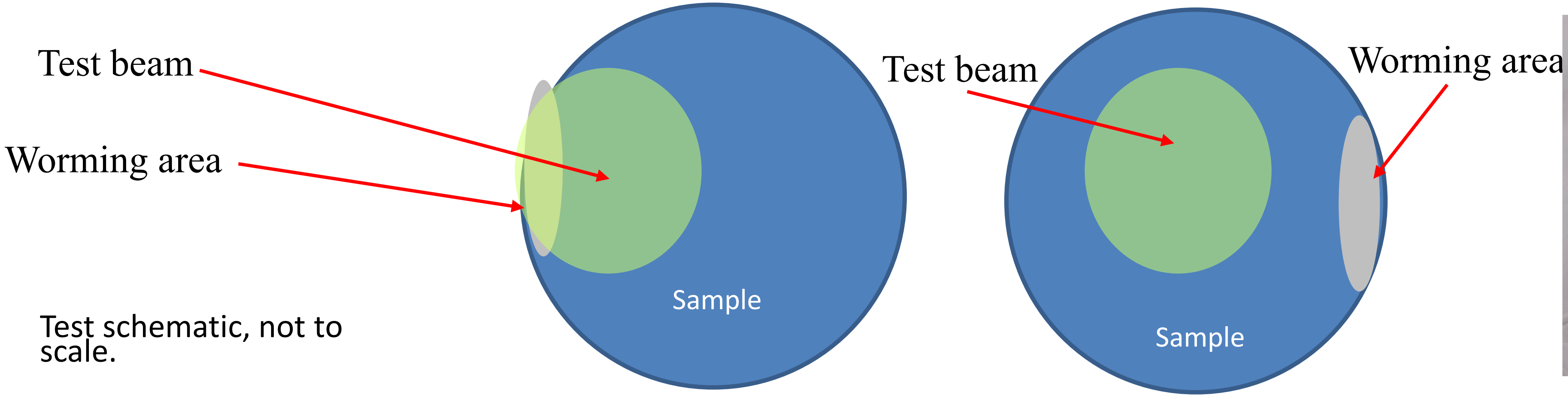
Roman Space Telescope
GRISM



RST Grism testing at different incident and scatter configurations

Roman Space Telescope
Optical Telescope Assembly - Optics Degradation test I.

- BRDF of the worming samples
  - No sample larger than 1” has worming. No worming sample has worming in the center.
- Therefore, for the new BRDF measurement the sample (1” diameter, which has the largest worming area of the L3Harris worming-samples) was measured twice; first with the worming plus some clean area in the view (a), then with the sample clocked horizontal 180 degrees to get a clean measurement with no worming present in the view (b).
- The data is a result of relative measurement – clean versus worming area, hence it does not present the actual BRDF of the clean or worming areas.
- The effect of worming area is clearly seen from this test.
- It has significant diffuse component when compared to the clean area data, which is very specular

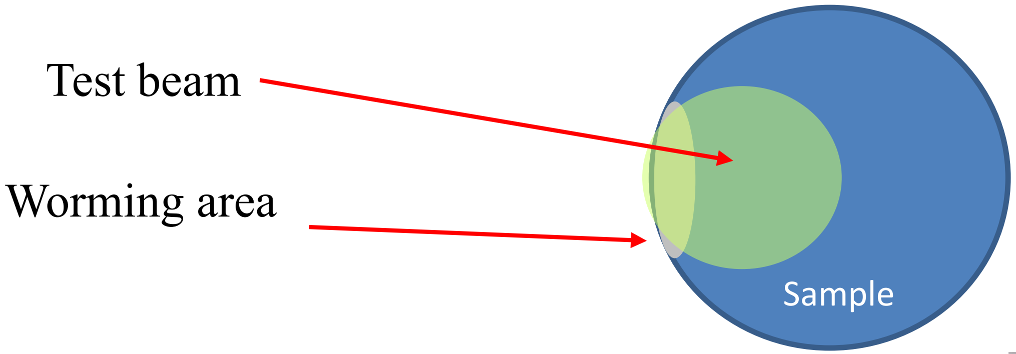


Orientation during test a

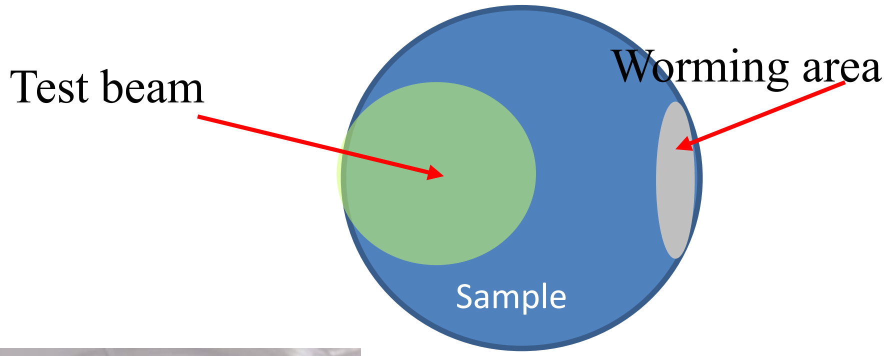
Orientation during test b

Sample

Roman Space Telescope
Optical Telescope Assembly - Optics Degradation test II.

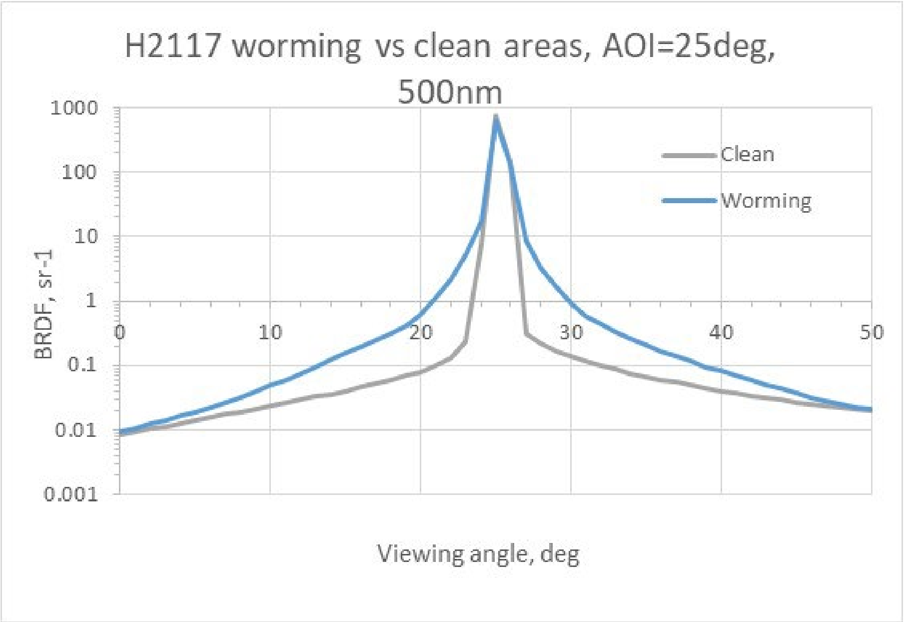


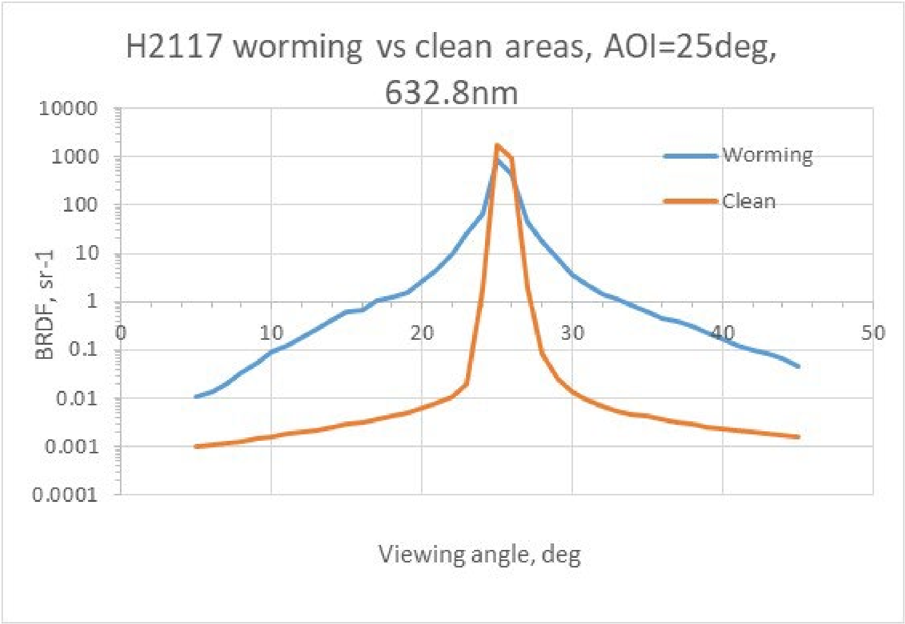
Orientation during test a



Orientation during test b

Test schematic, not to scale.





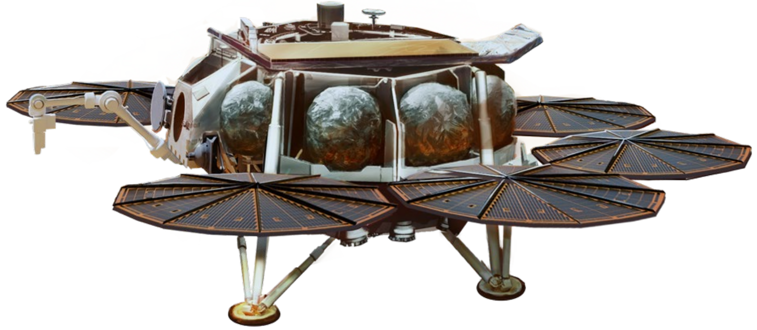
Mars Sample Return

Capture, Contain and Return System (CCRS)

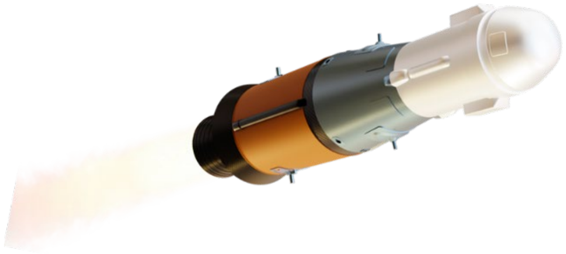
- Vision System
- Capture Lid Mechanism
- UV Sterilisation
- Capture and Configuration

Perseverance Rover

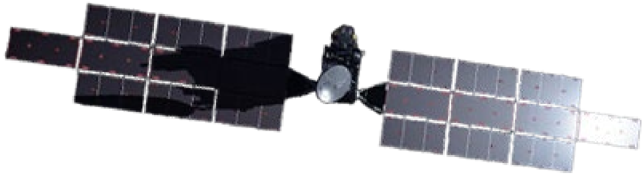
Sample Recovery Helicopters



Sample Retrieval Lander



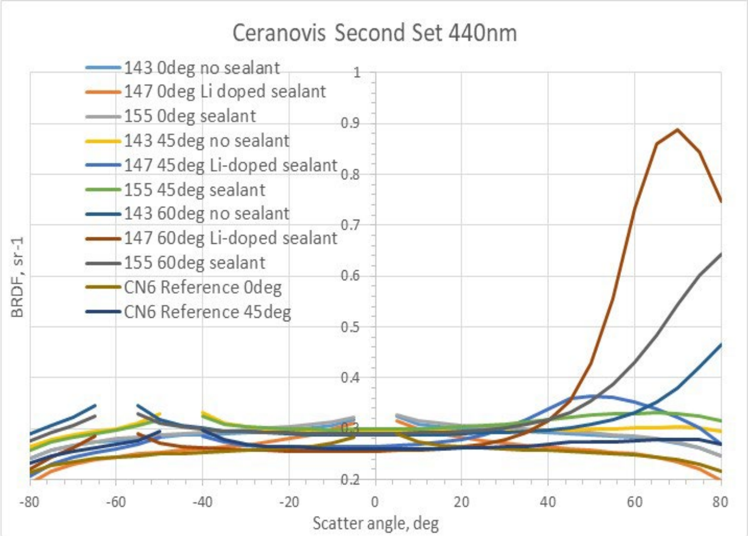
Mars Ascend Vehicle

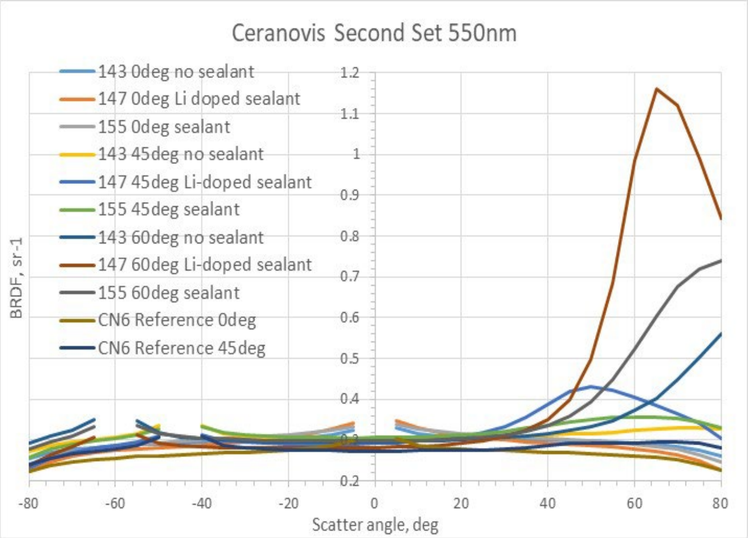


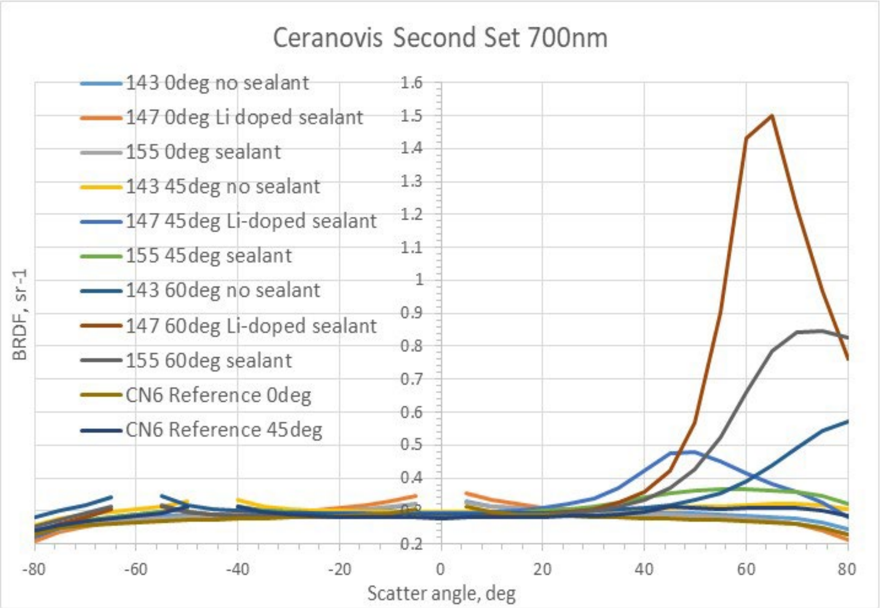
Earth Return Orbiter

CCRS – Vision

Ceranovis

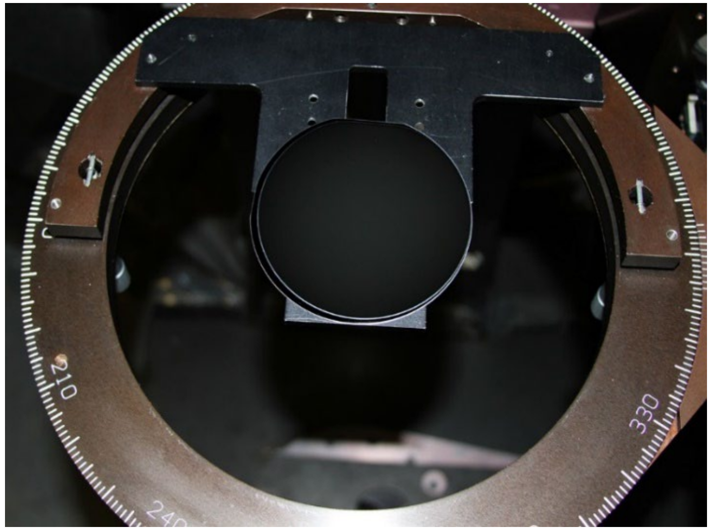




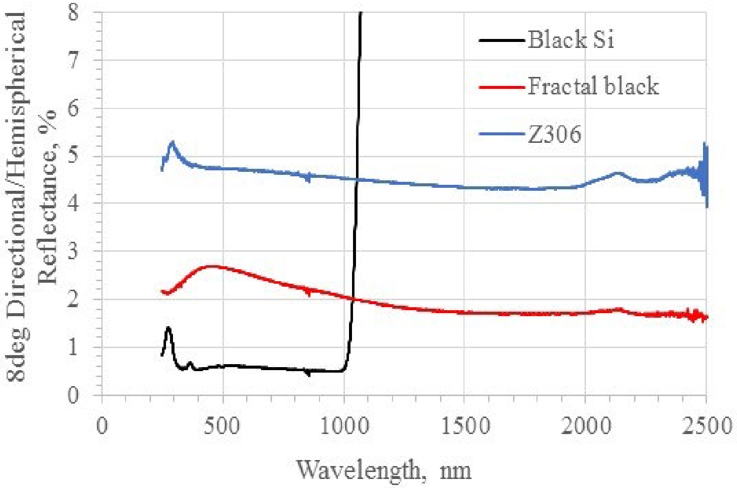


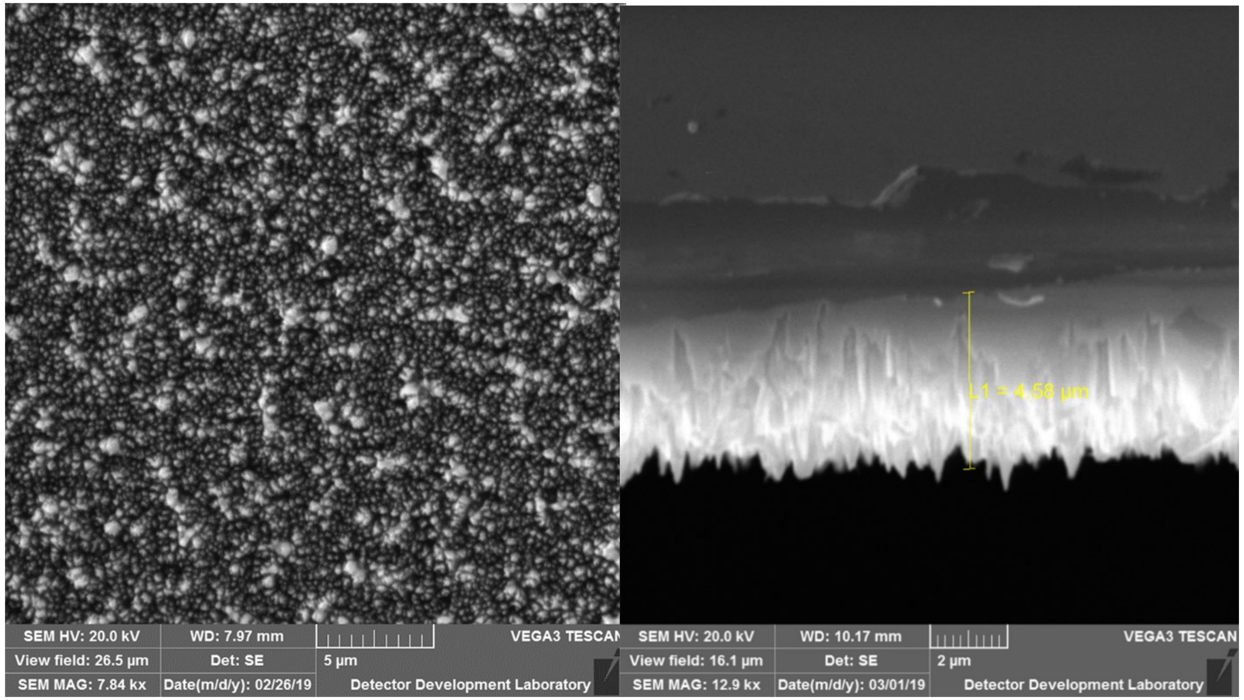
The current Ceranovis coupons exhibit rather diffuse scatter. The highest BRDF is at 60 deg incident angle, as expected. The sample with Li-doped sealant has the highest BRDF. The sample without any sealant has the lowest BRDF. The sample with unknown sealant has average BRDF values.

Black Silicon IRAD



Black Silicon sample on the sample stage

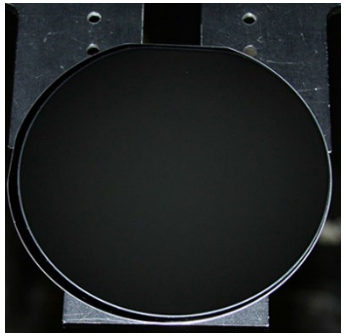




Scanning Electron Microscope (SEM) of cryogenic etching of black silicon on a flat Si wafer. (Left) Top view of the BSi and (Right) Side view of the BSi showing a 5-micron thickness height of the silicon grass or needle structures.

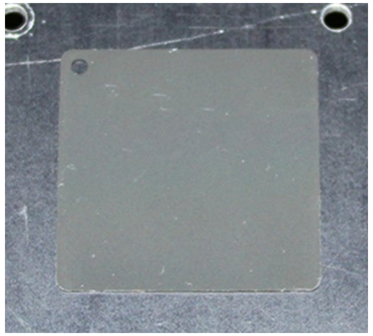
Black Samples

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

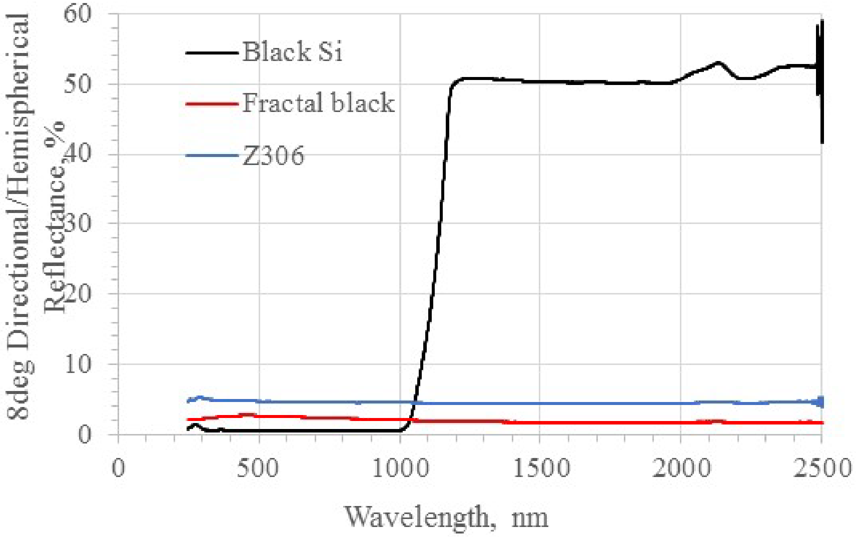
Z306

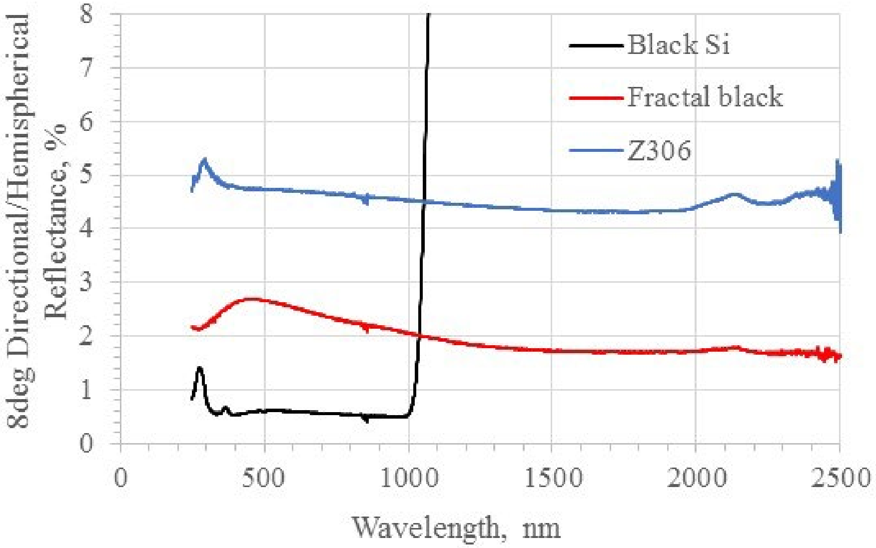


Fractal Black

Results and Discussion

8° directional/hemispherical reflectance



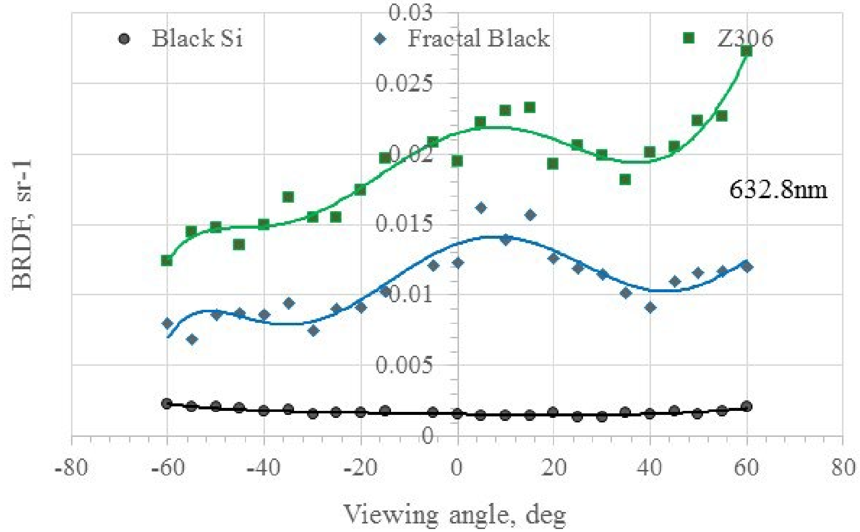


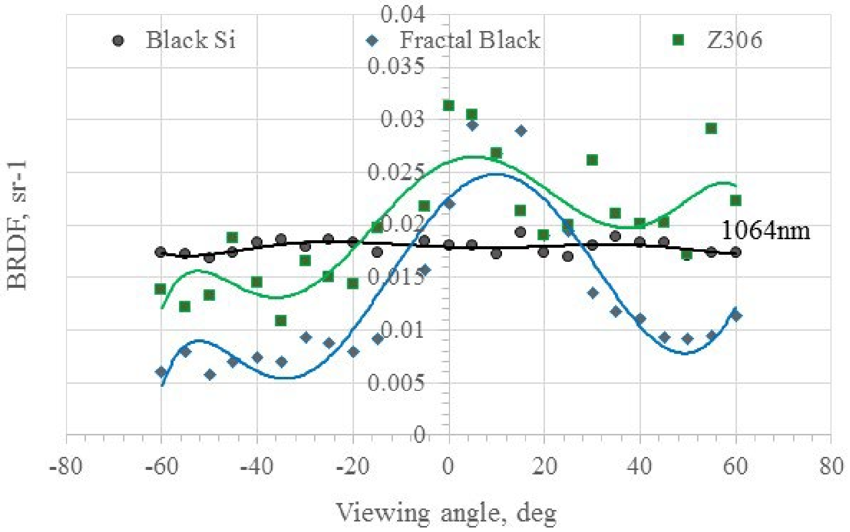
Black Si, Fractal black and Z306

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

Black Silicon

Bidirectional Reflectance II.





- 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
- 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,

Questions