BRDF measurements of graphite used in high-temperature fixed point blackbody radiators: a multi-angle study at 405 nm and 658 nm

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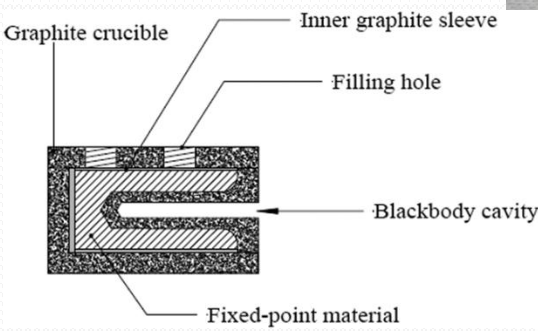
Motivation and Overview

Potential eutectic reference points:

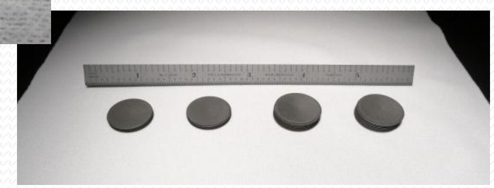
Co-C	1597 K
Pt-C	2011 K
Re-C	2747 K



Example HTFP, Batuello et al., Metrologia 2011

High-Temperature Fixed Point (HTFP) cavities
Courtesy Y. Yamada

A critical issue is the knowledge of the emissivity of the graphite blackbody radiator cavities. Modeling of the emissivity requires characterization of the reflectance of the graphite walls of the cavity, ideally as a function of incident angle, scattering angle, polarization, wavelength and temperature.



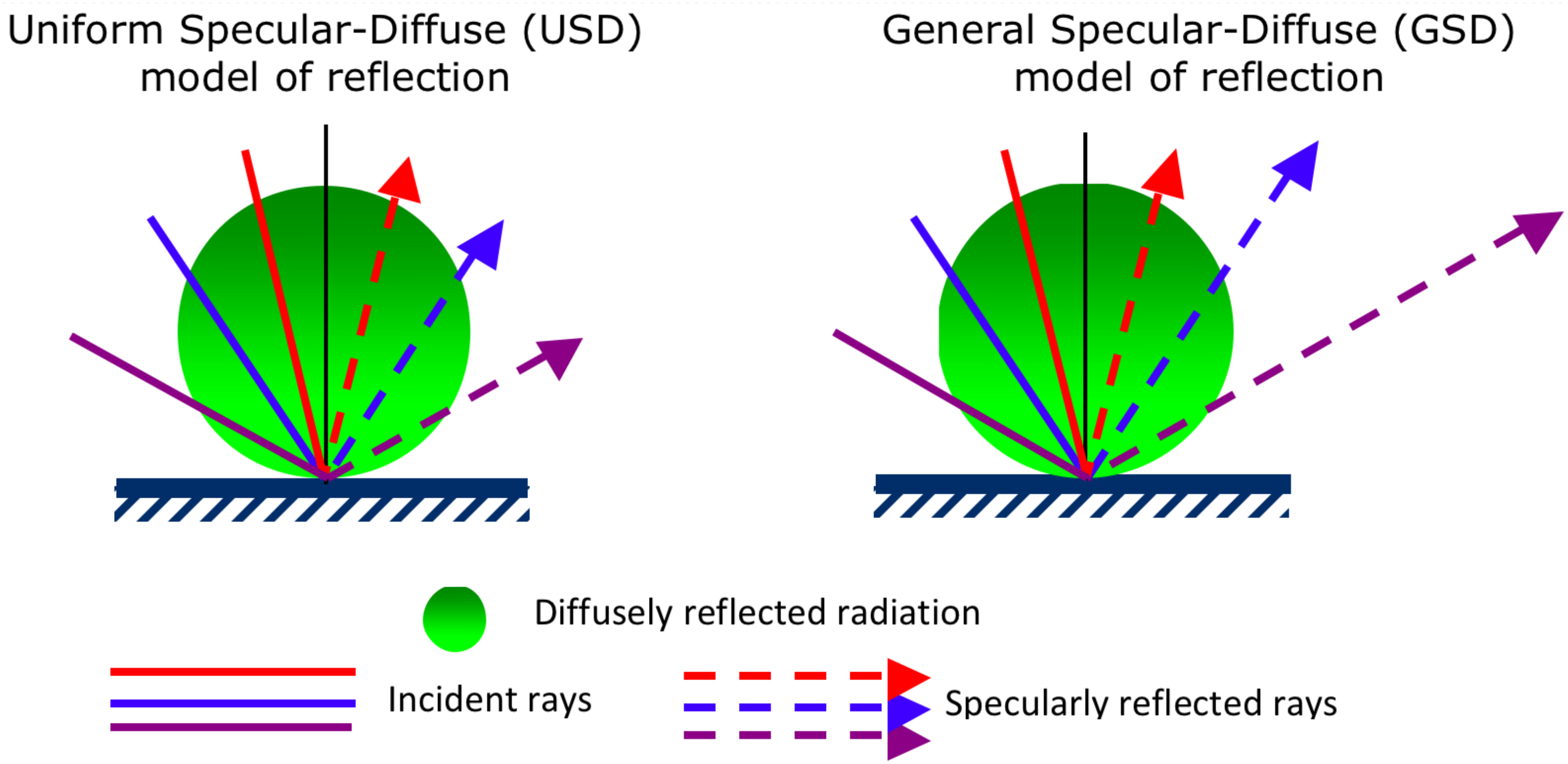
Graphite samples measured

In this work:

- In-plane and hemispherically-scanned BRDF (full hemisphere of polar, azimuthal scattering angles)
- Ambient temperature, 405 nm and 658 nm wavelengths
- 4 samples, of two graphite types: 7ST-1, 7ST-2, SGL-1, SGL-2
- Seven values of θ_i (0°, 8°, 15°, 30°, 45°, 60°, 70°)
- Two incident polarizations: s-polarized, p-polarized
- Integrate BRDF to DHR (ρ)

Only a subset of the data will be shown!

Previous BRDF Models for Monte Carlo Studies

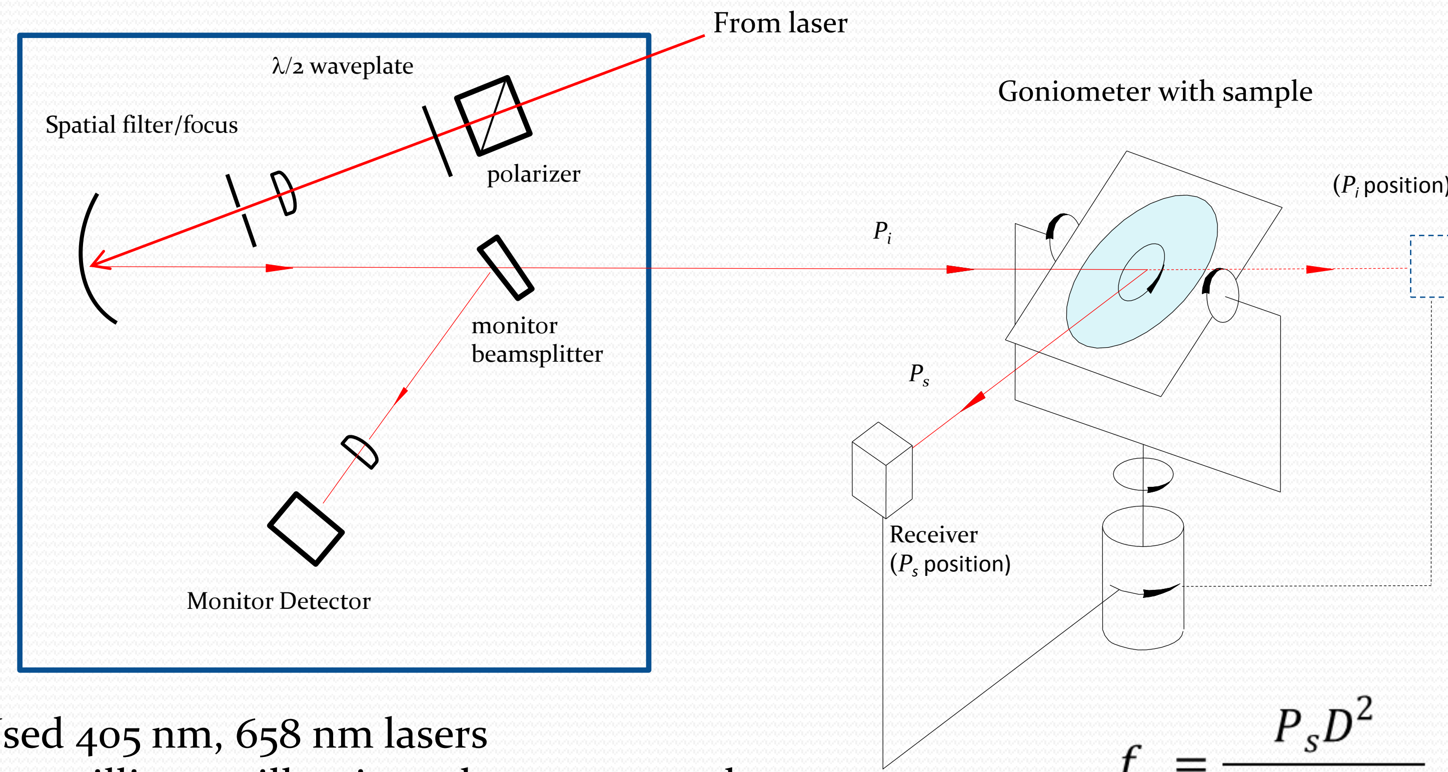


A simple specular-diffuse model widely used in the Monte Carlo modeling of blackbodies

(Lambertian diffuse+ non-varying specular)

More realistic specular-diffuse model taking into consideration dependence of specular component on incidence angle

Goniometric Optical Scatter Instrument (GOSI)



- Used 405 nm, 658 nm lasers
- Few millimeter illuminated spot on sample
- Linearly polarized incident light
- Power monitor to normalize for source fluctuations
- 5-dof sample positioning for in-plane and out-of-plane BRDF

$$f_r = \frac{P_s D^2}{P_i A \cos\theta_r}$$

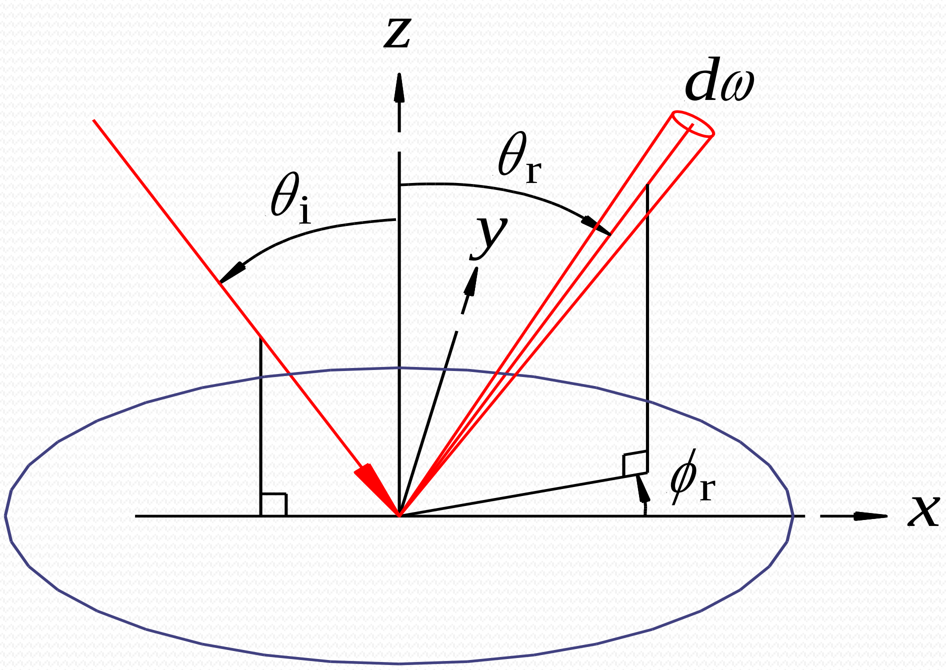
BRDF

D = aperture to receiver

A = aperture area

θ_r = scattering polar angle

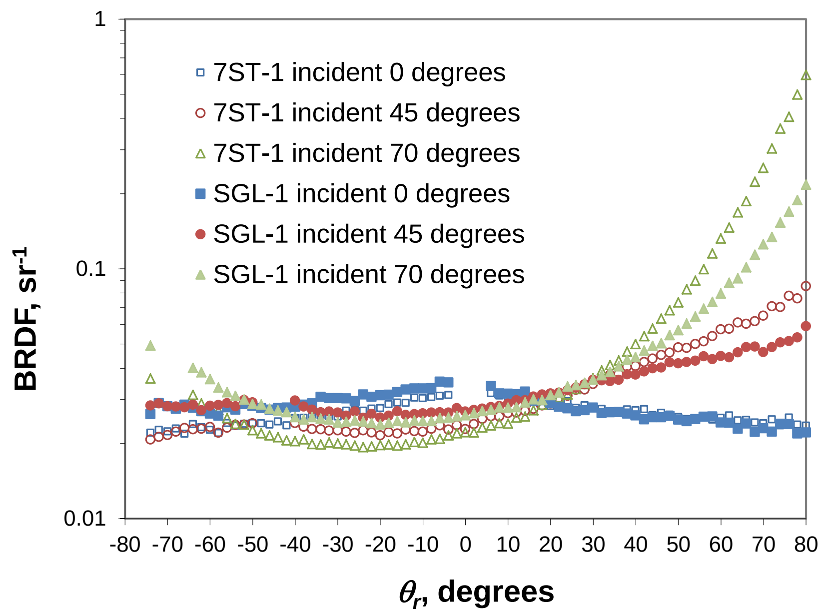
BRDF coordinates



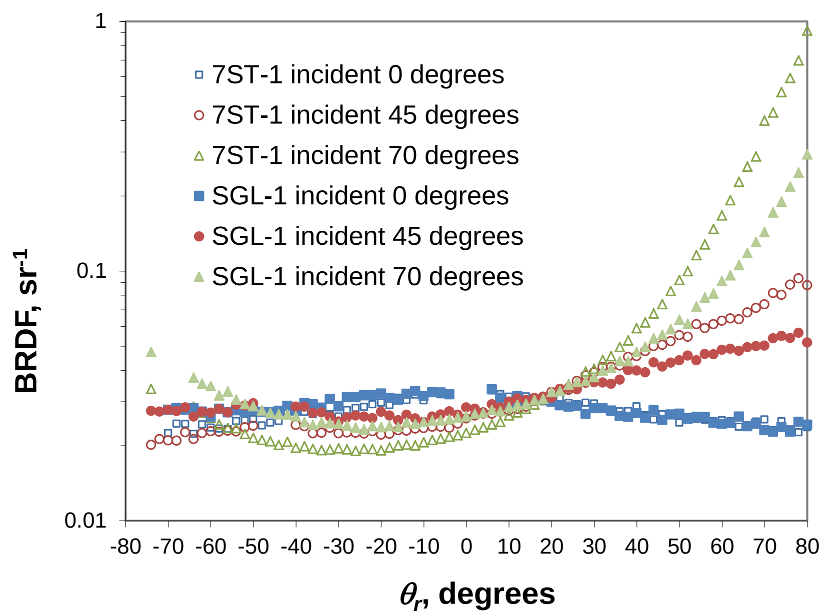
- z is sample normal
- x-z plane is plane of incidence
- Incident polar angle (θ_i) and polar scattering angle (θ_r) measured from z
- Azimuthal scattering angle (ϕ_i) measured from x
- For in-plane measurements, take negative θ_r to be scattering with ϕ_r = 180°

In-plane BRDF

405 nm, graphite



658 nm, graphite

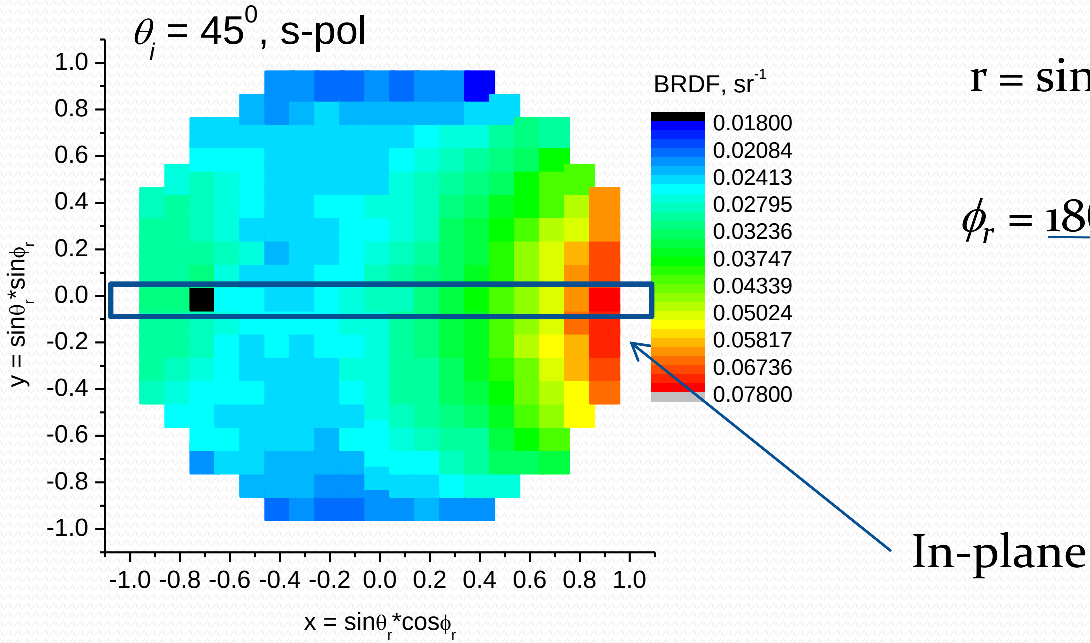


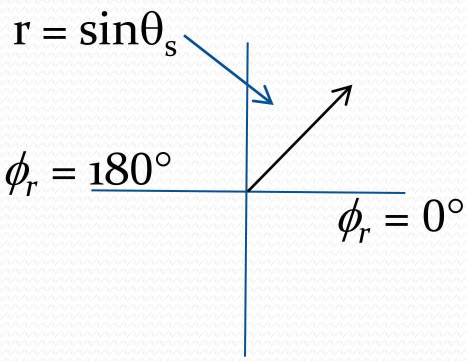
- 405 nm data shown, unpolarized incident light (average of s-pol and p-pol incident results)
- Graphite BRDF is highly non-Lambertian at high θ_i, θ_s

  Not a good fit to uniform specular diffuse models! May be able to adapt GSD model to approximate this behavior
- SGL samples a little less forward scatter enhancement
- 405 nm and 658 nm show similar trends
- Grey sample; BRDF values around 10% of pressed PTFE

Hemispherically-scanned BRDF - overview

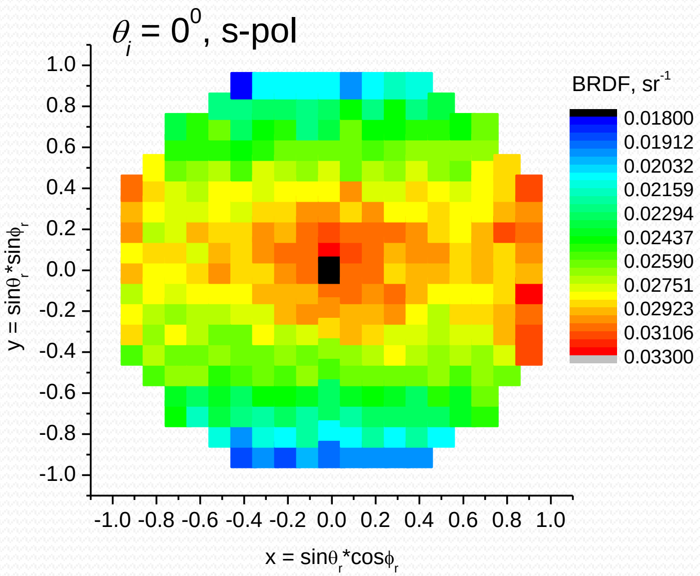
Example:
SGL-1
405 nm
$\theta_i = 45°$
s-pol incident

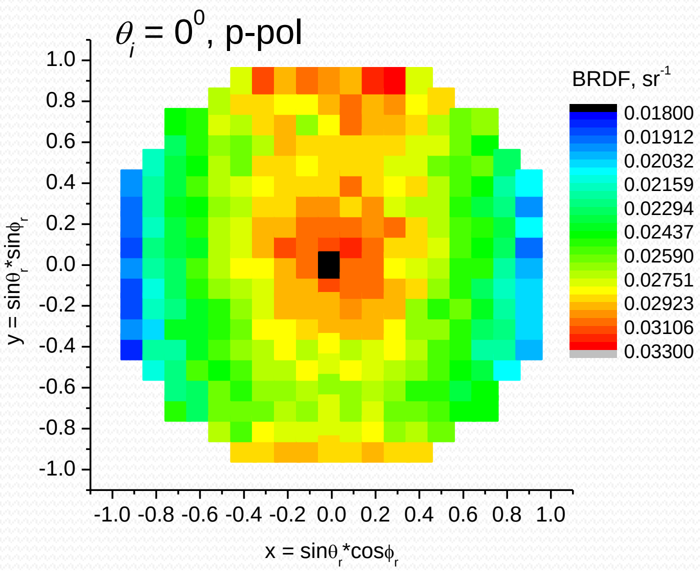




- Hemispherically scanned θ_r and ϕ_r for fixed θ_i
- Measured at points evenly spaced in x,y space where
  $x = \sin\theta_r \cos\phi_r$ $\qquad$ $y = \sin\theta_r \sin\phi_r$
- Spacing of x,y eases integration to total directional-hemispherical reflectance (DHR)

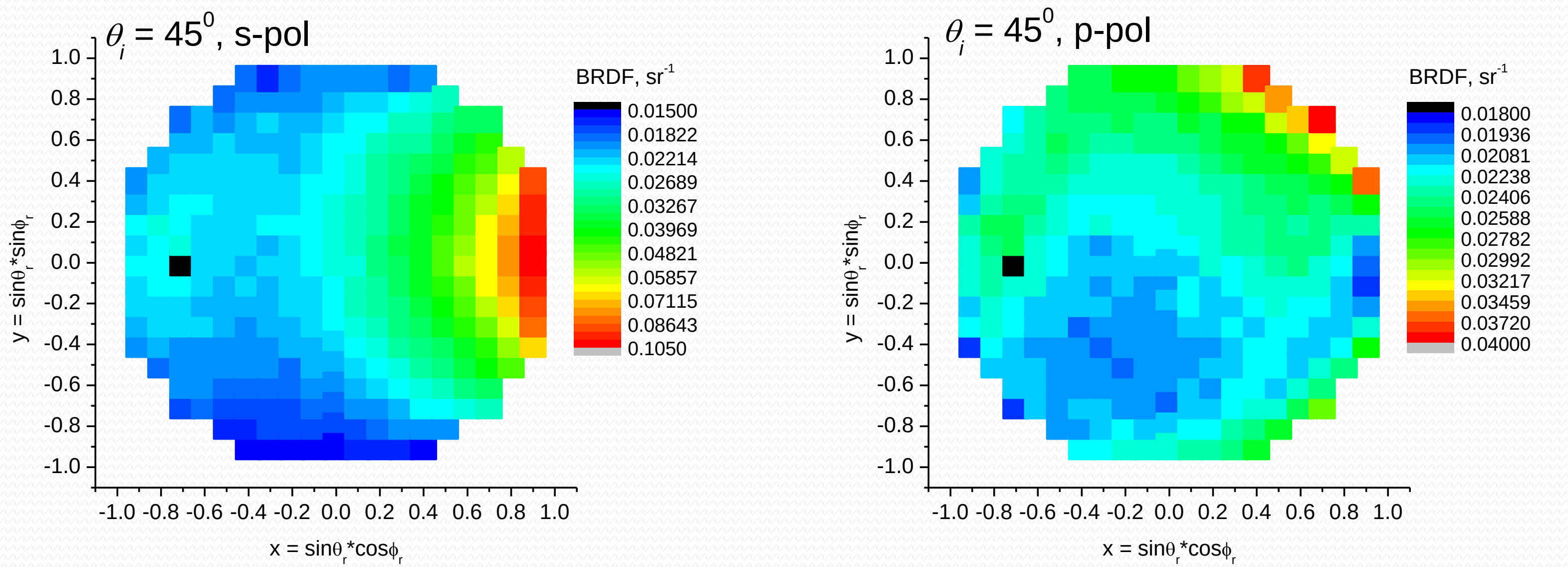
Hemispherically-scanned BRDF: example $\theta_i = 0°$





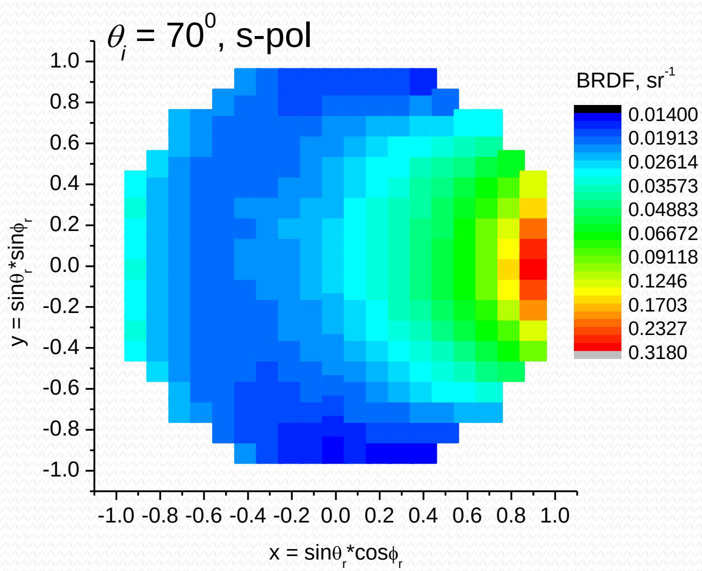
- Sample 7ST-1, 405 nm
- "s-pol" electric field along y, "p-pol" electric field along x
- See preference to scatter perpendicular to electric field (higher BRDF values)
- Slight asymmetry about x,y may indicate "lay" to surface finish at measured point, or surface nonuniformity

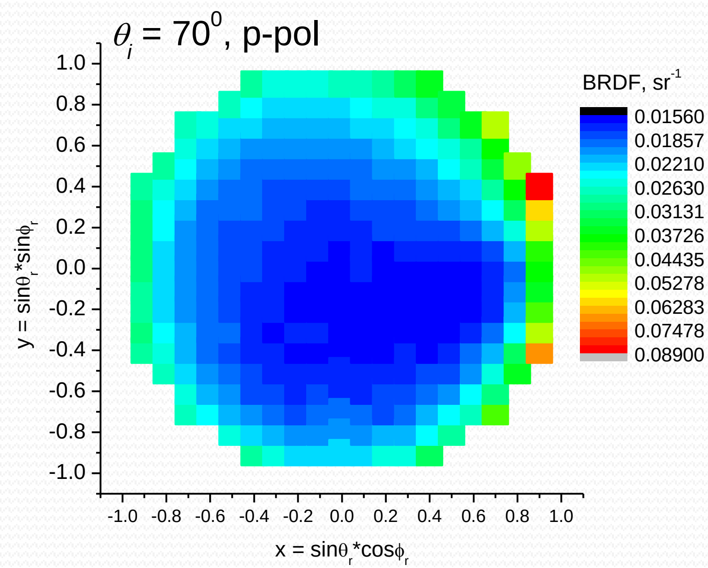
Hemispherically-scanned BRDF: example θ_i = 45°



- Sample 7ST-1, 405 nm
- Much higher BRDF values for s-polarized incident light (note scales are not same)
- Observed asymmetries, more pronounced when looking at p-polarization

Hemispherically-scanned BRDF: example θ_i = 70°





- Sample 7ST-1, 405 nm
- Greatly enhanced BRDF values for s-polarized incident light vs. p-polarized (note scales are not same)
- Unpolarized (averaged) result will be dominated by s-polarization; strong dependence of observed BRDF on ϕ_r at given θ_r
- Observed asymmetries, more pronounced when looking at p-polarization

Integrating BRDF to obtain DHR

DHR from BRDF* $\rho = \iint f_r(\theta_r, \phi_r)\cos\theta_r \sin\phi_r d\theta_r d\phi_r$

Variable substitution $x = \sin\theta_r \cos\phi_r \qquad y = \sin\theta_r \sin\phi_r$

$$\rho = \iint f_r(x,y) \begin{vmatrix} \frac{\partial x}{\partial \theta} & \frac{\partial x}{\partial \phi} \\ \frac{\partial y}{\partial \theta} & \frac{\partial y}{\partial \phi} \end{vmatrix}^{-1} \sin\theta\cos\phi dxdy$$

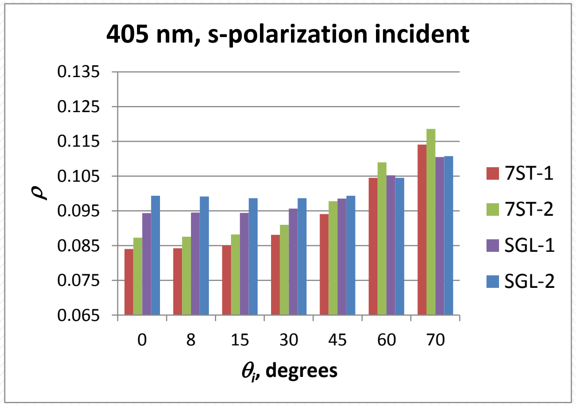
$$\rho = \iint f_r dxdy = \frac{\pi \iint f_r dxdy}{\iint dxdy} = \pi \langle f_r \rangle_{xy}$$

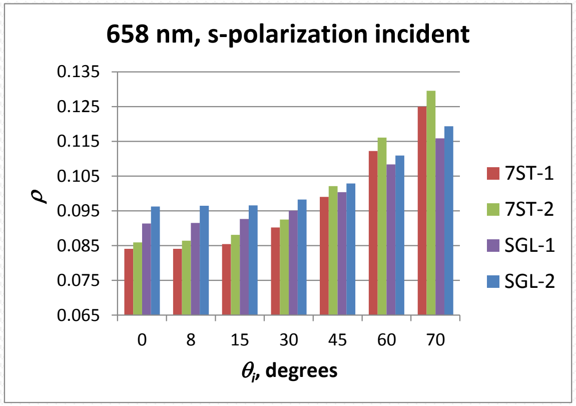
$\rho = \pi\langle f_r\rangle_{xy}$ since BRDF measured at evenly spaced pts in *x*,*y*

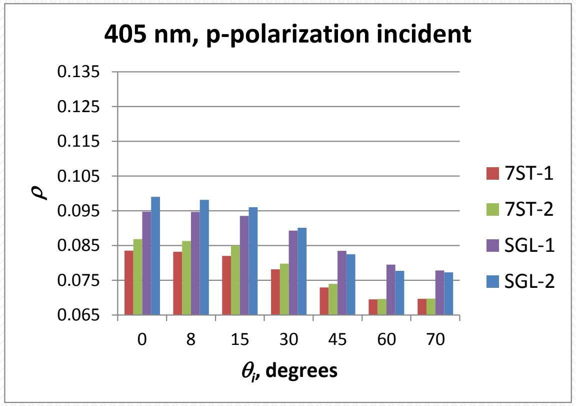
- For white Lambertian reflector, DHR $\rho = 1$

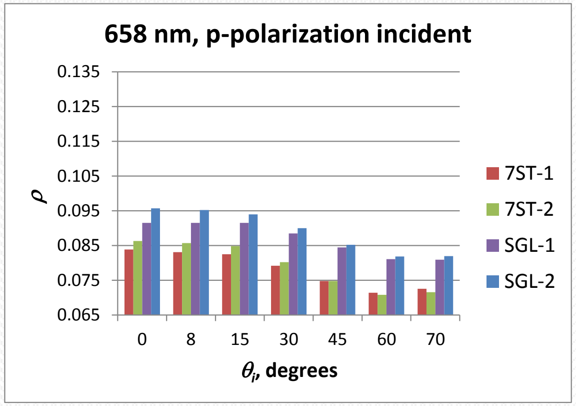
*ASTM E2387-05, "Standard practice for goniometric optical scatter measurements," ASTM International, West Conshoken, PA, 2005.

DHR, polarization-resolved



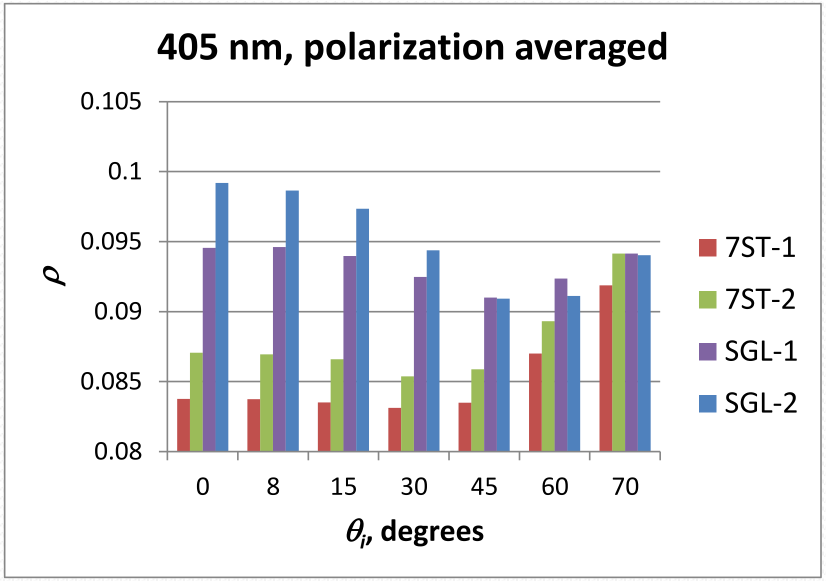


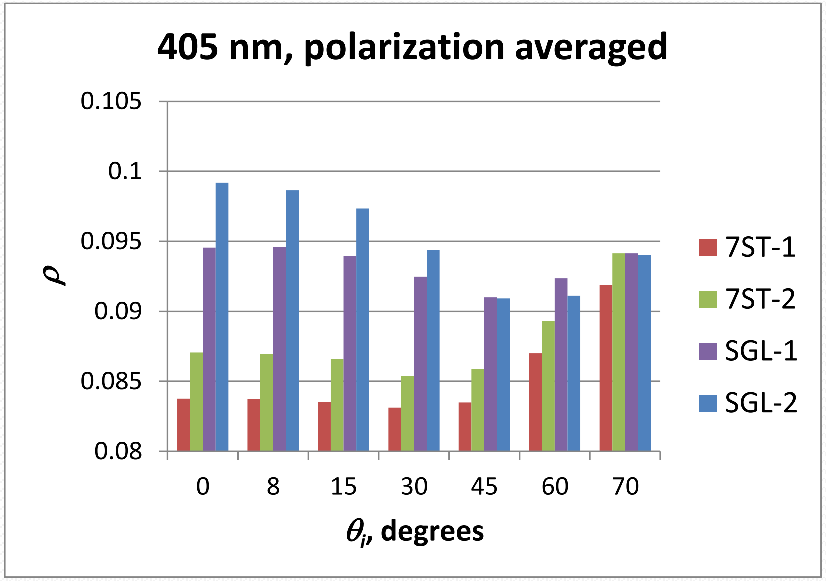




- Results for all samples, wavelengths investigated
- Two samples within type (7ST or SGL) show similar trends
- 7ST polarization dependence more pronounced (different surface finish?)

DHR, unpolarized incident light

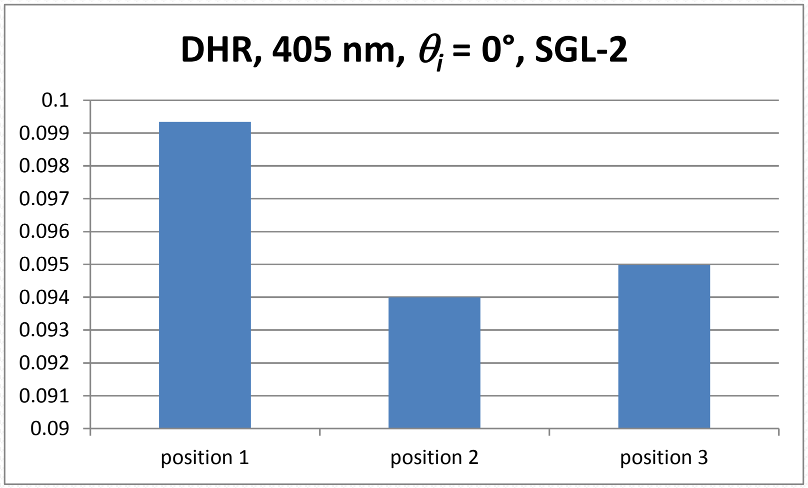




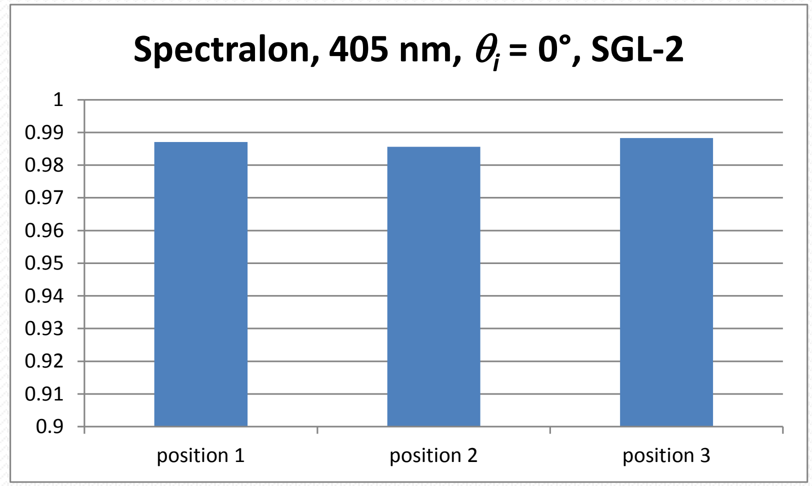
- Results for all samples, wavelengths investigated
- Two samples within type (7ST or SGL) show similar trends
- DHR 0.083 to 0.101 for all samples/wavelengths/incident angles

Variation of DHR over surface?

405 nm, graphite



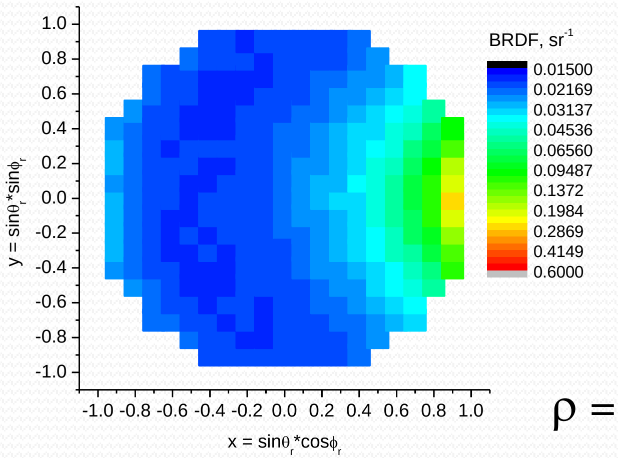
405 nm, spectralon



- 405 nm DHR for unpolarized incident light, $\theta_i = 0°$
- Graphite SGL-2 sample showed ≈ 5% $\Delta\rho$ vs. position
- In contrast, a Spectralon sample showed ≈ 0.3% $\Delta\rho$ vs. position
- Surface non-uniformity of graphite samples plays a role!
- Surface non-uniformity may also contribute to apparent asymmetries in hemispherically –scanned BRDF, as illuminated area expands with θ_i

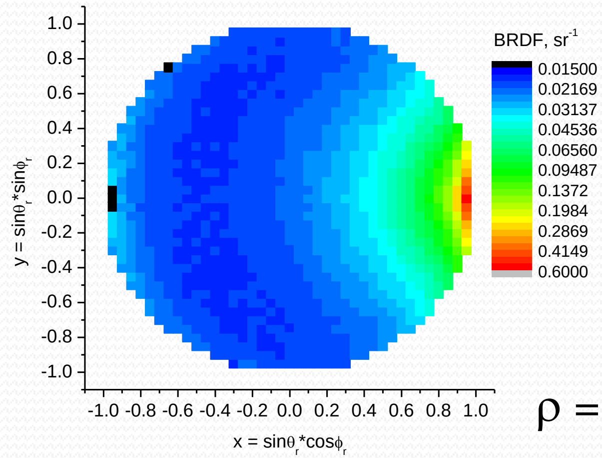
Dependence of DHR on scanning range?

Typical, 305 pts



ρ = 0.01

Fine spacing, 1245 pts



ρ = 0.0106

- 658 nm DHR for unpolarized incident light, $\theta_i = 70°$, sample 7ST-2
- On left, 0.1 spacing x,y grid (typical). On right, 0.05 spacing (accesses higher θ_s)
- $\Delta\rho \approx +6\%$ when spacing decreased (for sample with largest effect)
- Only affects $\theta_i = 70°$
- May need to consider for very non-Lambertian BRDF, highest

Discussion

- Graphite samples show strongly non-Lambertian BRDF
  - Strong enhancement of forward-scattering, dominated by BRDF from s-pol component of incident light

- DHR from 0.083 to 0.101 calculated from BRDF measurements
  - Dependent on θ_i, polarization, sample type, position on sample
  - Likely also very dependent on exact surface finish
    - Hanssen et al. report 0.1 to 0.3 rough-polished at 2 μm wavelength

- Effect on models of emissivity/blackbody temperature?
  - TBD! Plan to adjust models to more appropriately account for BRDF measurements – may be able to adapt GSD model to approximate our results
  - Also compare elevated T measurements with these room T results
  - One study showed changing DHR from 0.2 to 0.3 gave ≈ 20 mK change in T – but assumed a Uniform Specular Diffuse model. Goals for all source-based components of uncertainty budget 30 mK – 110 mK

- Ability to hemispherically scan BRDF gives more detailed BRDF picture compared to sphere-based and in-plane measurements

Thank you!