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Development of a new absolute diffuse reflectometer at NRC

Status and Outlook

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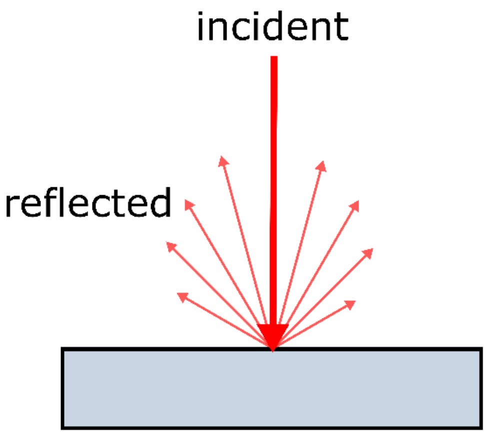
Outline

- ❑ Realizing a scale for diffuse reflectance via the Sharp-Little method
- ❑ NRC’s new absolute diffuse reflectometer
- ❑ Beyond Sharp-Little: sphere non-uniformity, finite port thickness & baffle
- ❑ Preliminary data
- ❑ Future work

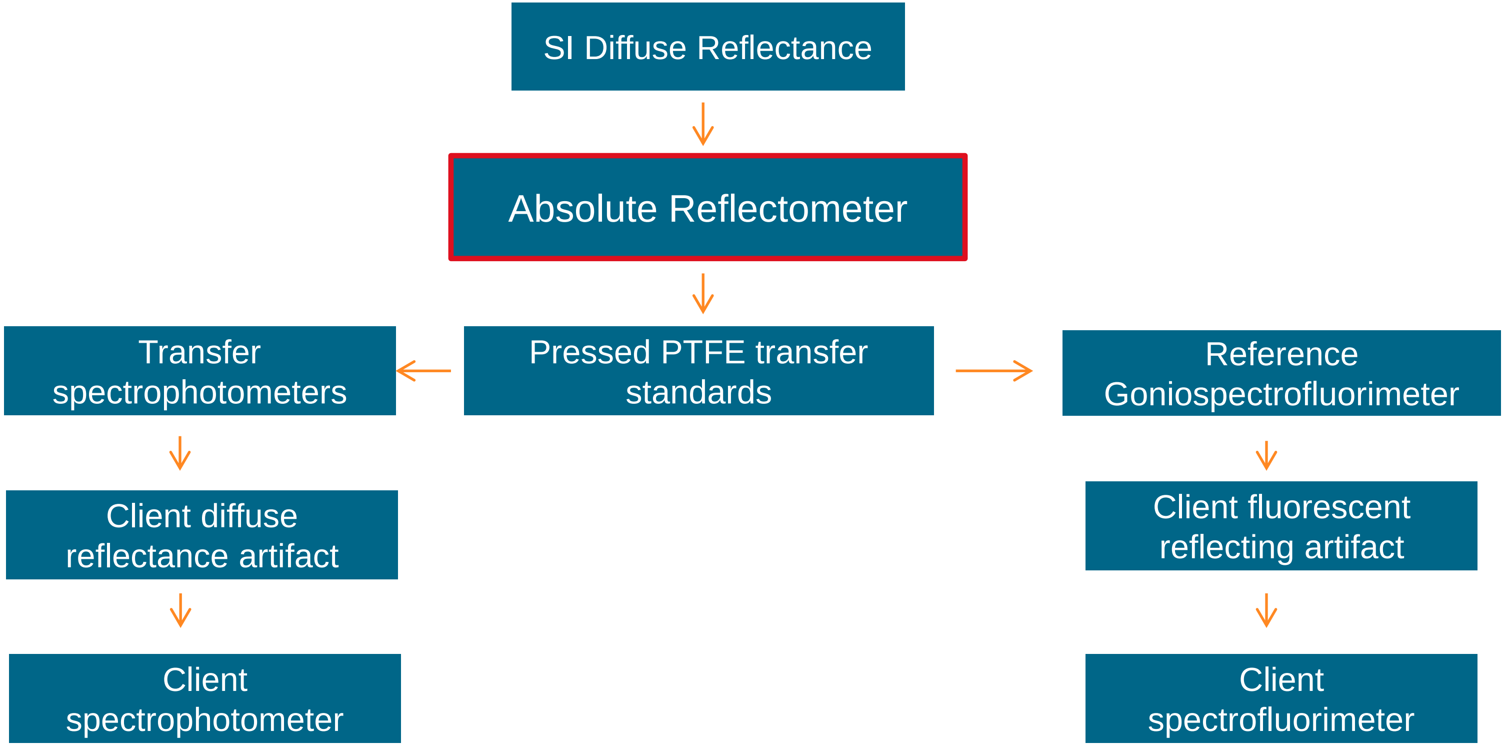
Diffuse reflectance

- Illumination and/or viewing is diffuse (spans entire hemisphere above sample)
- Suitable for matte surfaces
  - paper
  - textiles
  - powders
- Various configurations: (d,0°), (d,d), etc.

Directional-hemispherical (0°,d)

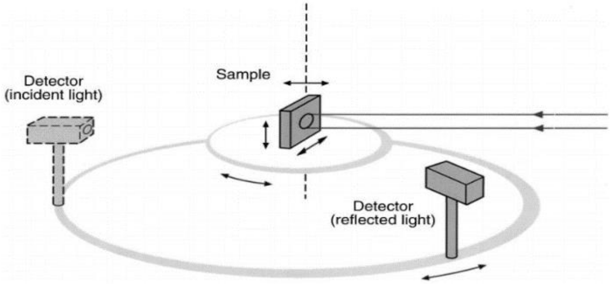


Traceability chain for diffuse reflectance at NRC

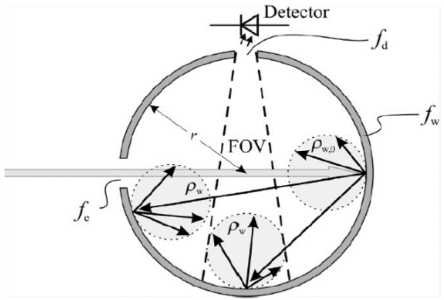


How to measure *absolute* diffuse reflectance?

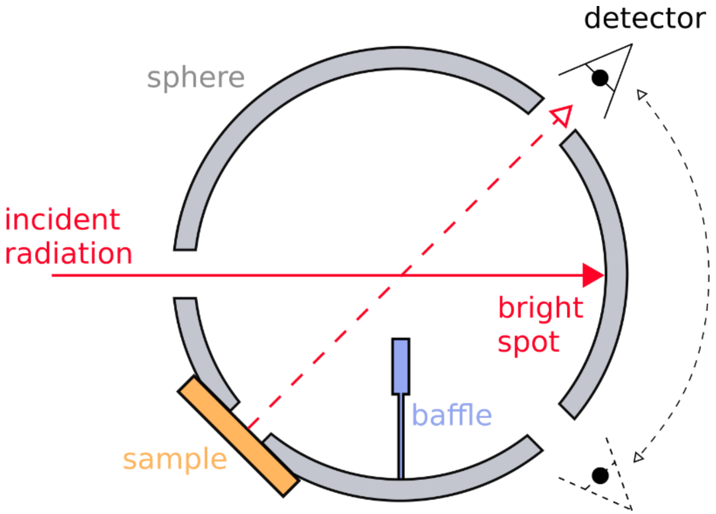
- Goniometric techniques
  - NPL, MIKES



- Integrating sphere-based techniques
  - NRC, NIST, PTB, KRISS, others…



The Sharp-Little method for (*d*,0°) reflectance



- Shading effect of the baffle

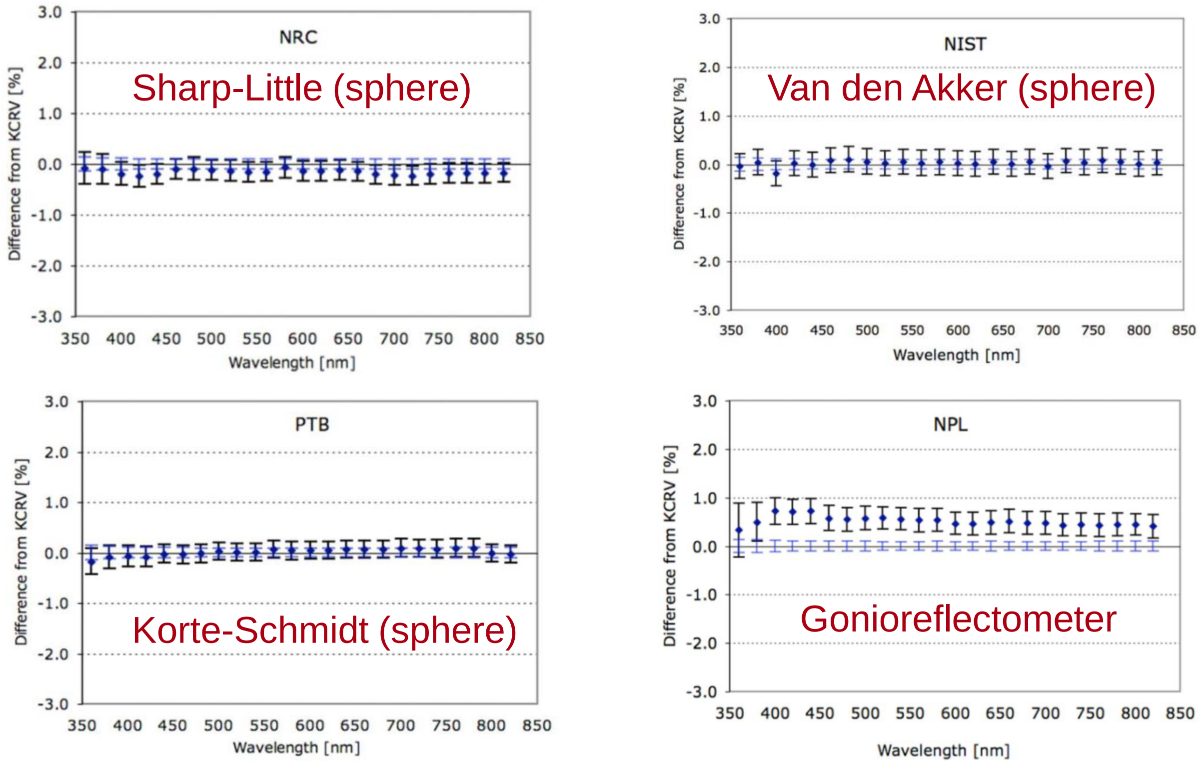
$$\frac{E_s}{E_w} = \rho_{ave} = \rho_w a_w$$

- Ratio of detector signals

$$\frac{i_s}{i_r} = \frac{\rho_s}{\rho_w} \times \frac{E_s}{E_w} = \frac{\rho_s}{\rho_w} \times \rho_w a_w$$

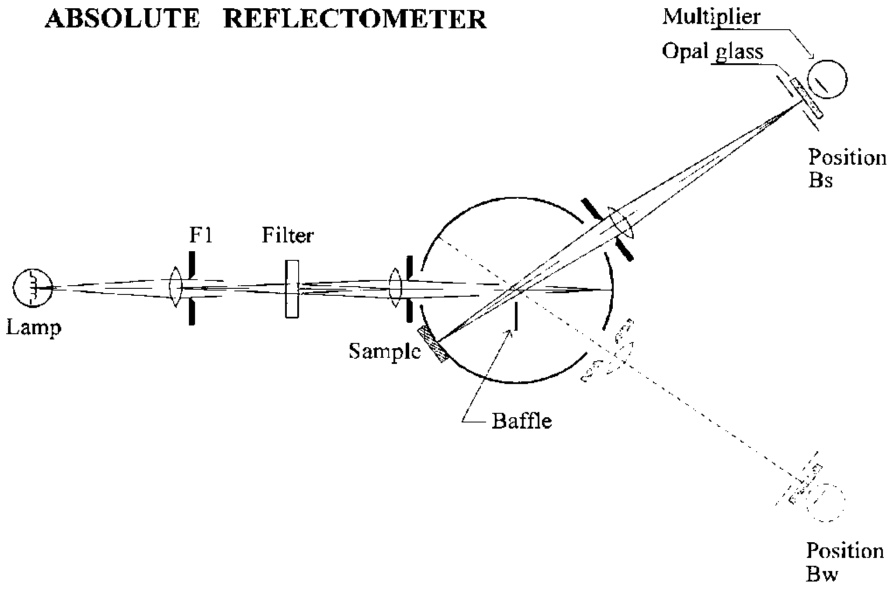
$$\rho_s = \frac{i_s}{i_r} \times \frac{1}{a_w}$$

CCPR-K5 Key Comparison



Sample: Spectralon (sintered PTFE)

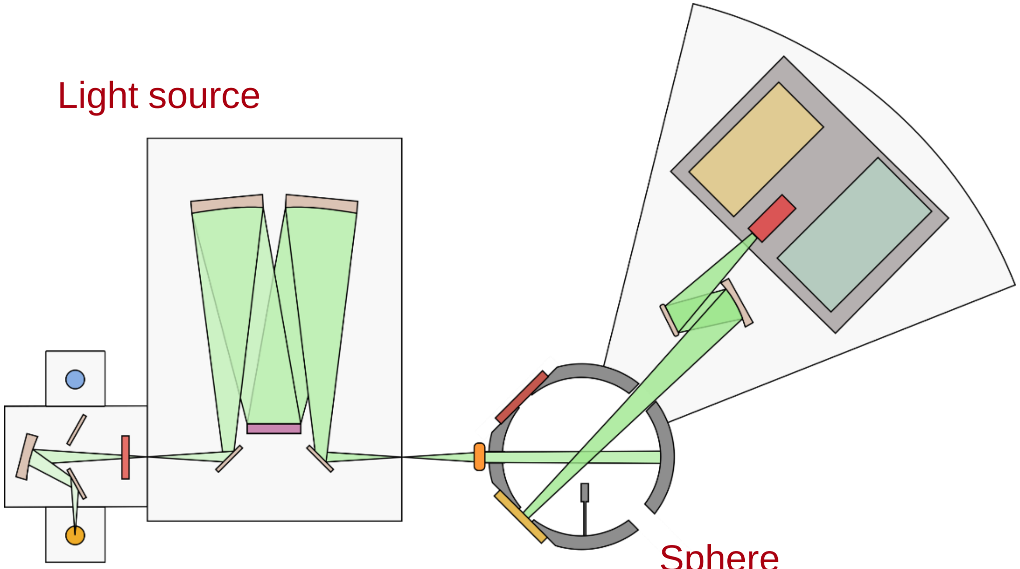
The existing NRC absolute reflectometer



Limitations

- ❑ Filter-based (fixed wavelengths & bandpass)
- ❑ Restricted spectral range (UV-VIS)
- ❑ Labour-intensive

New absolute reflectometer



Key features:

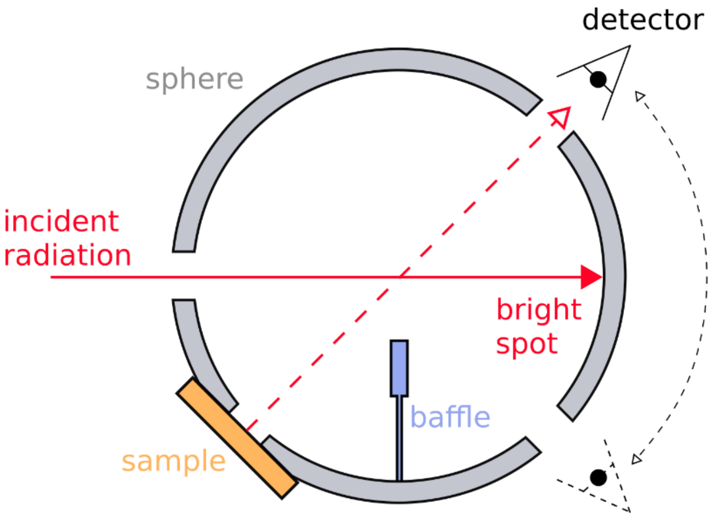
- ❑ Broadband (250-2000 nm)
    - ❑ W & D lamps
    - ❑ Detectors: Si, PMT, Ext. InGaAs

- ❑ Variable bandwidth
- ❑ Full automation
- ❑ Custom sintered PTFE integrating sphere

Challenges from sphere asymmetry

Assumptions of SL method:

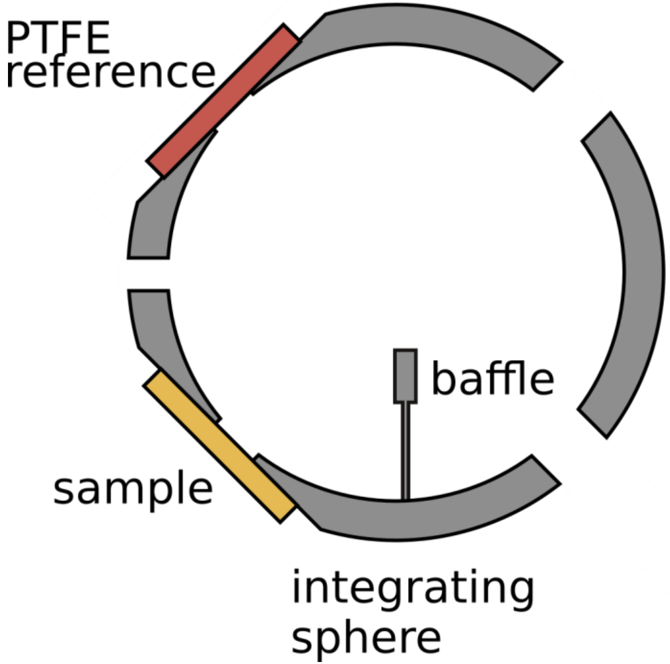
- ❑ Spherical symmetry (including sample)
- ❑ Homogeneous sphere surface
- ❑ Ports have zero reflectance
- ❑ Ignore baffle beyond shading effect



$$\frac{E_s}{E_w} = \rho_{ave} = \rho_w a_w$$

$$\frac{i_s}{i_r} = \frac{\rho_s}{\rho_w} \times \frac{E_s}{E_w} = \frac{\rho_s}{\rho_w} \times \rho_w a_w$$

Mitigating sphere asymmetry



Steps:

- ❑ Secondary ‘reference’ port
  - ❑ Ensures local geometry viewed by sample and reference are similar
  - ❑ Characterize multiple PTFE references to characterize/correct nonuniformity

- ❑ Modelling
  - ❑ Monte Carlo ray tracing of directional dependence of real port reflectance
  - ❑ Numerically evaluate effective baffle area

PTFE non-uniformity

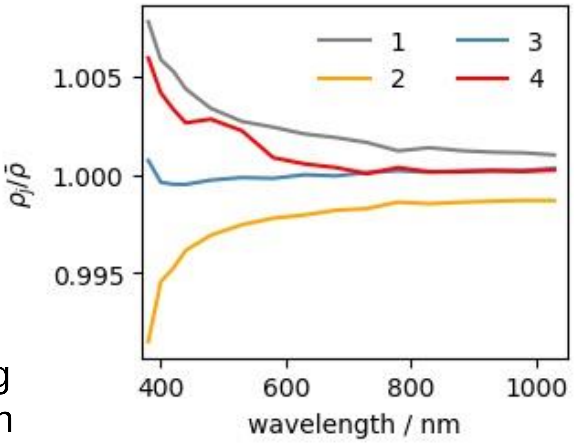
See also: Sun & Ma, SPIE 2014

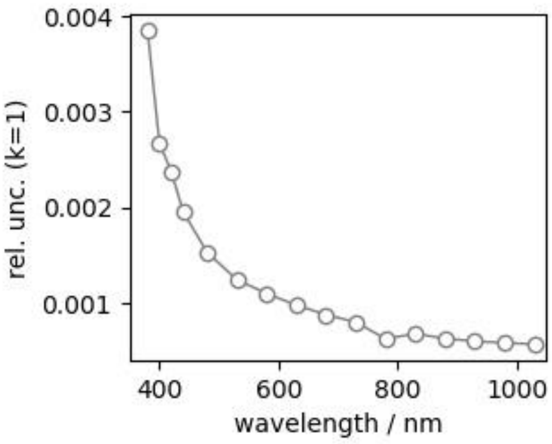
- Accounting for non-uniformity:

reflectance of specific reference part

$$\rho_s = \frac{i_s}{i_w} \times \frac{1}{a_w} \times \frac{\rho_w}{\bar{\rho}}$$

average PTFE reflectance

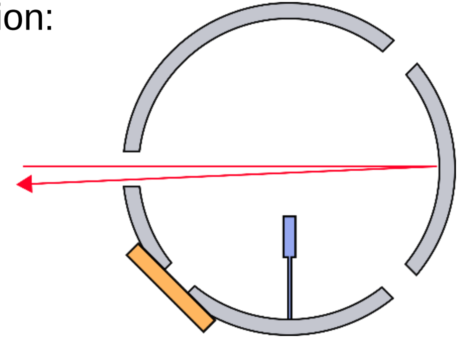




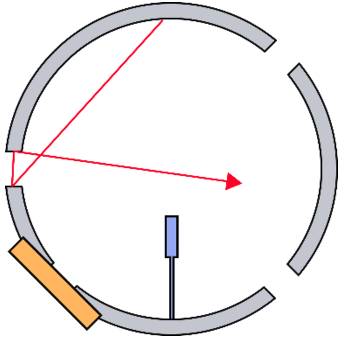
- Estimate non-uniformity by measuring reflectance of an arbitrary sample with multiple PTFE reference parts.

Reflectance of realistic port

First reflection:



Second reflection:



- Accounting for differences between first and second reflections:

$$\rho_s = \frac{i_s}{i_w} \times \frac{1}{a_w} \times \frac{\rho_w}{\bar{\rho}} \times (1 - a_p \Delta\rho)$$

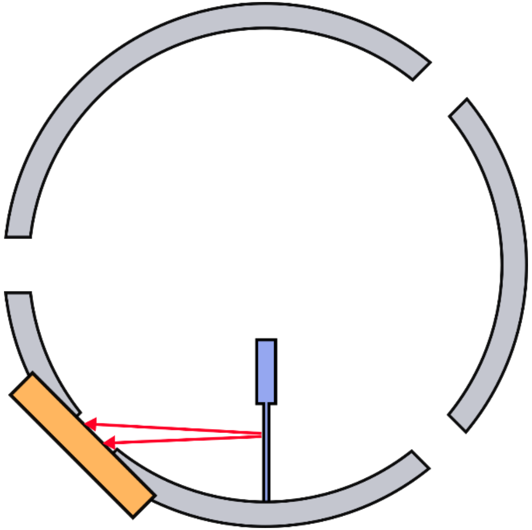
fractional port area → a_p; reflectance difference → $\Delta\rho$

- Can estimate $\Delta\rho$ using Monte Carlo ray tracing
  - C. Tang *et al.*, Applied Optics 2018

- Correction: - 0.08%

See also: Hwang *et al.*, Metrologia 2013

Port screening by baffle



- Viewed from the sample position, the baffle stem obscures one of the two view ports
- Compared with the 'reference' wall position, the sample sees a slightly larger effective area and receives a correspondingly larger diffuse flux

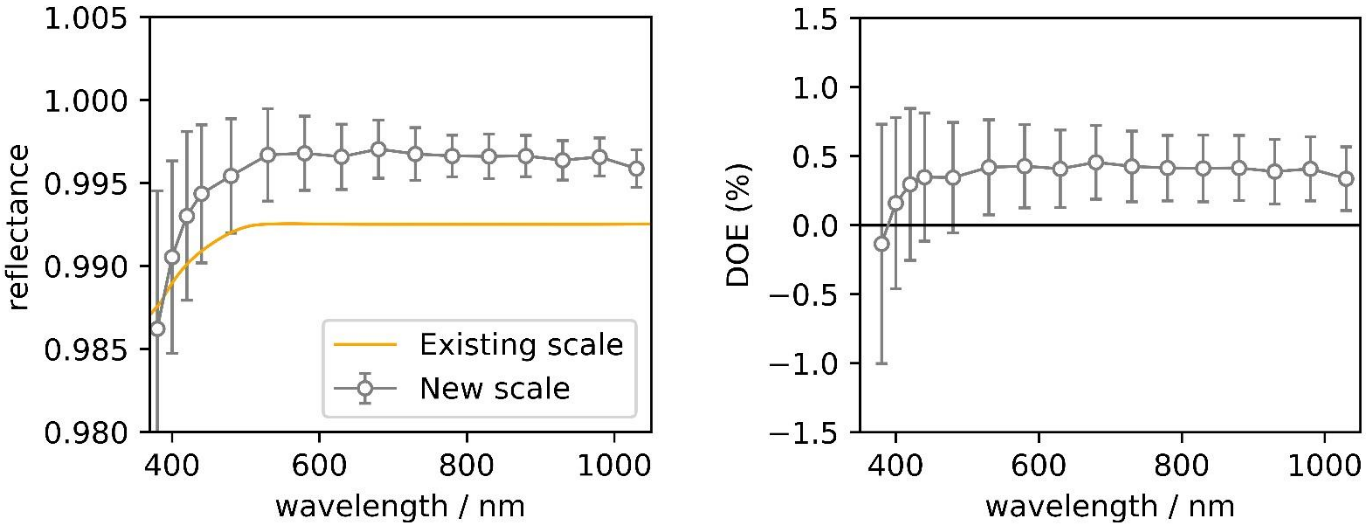
$$\rho_s = \frac{i_s}{i_w} \times \frac{1}{a_w} \times \frac{\rho_w}{\bar{\rho}} \times \frac{1 - a_p \Delta\rho}{1 + a_{stem}}$$

Effective fractional stem area

- Correction: ~ - 0.24%

Preliminary data: pressed PTFE tablet

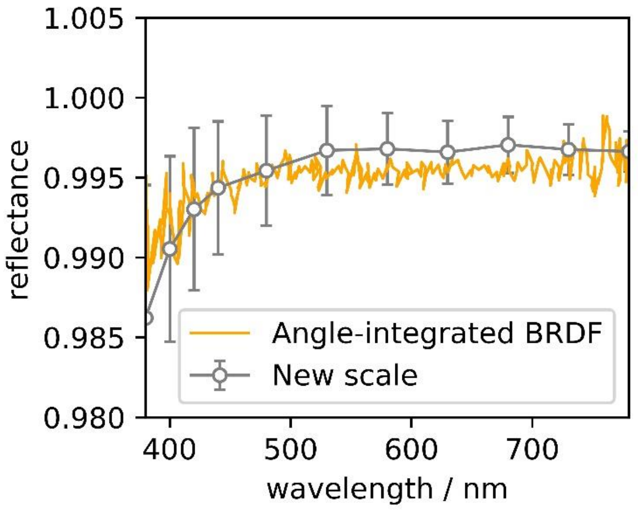
W source, Si photodiode, 8 nm bandpass, 380 to 1030 nm, compared with existing NRC Sharp-Little scale

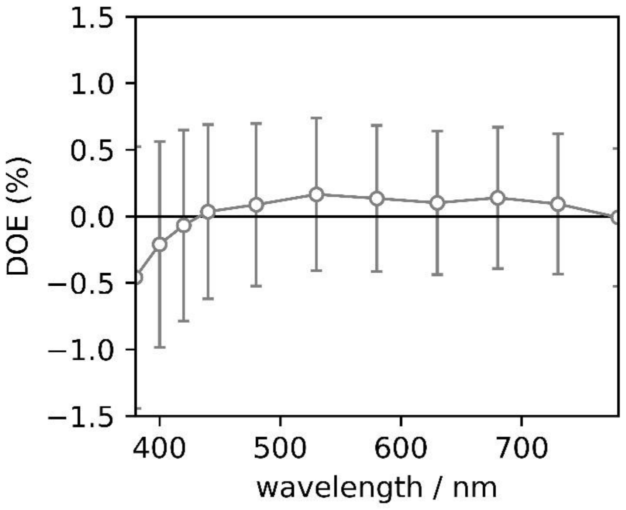


Level is ~ 0.4% higher, more rapid dispersion in UV

Preliminary data: pressed PTFE tablet

W source, Si photodiode, 8 nm bandpass, 380 to 1030 nm, compared with angle-integrated BRDF data



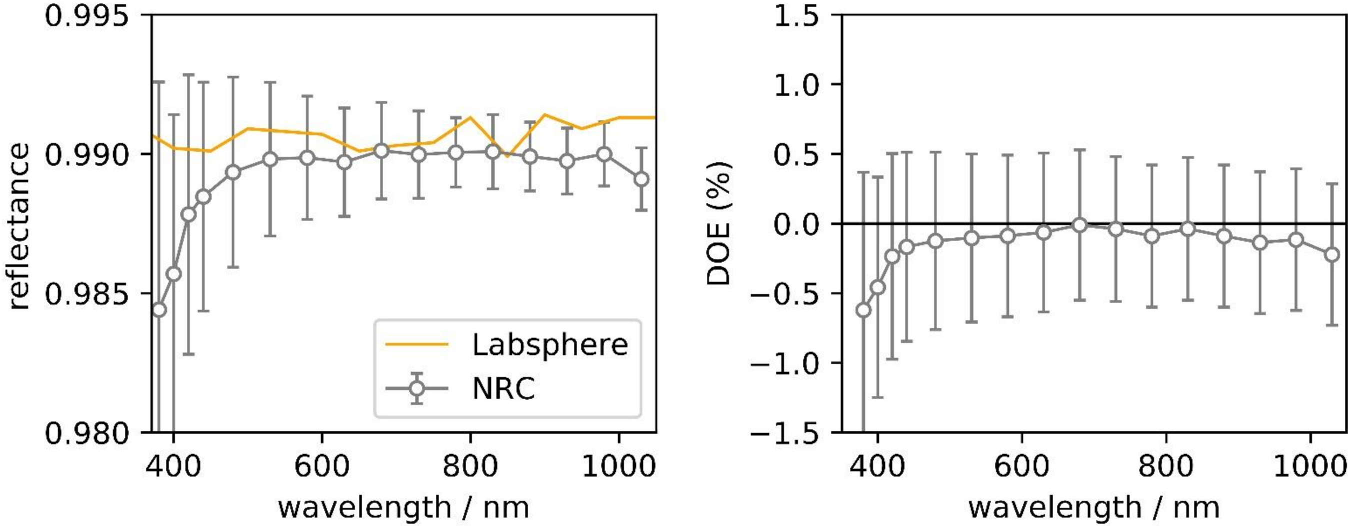


BRDF Data: Baribeau & Zwinkels, SPIE 2012

Level in good agreement, more rapid dispersion in UV

Preliminary data: sintered PTFE (Spectralon)

W source, Si photodiode, 8 nm bandpass, 380 to 1030 nm



Overall level in good agreement, modest spectral distortion in UV

Future

- Measure more PTFE reference parts
  - Reduce uncertainty due to nonuniformity
- Uncertainty budget
- Extend spectral range with PMT (UV) and InGaAs (NIR)
- CCPR-K5 Spectral Diffuse Reflectance (2020)

Thank you for your attention!

Acknowledgements

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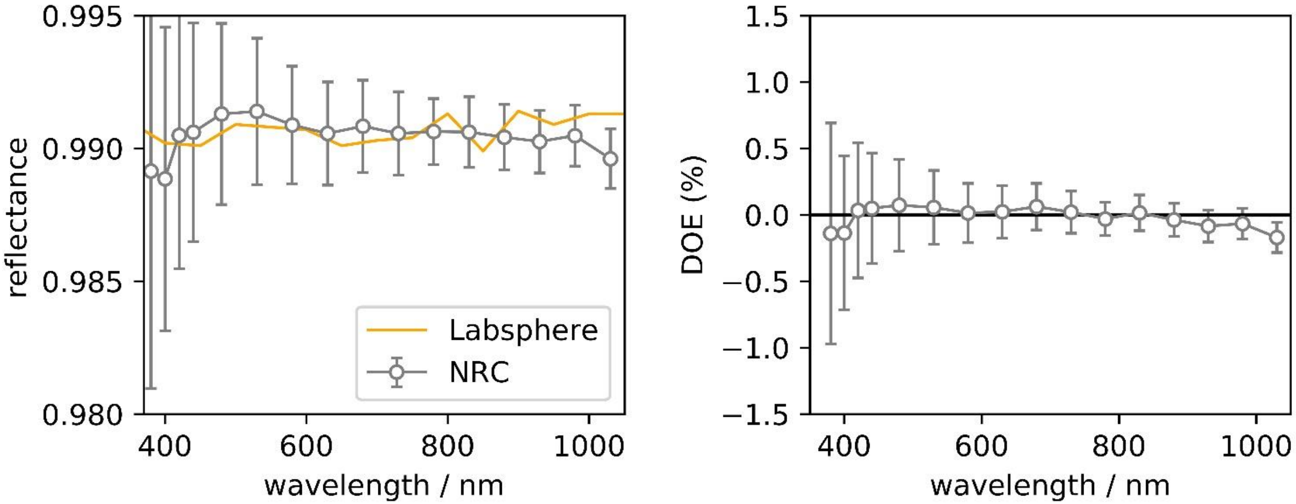
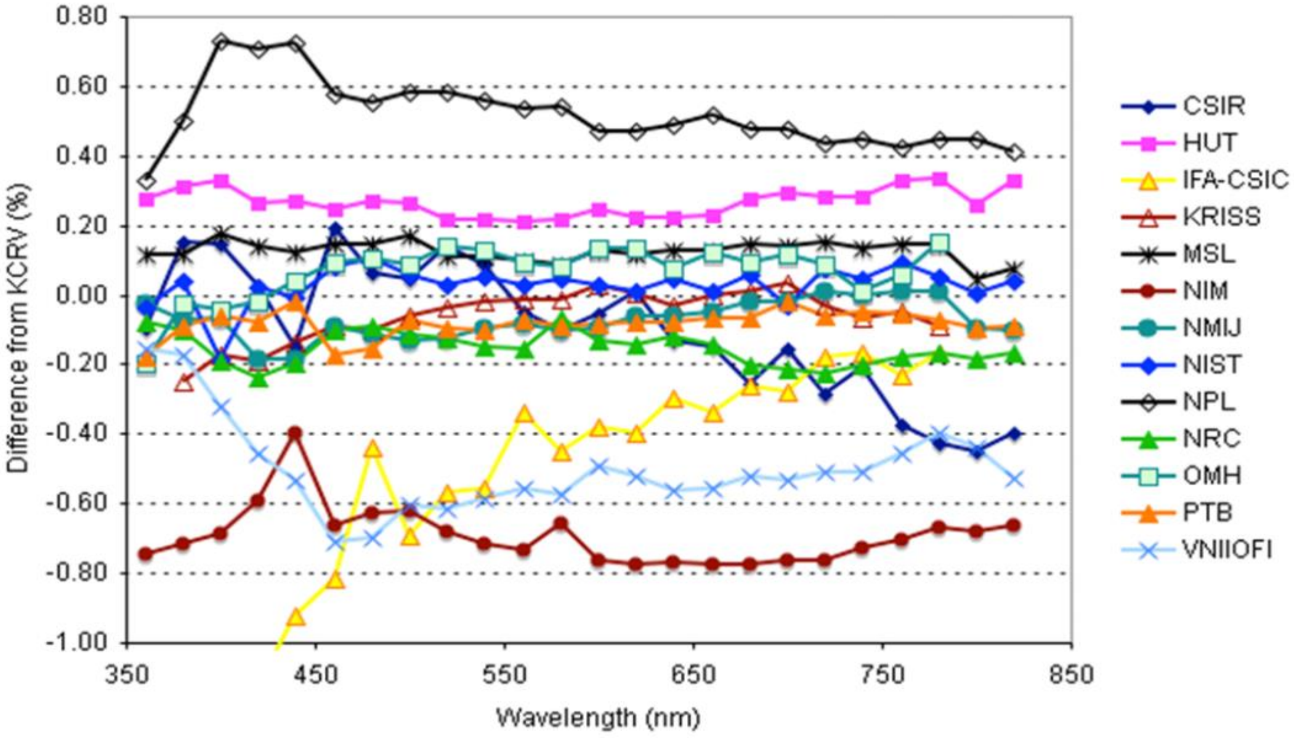
Preliminary data: sintered PTFE (Spectralon)

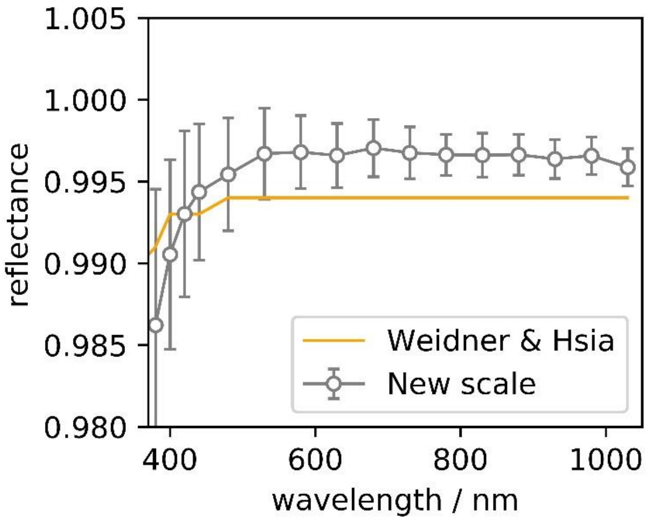
*outlier PTFE reference specimen removed

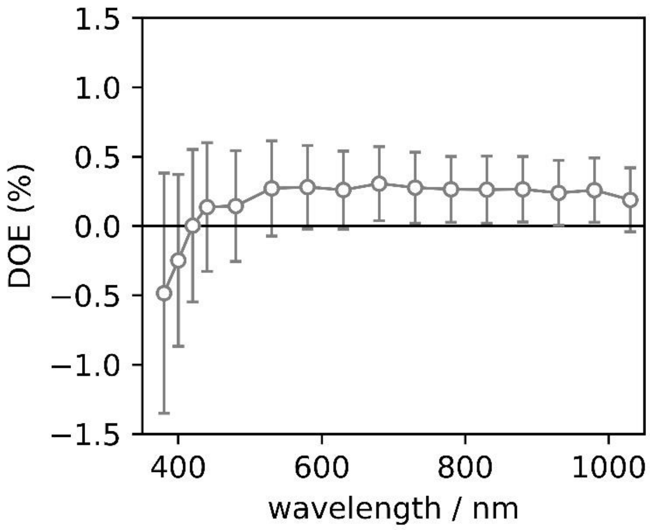


CCPR-K5 Key Comparison

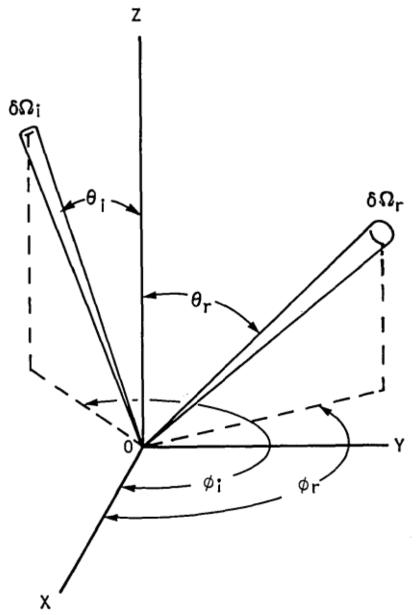


Preliminary data: pressed PTFE (Weidner & Hsia)





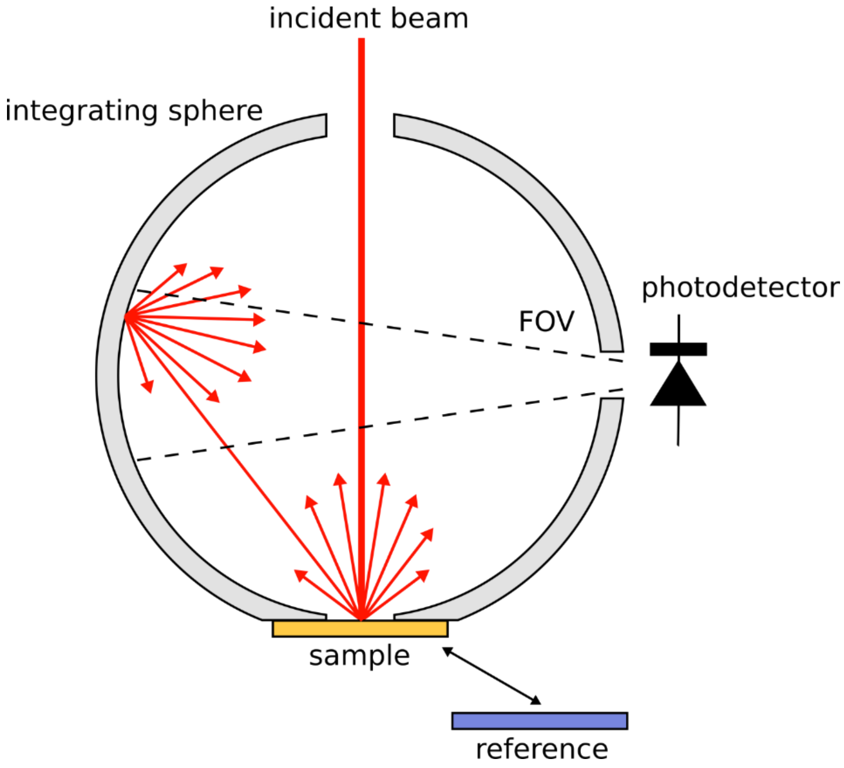
Reflectance geometries



$$\rho = \frac{P_r(\Omega_r, \theta_r, \varphi_r, \Omega_i, \theta_i, \varphi_i)}{P_i(\Omega_i, \theta_i, \varphi_i)}$$

Measurement	Geometry	Example materials
Specular	$\theta_i = \theta_r$ $\Omega_i, \Omega_r \to 0$ In plane	Mirror
Bidirectional (0°/45°)	$\theta_i = 0$ $\theta_r = \pi/4$ $\Omega_i, \Omega_r \neq 0$	Safety materials
Hemispherical (diffuse)-directional	$\Omega_i = 2\pi$ $\Omega_r \to 0$ $\theta_r = 0$	Paper, textiles

How to measure diffuse reflectance?



For *perfectly* diffusing surfaces + spherical geometry, reflected flux distributed evenly over the sphere surface.

Sum up multiple reflections:

$$\begin{aligned} v &\propto \phi_1 + \phi_2 + \phi_3 + \dots \\ &\propto \phi_1 \times (1 + \rho_{ave} + \rho_{ave}{}^2 + \dots) \\ &\propto \frac{\rho_{0,d}\phi_o}{1-\rho_{ave}} \end{aligned}$$

$$\phi_1 = \rho_{0,d}\phi_o$$

$$\phi_2 = \rho_{ave}\phi_1$$

Compare with a reference to get absolute value.