UV-C Directional Reflectance Measurements of Common Materials

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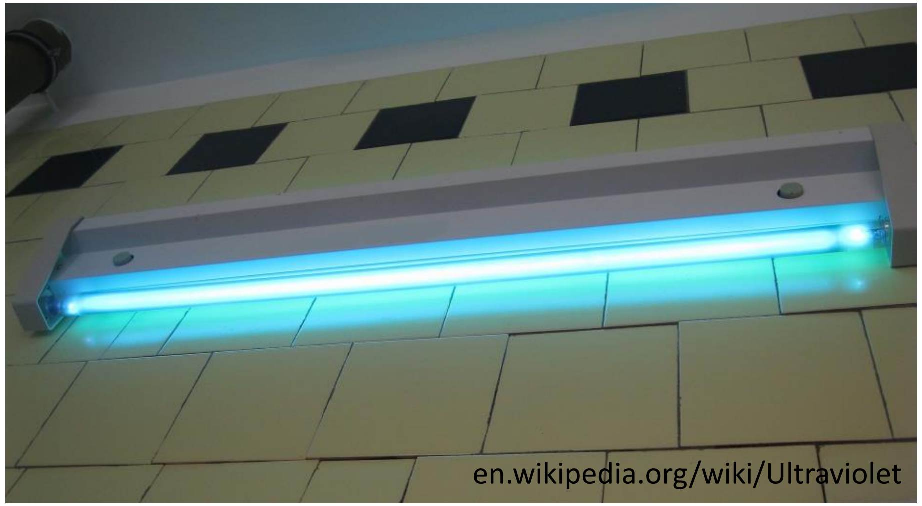
UV-C radiation is being increasingly used to disinfect public spaces.

NIST

Germicidal UV range is ~ 220 nm to 280 nm



en.wikipedia.org/wiki/Ultraviolet

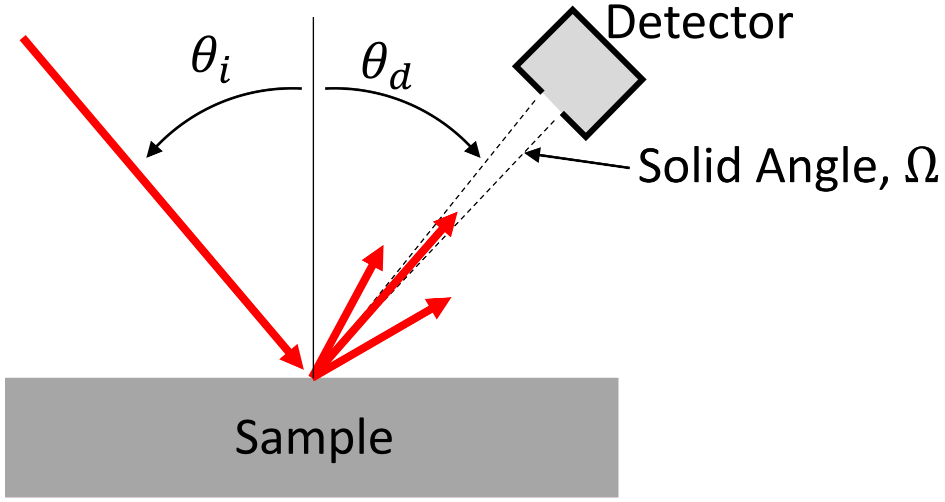
Directional Reflectance is Key for Efficacy and Safety

Lindblad, Tano, Lindahl, Huss, *Burns*, 2020

Reflectance of common materials hasn't been published at UV-C wavelengths.

- Key wavelengths are 222 nm, 255 nm, and 280 nm.
- Will the irradiance be sufficient to kill the pathogen?
- Will the irradiance be safe for any room occupants?

BRDF quantifies directional reflectance.



detector flux

$$BRDF = \frac{\phi_d}{\phi_i} \frac{1}{\Omega \cos \theta_d}$$

incident flux

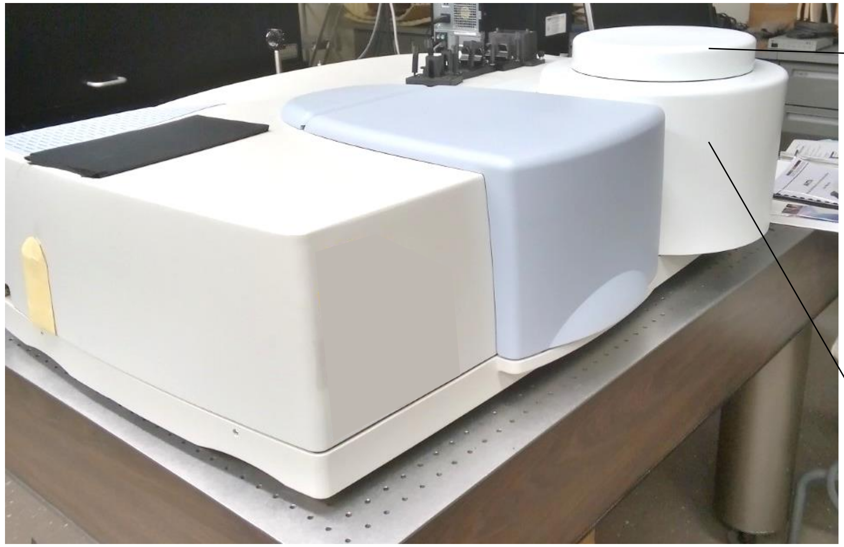
NIST's BRDF reference instrument (ROSI) and doesn't cover the full germicidal UV-C range

ROSI: 250 nm – 2400 nm

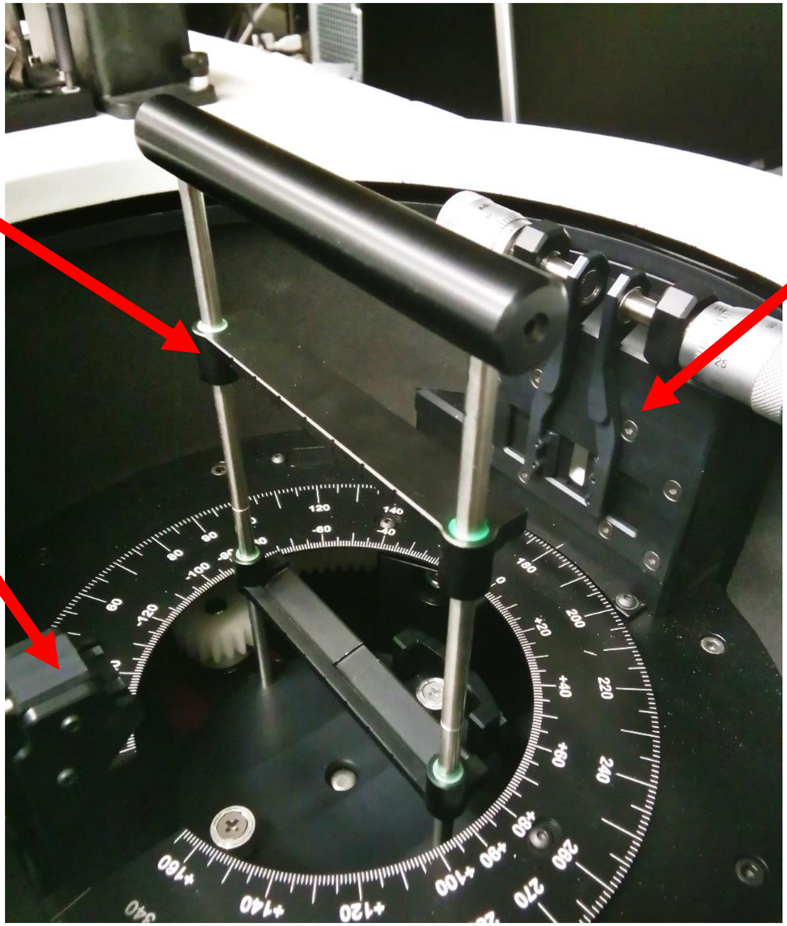
Patrick, Cooksey, Germer, Nadal, Zarobila. *Appl. Opt*. 2021

We use a commercial spectrophotometer with a directional reflectance accessory to measure BRDF.

Commercial Spectrophotometer



Directional Reflectance Accessory

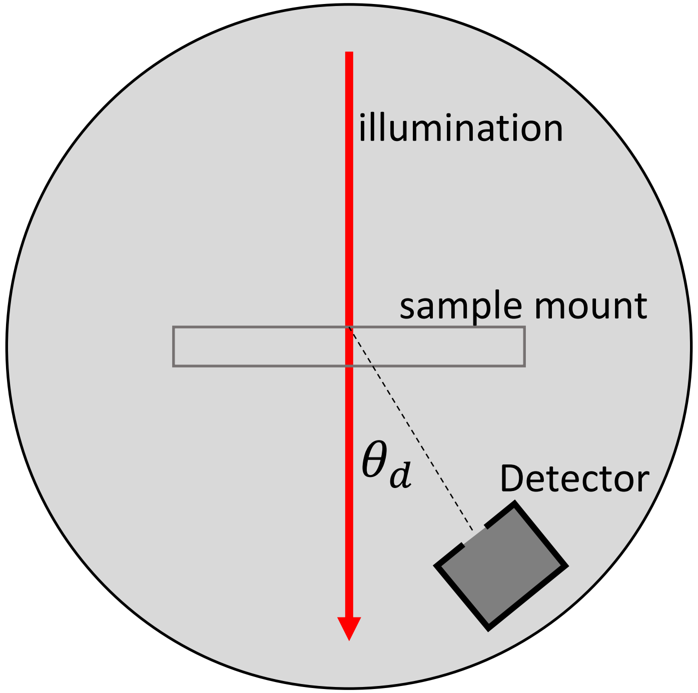


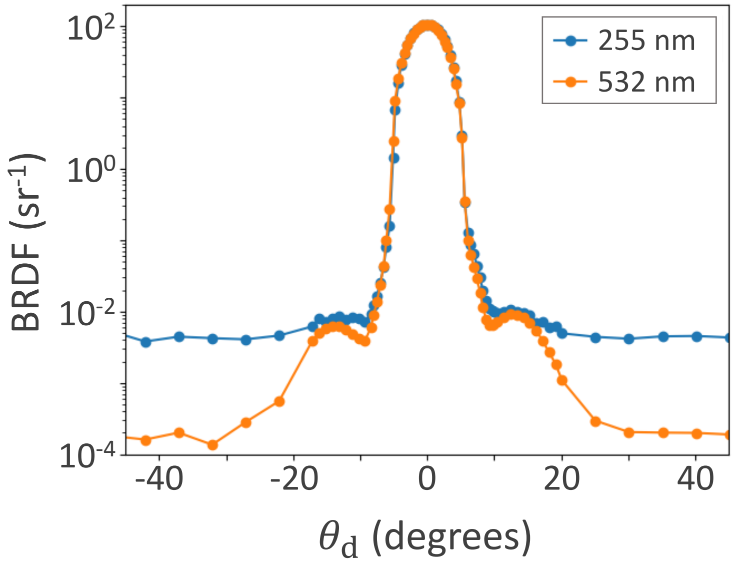
- Spectral Range: 220 nm to 2400 nm
- Spectral Bandwidth: 1 nm to 5 nm
- Variable linear incident polarization
- 5 mm × 7 mm spot size
- Can perform absolute BRDF measurements

As a first test we measure the instrument signature.

Instrument Signature

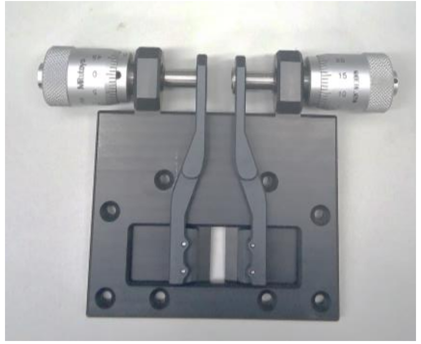
Direct Transmission, No Sample





- Angular Resolution (FWHM): 6°
- Dynamic range: ~10^4 in UV-C

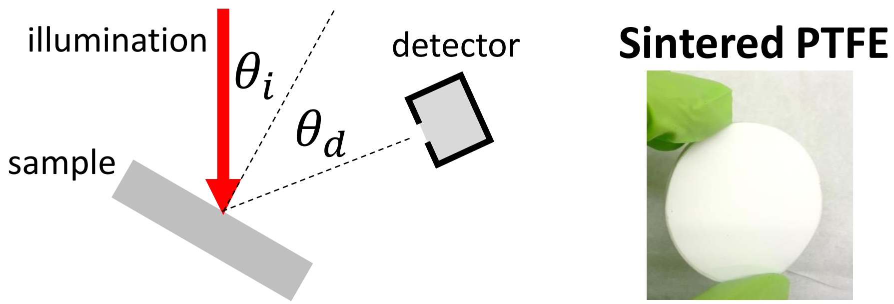
Original Aperture

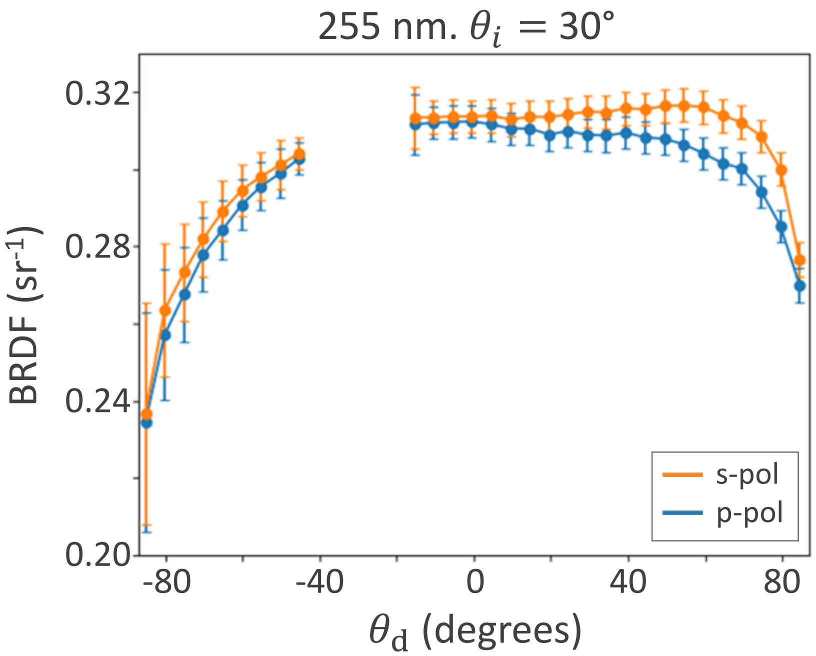


New Precision Aperture

r = 5.01 ± 0.02 mm

Example uncertainty budget (K=1) for sintered PTFE.

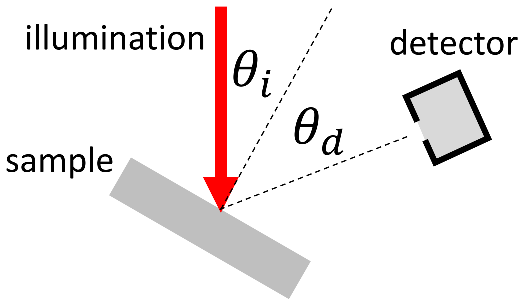




Uncertainty Budget for $\theta_d = 30°$, p-pol

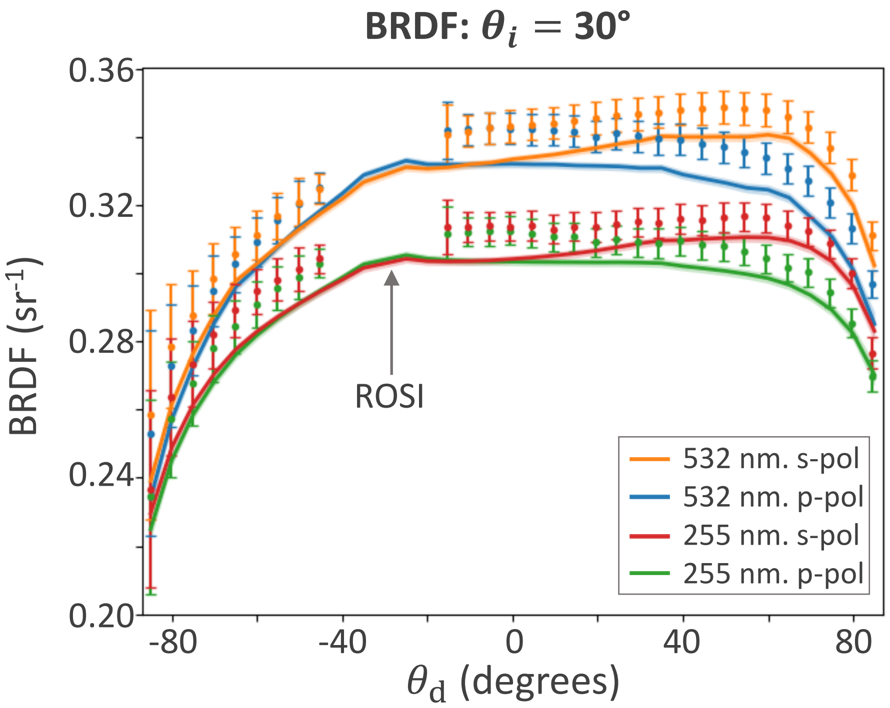
	Value (Uncertainty)	Uncertainty Contribution (%)
Aperture-Sample Distance	91.1 (0.2) mm	0.4
Aperture Radius	5.01 (0.02) mm	0.8
Reflected Signal	0.273 (0.001)	1.0
Incident Signal	99.96 (0.02)	0.03
Dark Signal	0.00009 (0.00001)	0.01
Detection θ	29.4 (0.3) degrees	0.002
Incident θ	30.2 (0.2) degrees	Not Evaluated
Wavelength	255 (0.2) nm	Not Evaluated
BRDF	**0.309 (0.004) sr^{-1}**	**1.4**

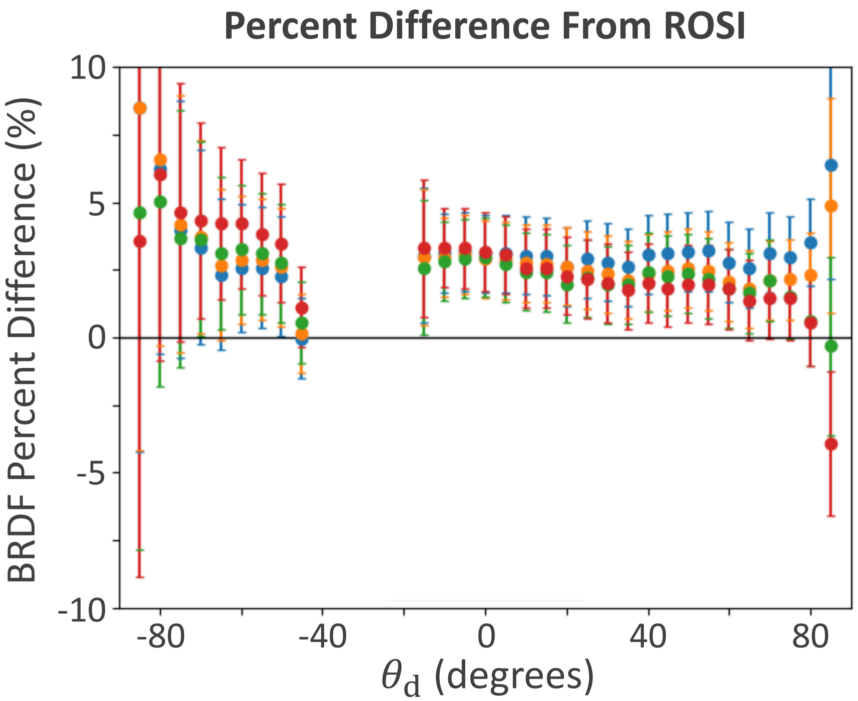
We validate the BRDF through comparisons to ROSI.



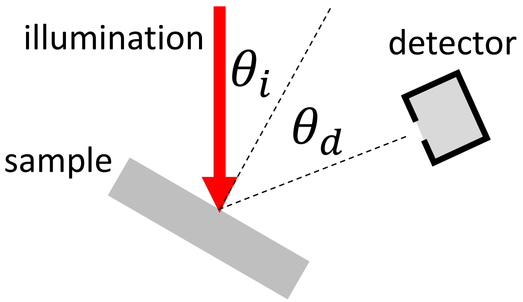
Sintered PTFE

- BRDF is ~ 2 % to 5% higher than ROSI's.
- Not quite consistent with ROSI within k=1 uncertainty.
- Suspect difference is due to stray light.

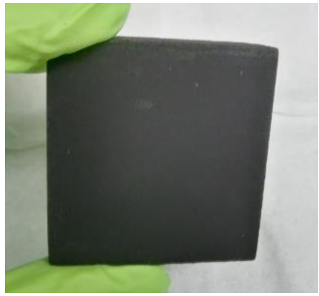


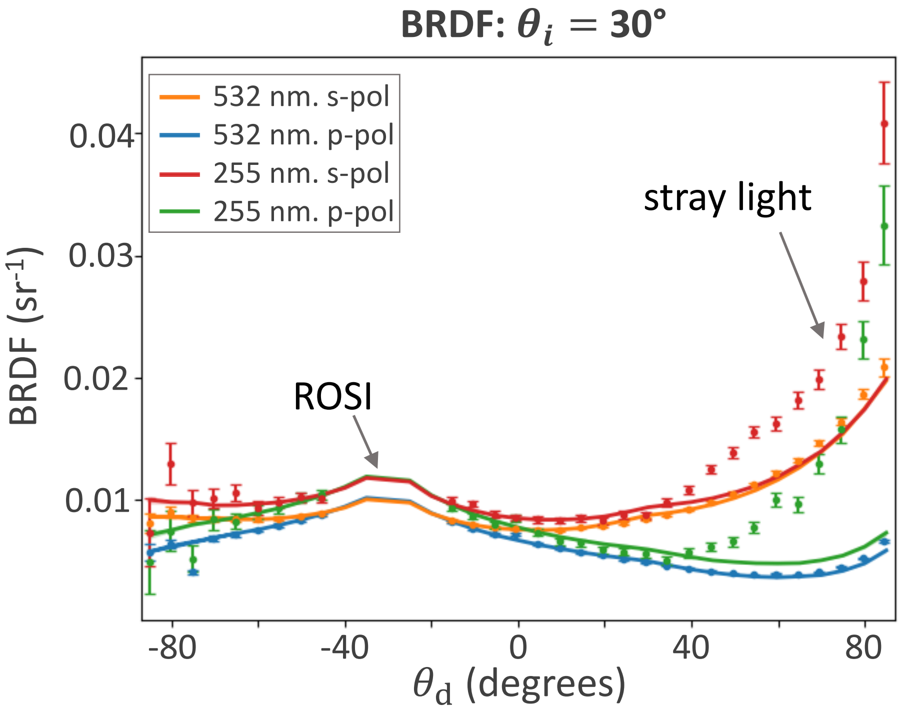


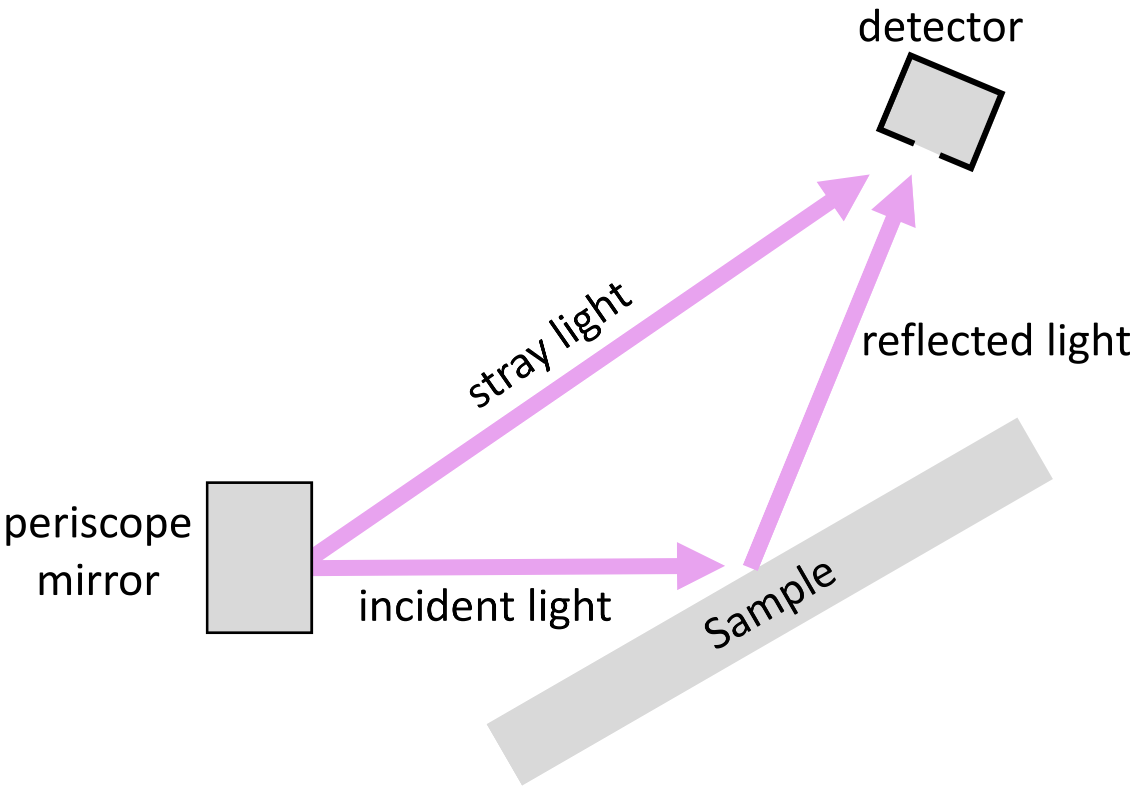
Comparisons to ROSI with a low-reflectance sample revealed stray light issues in the UV.



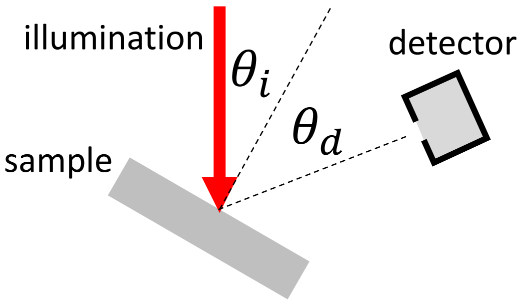
Black Sintered PTFE
~ 2% Reflectance



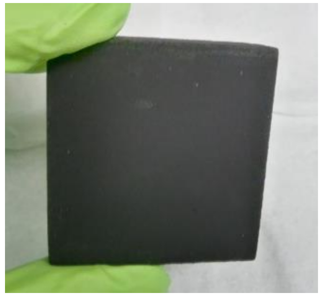


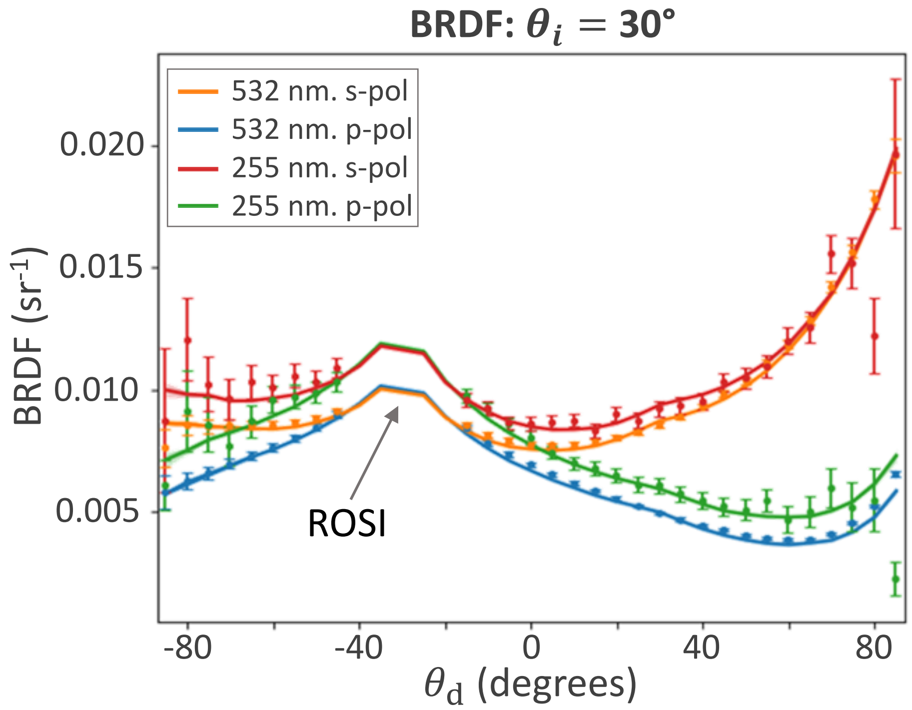


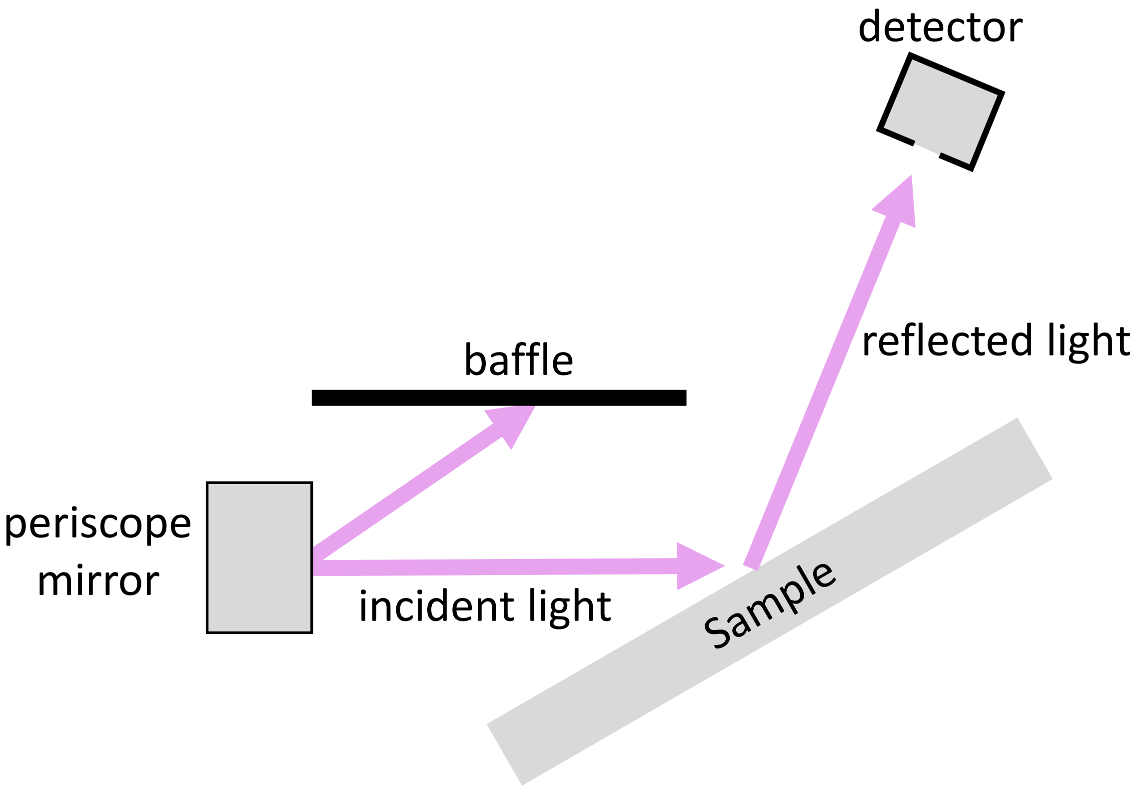
Comparisons to ROSI with a low-reflectance sample revealed stray light issues in the UV.



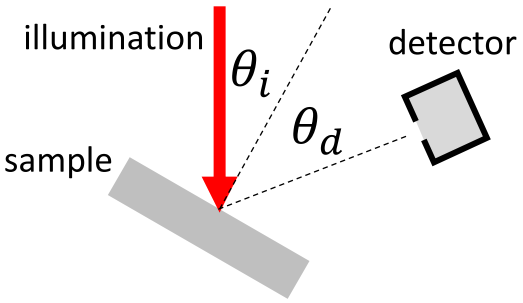
Black Sintered PTFE
~ 2% Reflectance



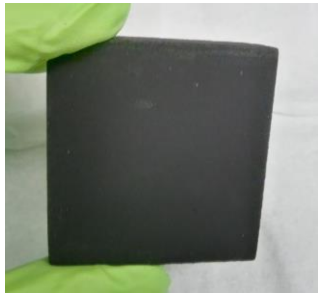




Blocking the stray light gives reasonable agreement with ROSI.

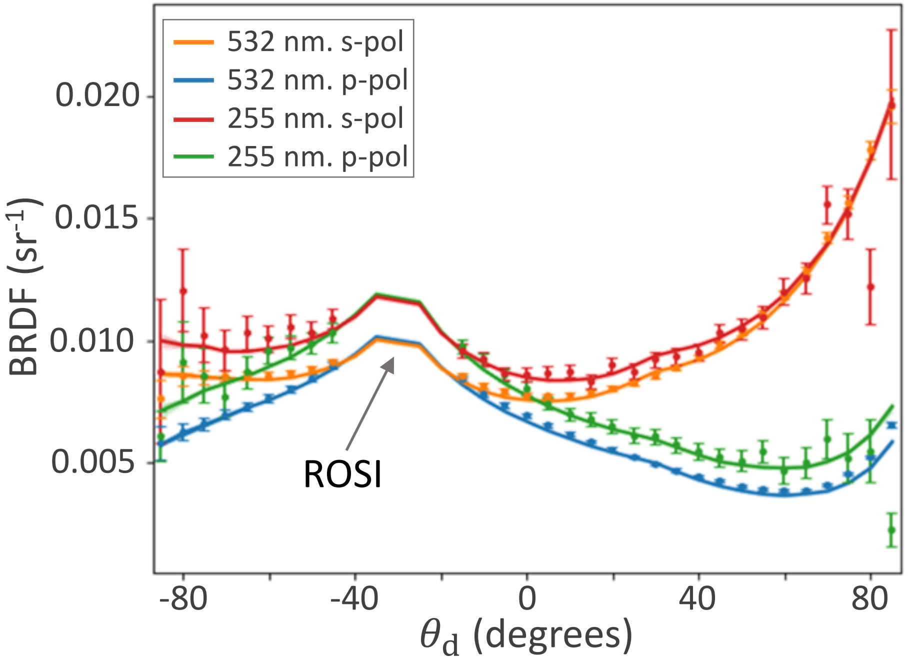


Black Sintered PTFE
~ 2% Reflectance

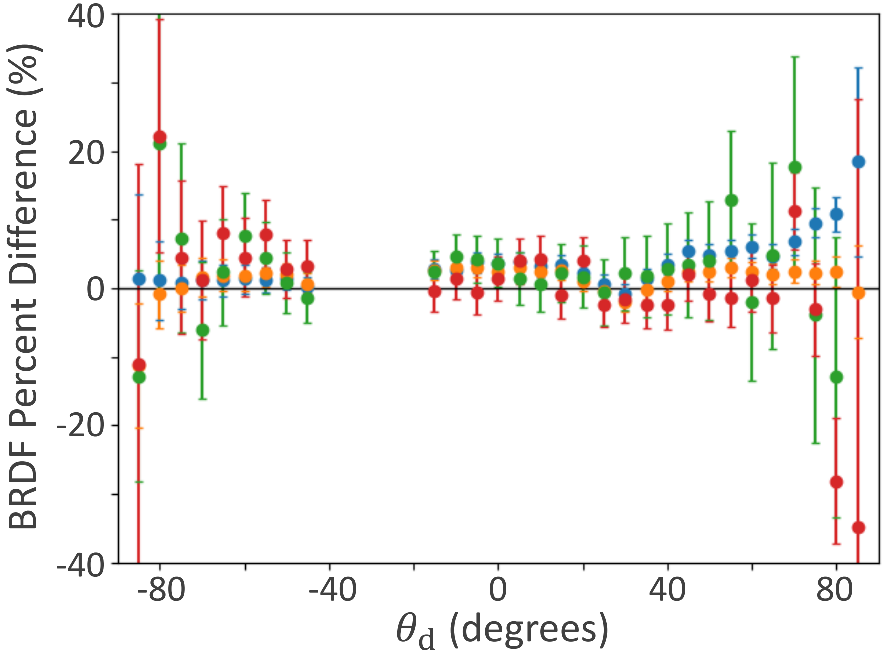


- Agrees within 5% at moderate θ_d.
- Larger differences at high θ_d where signal is low.
- Mostly agrees with ROSI within k=1 uncertainty.

BRDF: $\theta_i = 30°$

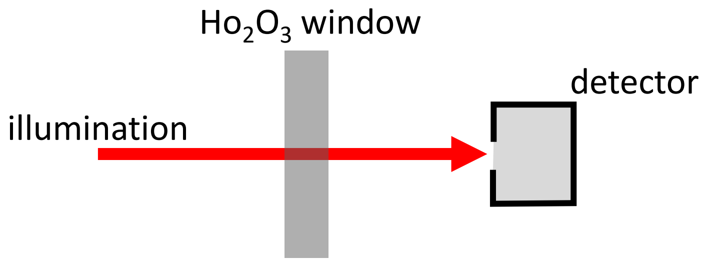


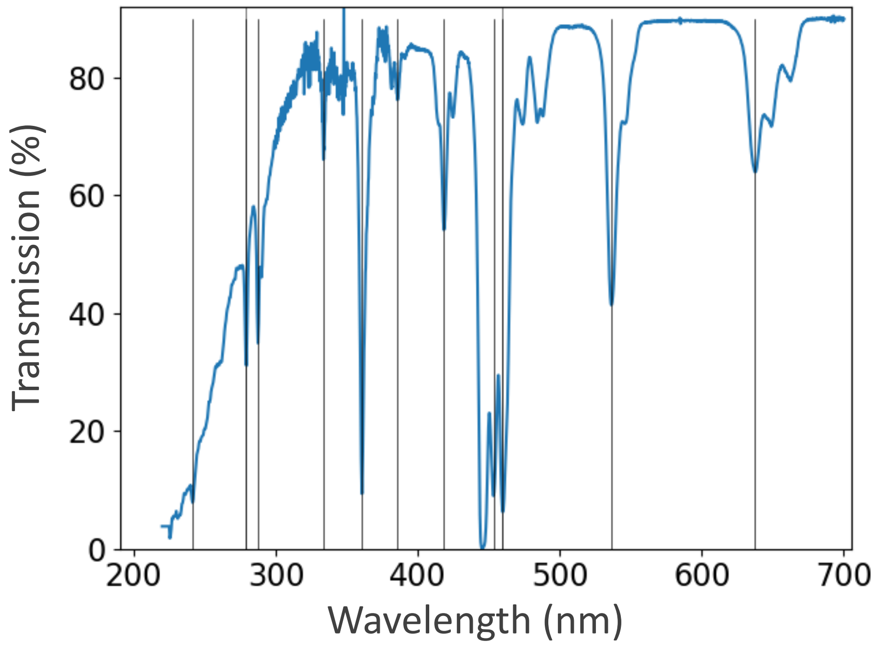
Percent Difference From ROSI

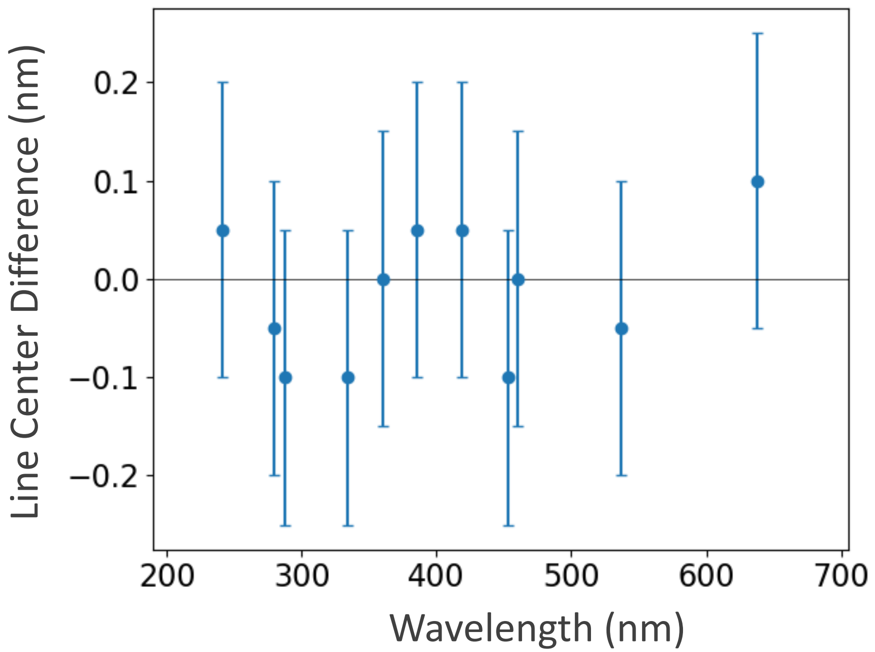


Can we trust data at 222 nm?
1. Wavelength scale validation.

Holmium Oxide Window Transmission



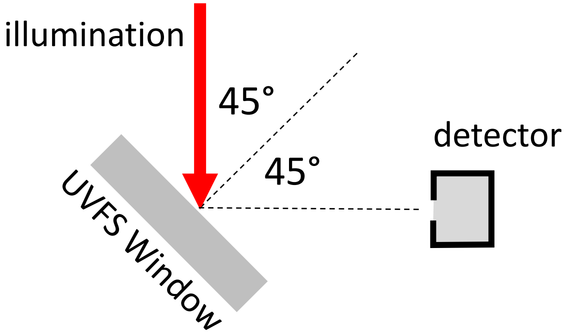


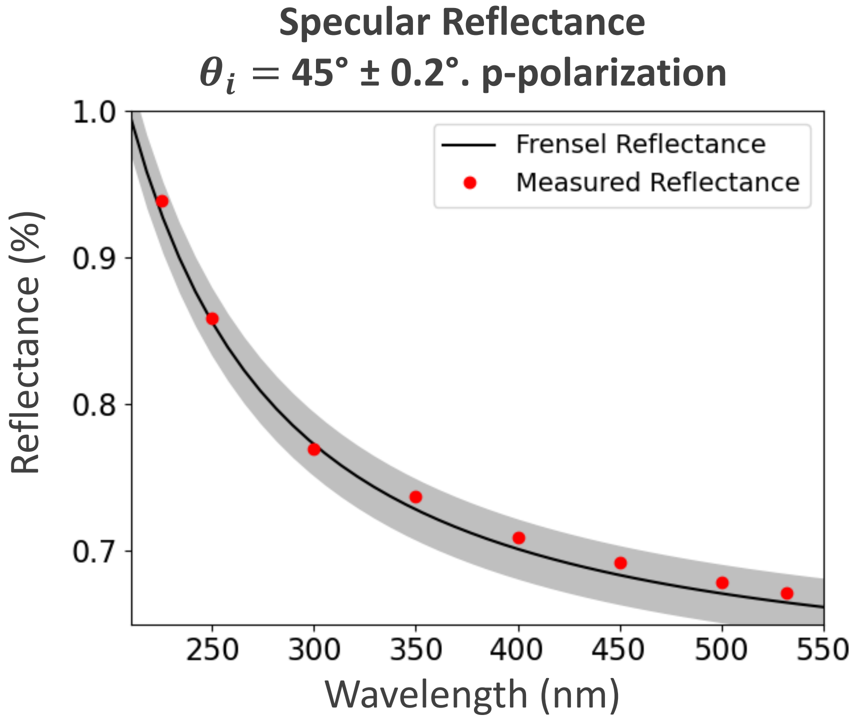


Line wavelengths from: Allen. *J. Res. NIST*. 2007.

Can we trust data at 222 nm?
2. UV fused silica for signal level.

UV fused silica has known reflectance from 210 nm to the IR.
Malitson. *J. Opt. Soc. Am.* 1965.

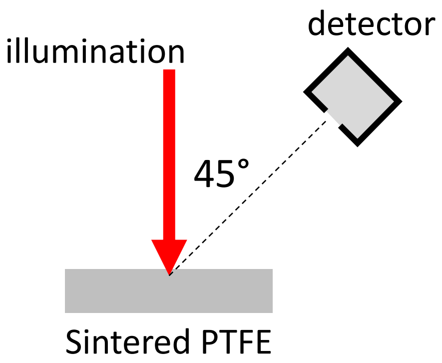




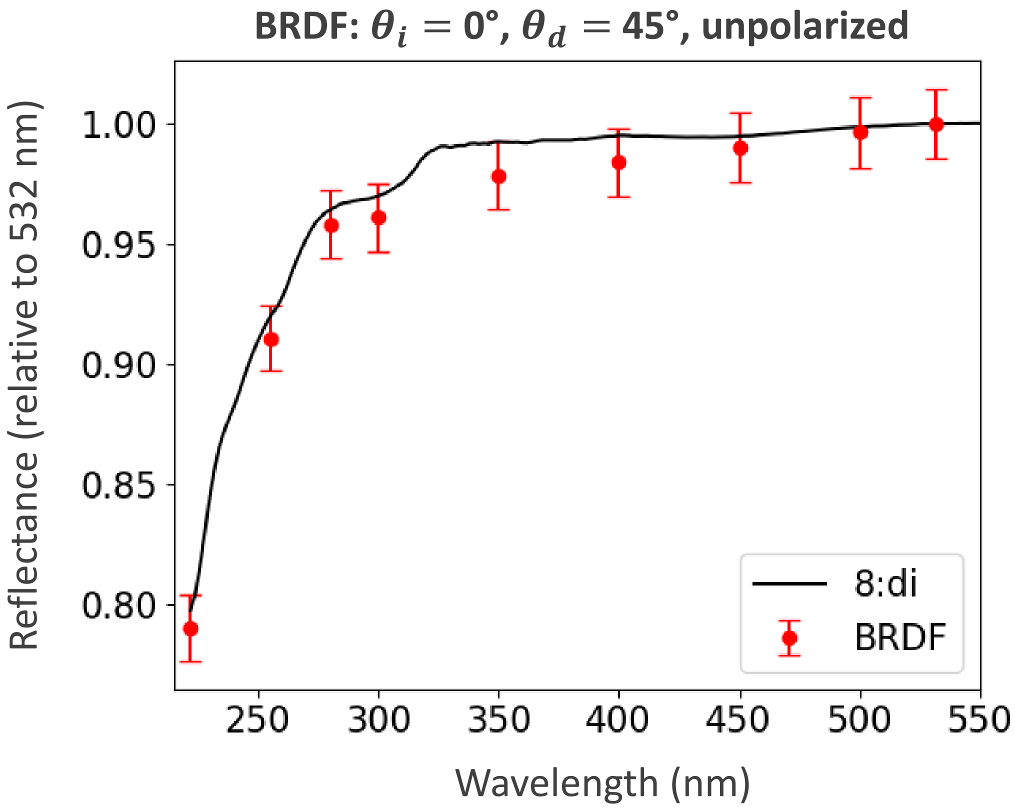
Measured and theoretical reflectance agree within 1.5 % from 222 nm to 532 nm.

Can we trust data at 222 nm?
3. Relative BRDF compared to hemispherical diffuse reflectance.

Diffuse hemispherical reflectance has a trusted scale (pressed PTFE) down to 220 nm.



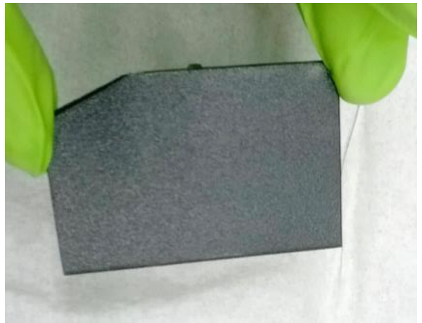
Sintered PTFE

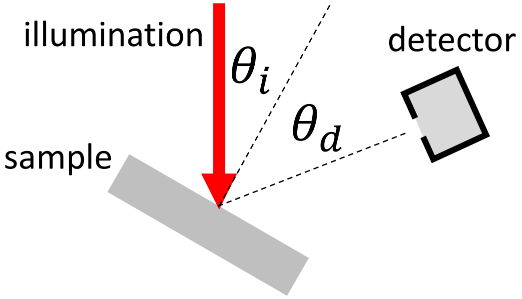


Relative reflectance agrees well at 222 nm.

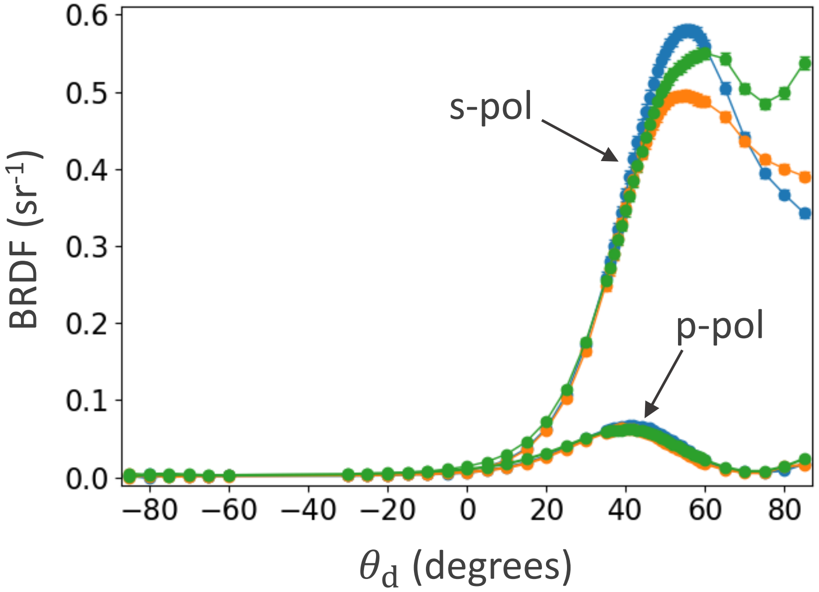
Real-world sample have non uniform BRDFs.

ABS Plastic

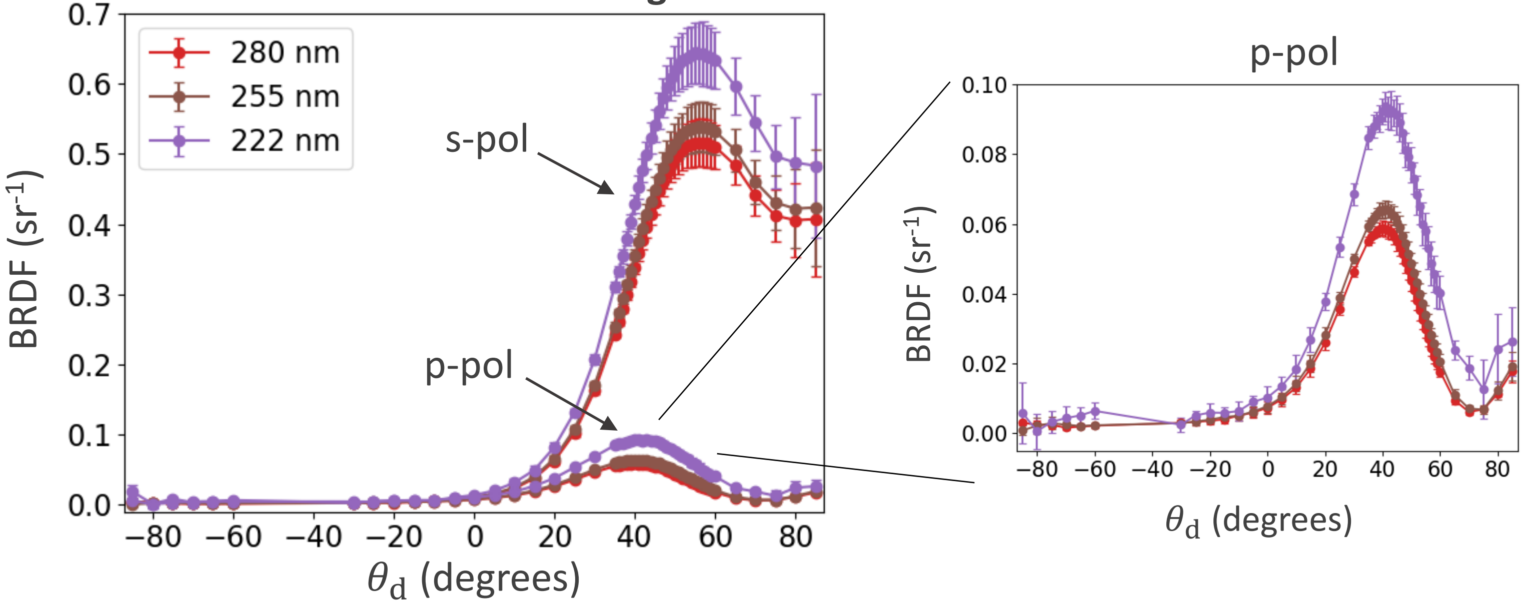




255 nm. $\theta_i = 45°$.
Three Repeat Measurements

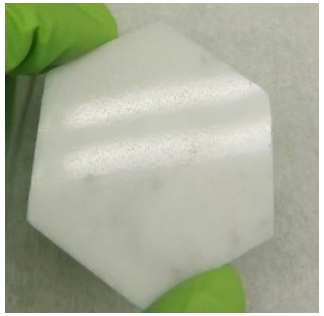


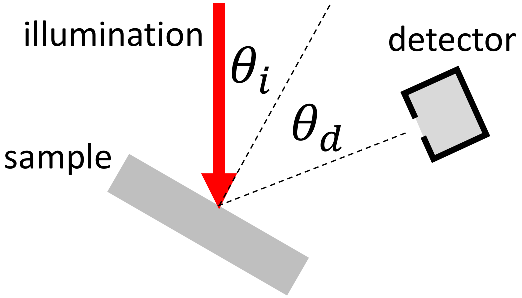
$\theta_i = 45°$.
Mean at Each Wavelength

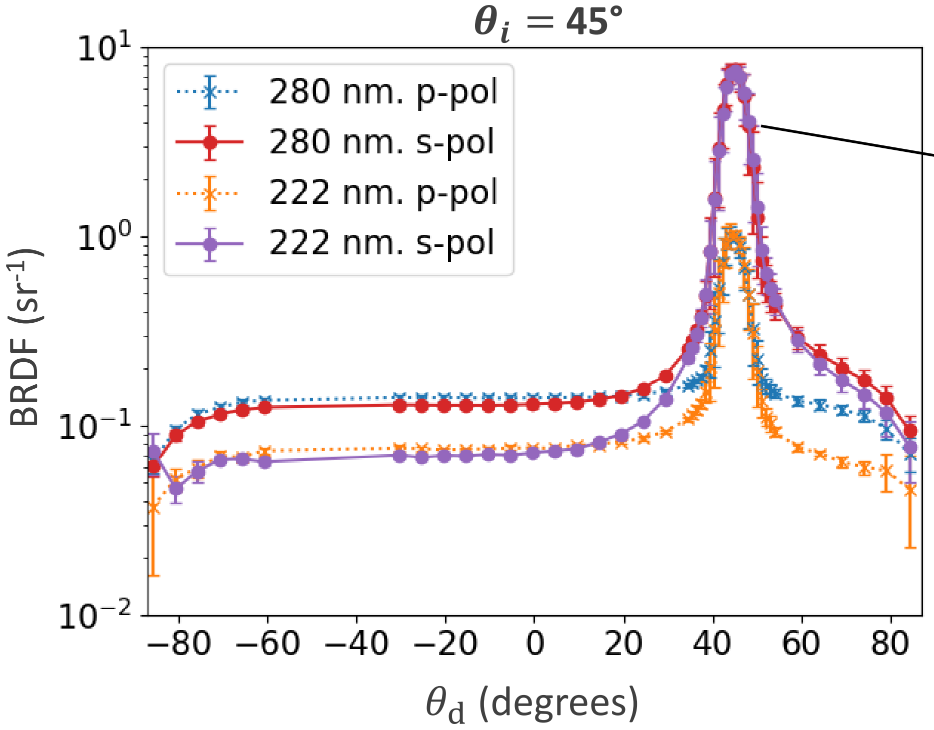


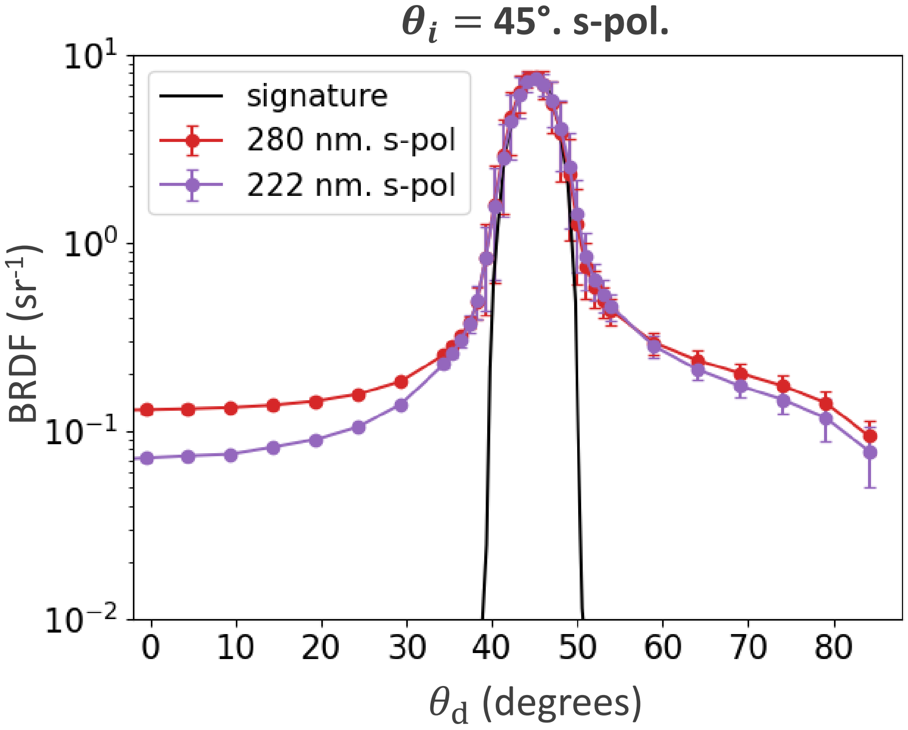
The BRDF of specular samples should be interpreted with the instrument signature in mind.

White Ceramic



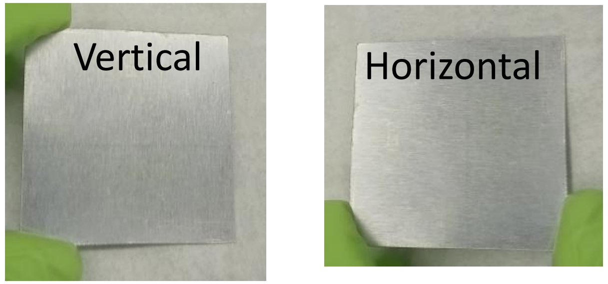


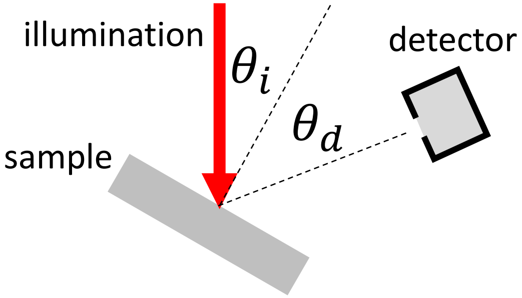


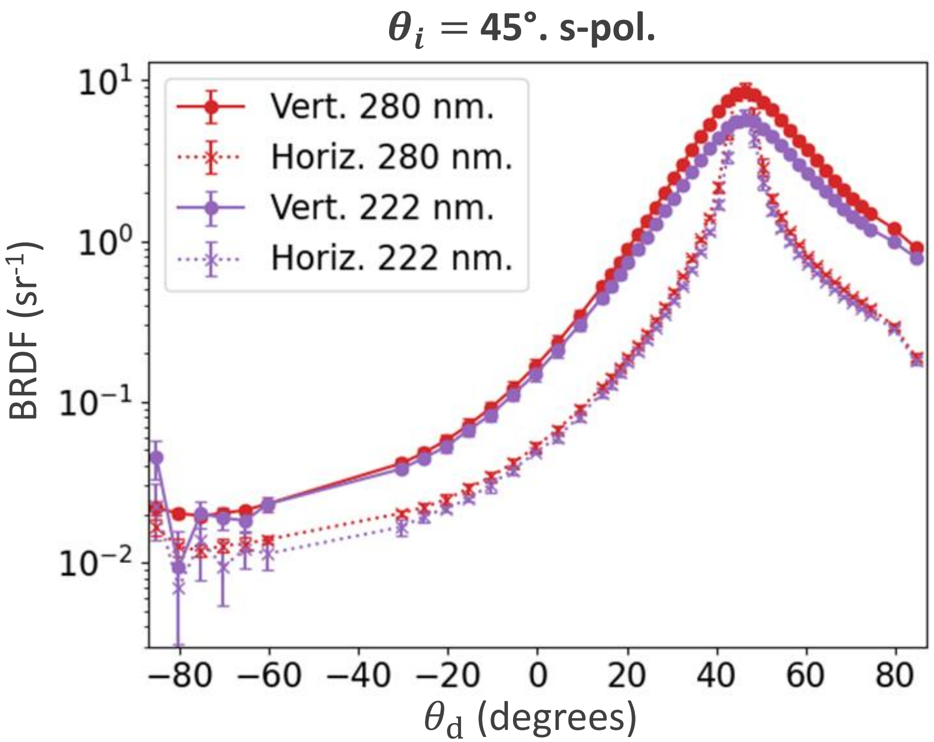


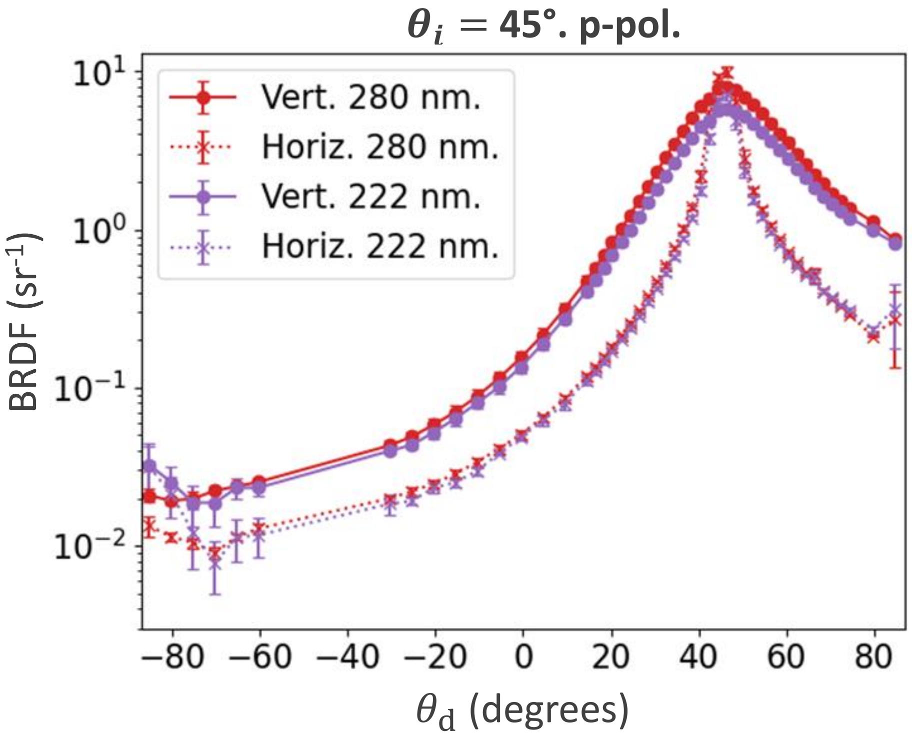
Sample orientation strongly affects BRDF of striated surfaces.

Brushed Aluminum





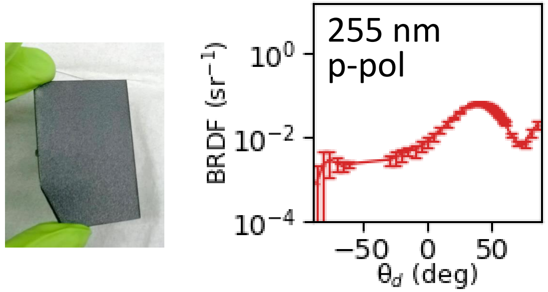




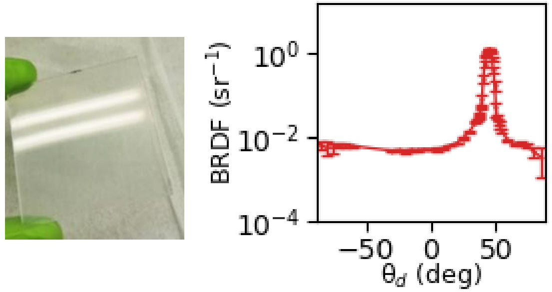
We have collected UV-C BRDF data for 8 samples.

- **Incident Angles:**
  - $\theta_i = 45°$ (all samples)
  - $\theta_i = 0°$ (ABS and gray ceramic)
- **Detector Angles:** θ_d scan from $-85°$ to $+85°$
- **Wavelengths:** 280 nm, 255 nm, and 222 nm
- **Polarizations:** s-pol and p-pol
- **Repeat Measurements:**
  - 3 for non-striated samples
  - 4 for striated samples (2 each orientation)

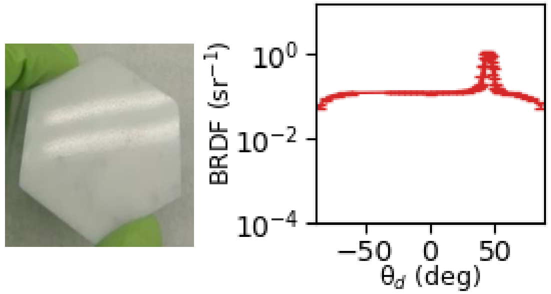
Gray ABS Plastic



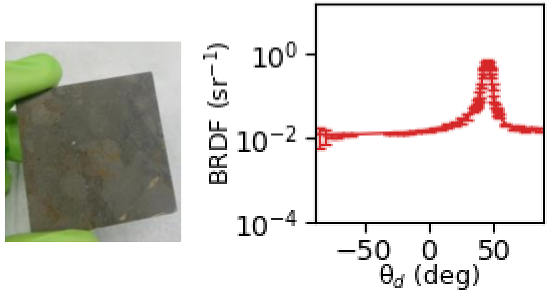
Polypropylene



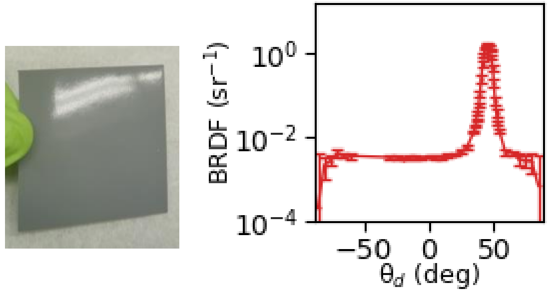
White Ceramic



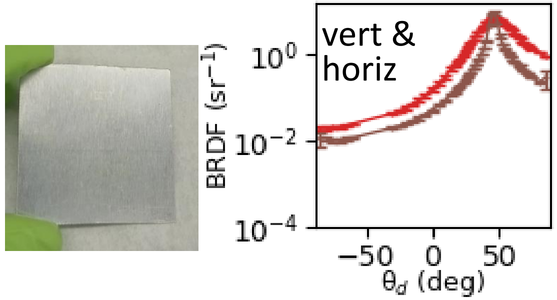
Gray Ceramic



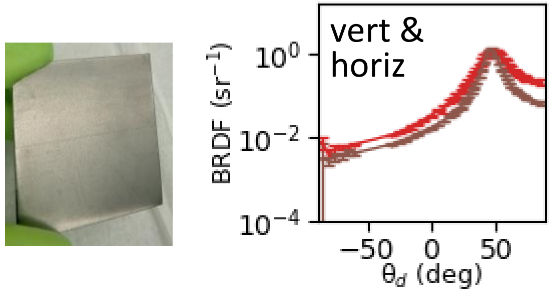
Gray Vinyl



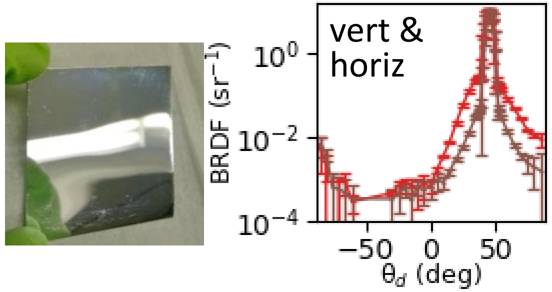
Aluminum



Steel



Silver-Coated Reflector



Conclusions and Future Work

NIST

Conclusions

- Validated BRDF measurements in UV and VIS.
- Uncertainty level of 3 % to 10 %.
- Measured in-plane UV-C BRDF of 8 real world samples.

Future Work

- Check for fluorescence.
- Publish BRDF data in upcoming data release.
- Continue discussing BRDF needs with stakeholders.
- New BRDF instrument being procured for faster and higher precision measurements.
  - Out-of-plane BRDF data.
  - More samples.

Thank you!

Grace Waters (NIST)

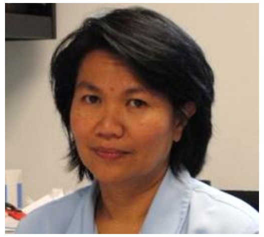
Heather Patrick (NIST)

Lynn Davis (RTI)

Thom Germer (NIST)

Catherine Cooksey (NIST)

Toni Litorja (NIST)



Correction factor for finite illumination spot and finite aperture diameter.

Calculate Correction Factor as Done for ROSI

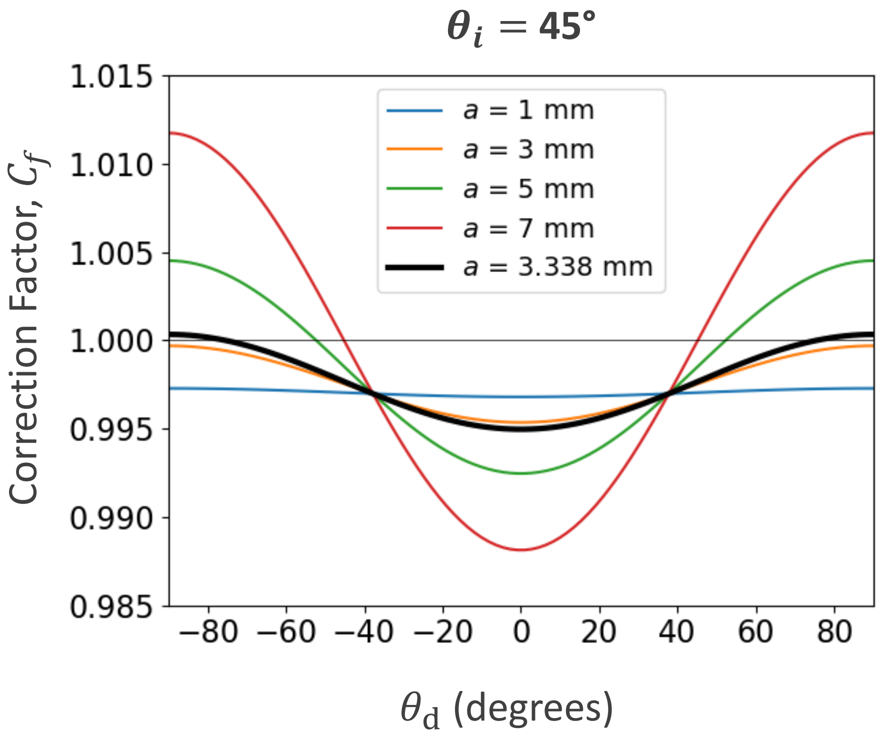
- Beam shape at sample: 5 mm x 7 mm
  - Assume circle with same area: radius $a = 3.338$ mm.
- Detector Aperture radius: $r = 5.014$ mm
- Sample-Aperture Distance: $R = 91.1$ mm

$$BRDF(\theta_\mathrm{i}, \theta_\mathrm{d}) = \frac{V_\mathrm{r}(\theta_\mathrm{i}, \theta_\mathrm{d})}{V_\mathrm{i}} \frac{1}{\Omega \cos\theta_\mathrm{d}}$$

$$\Omega = \frac{\pi r^2}{R^2} C_\mathrm{f}$$

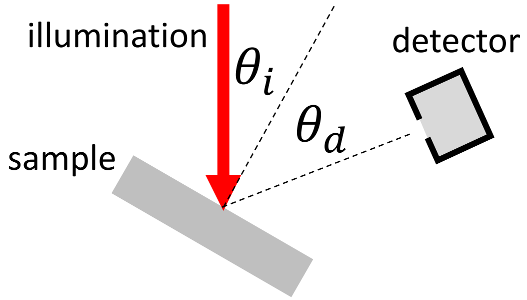
$$C_\mathrm{f} = 1 - \frac{r^2}{R^2} + \frac{a^2}{R^2 \cos^2\theta_\mathrm{i}} \left[\sin^2\theta_\mathrm{i} \sin^2\theta_\mathrm{d} - \cos(2\theta_\mathrm{d}) \frac{3 + \cos(2\theta_\mathrm{i})}{4} \right]$$

Patrick, Cooksey, Germer, Nadal, Zarobila. *Appl. Opt*. 2021

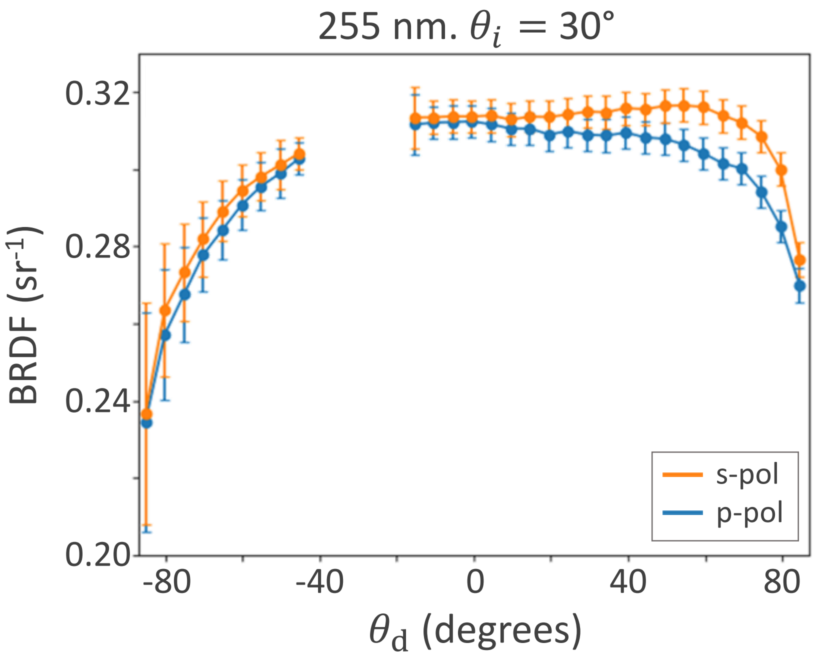


- **Correction factor magnitude < 0.5%**
- **Well within uncertainty budget**

Example uncertainty budget (K=1) for sintered PTFE



Sintered PTFE



Uncertainty Budget for θ_d = -60°, p-pol

	Value (Uncertainty)	Uncertainty Contribution (%)
Aperture-Sample Distance	91.1 (0.2) mm	0.4
Aperture Radius	5.01 (0.02) mm	0.8
Reflected Signal	0.137 (0.001)	1.0
Incident Signal	99.6 (0.02)	0.03
Dark Signal	0.00009 (0.0001)	0.02
Detection θ	-60.3 (0.3) degrees	1.8
Incident θ	30.2 (0.2) degrees	Not Evaluated
Wavelength	255 (0.2) nm	Not Evaluated
BRDF Overall	**0.291 (0.007) sr^{-1}**	**2.3**