Aalto University
School of Electrical
Engineering

Reflectance Measurement

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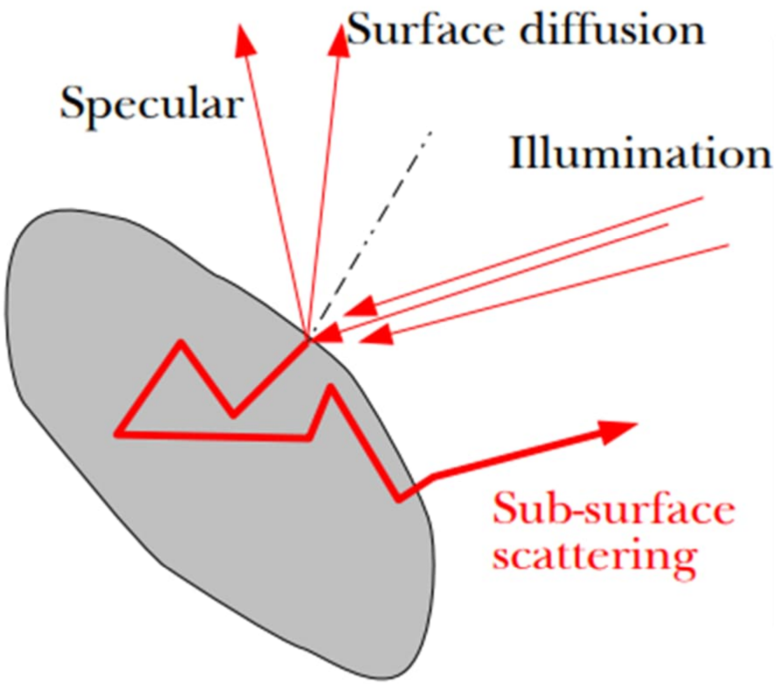
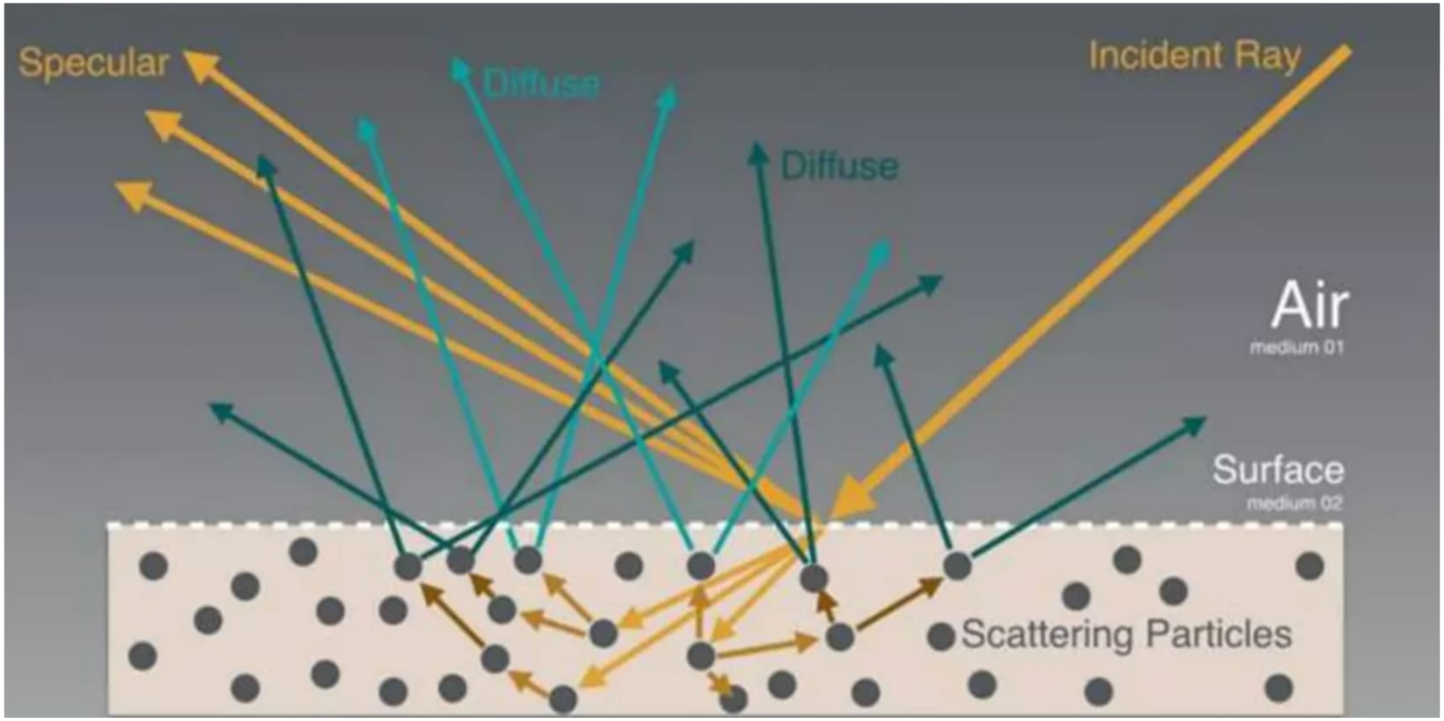
Contents

- Theory
- Measurement devices
- Uncertainty

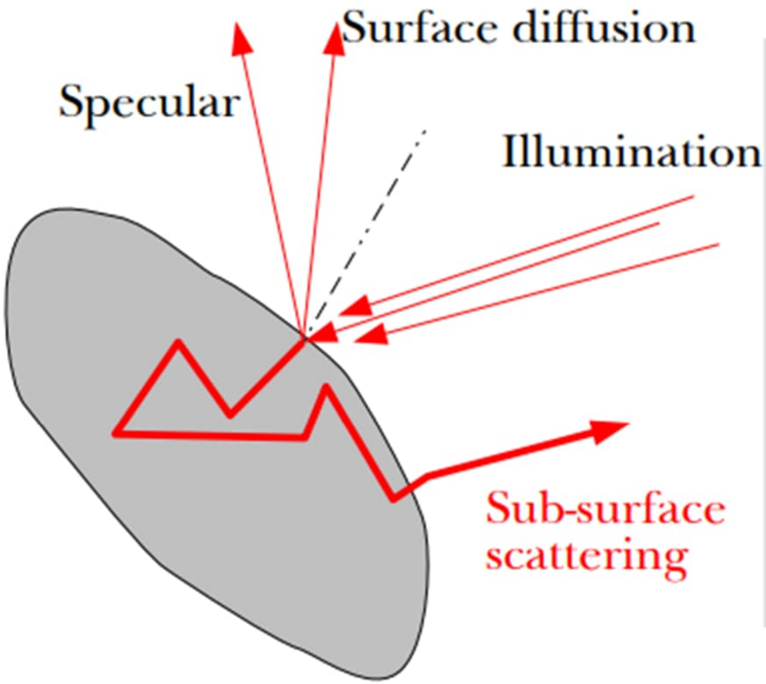
Light and matter



Light and matter



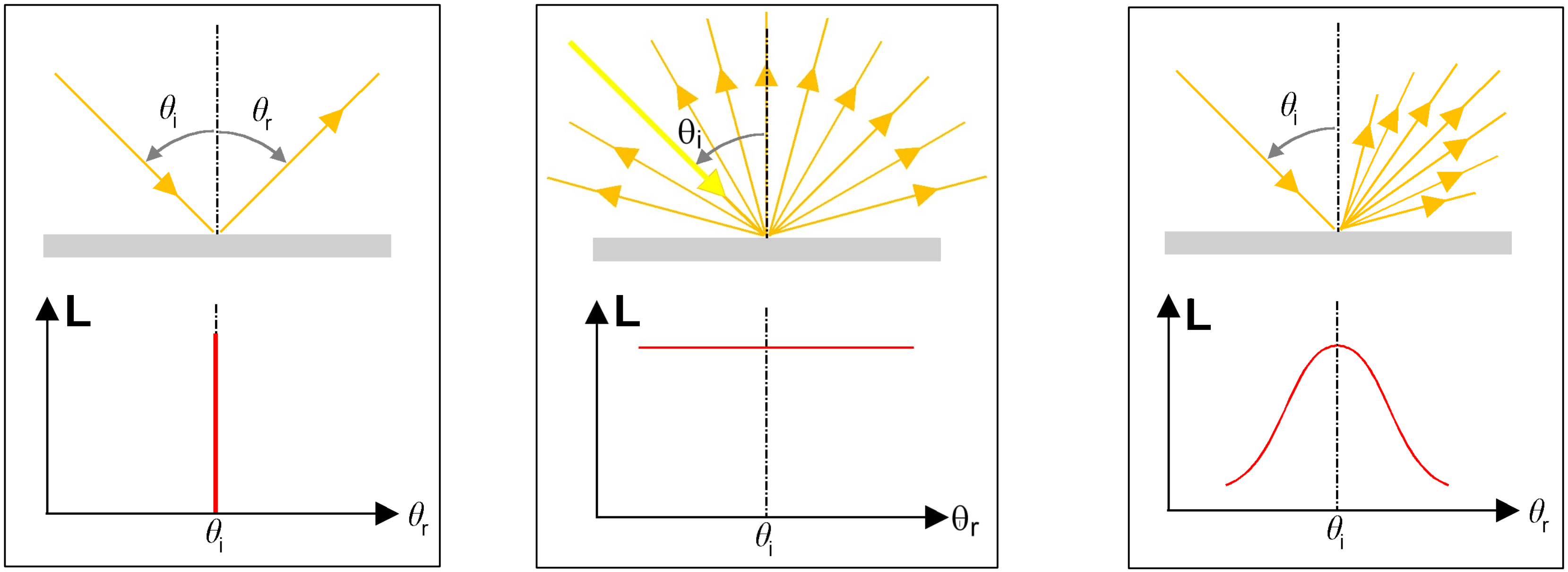
Light and matter



- **Wavelength** : spectrometry
- **Photometry** : albedo, colours
- **Position** on surface : imaging or scan
- **Angles** : goniometry
- **Polarisation**
- **Phase** (interferometry)

Light offers many ways to explore a complex material

Reflection



Regular	Diffuse	Diffuse
Specular	Isotropic	Haze

There is always some amount of reflection haze due to surface roughness, dust, scratches etc.

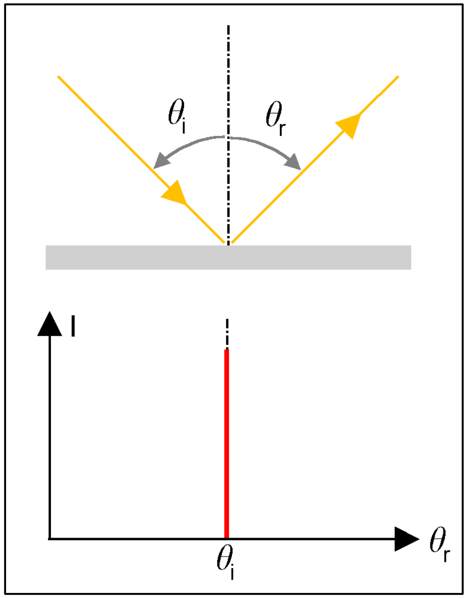
Regular reflectance measurements

Spectral radiant flux Φ – power per wavelength band [W/nm]

- Regular spectral reflectance ρ is defined as the ratio of reflected spectral radiant flux $\Phi_{\lambda,R}$ to the incident spectral radiant flux Φ_{λ}.

$$\rho(\lambda, \theta_i) = \frac{\Phi_{\lambda,R}}{\Phi_{\lambda}}$$

- Law of reflection $\theta_i = \theta_r$
- Regular reflectance is dependent on the optical properties of the material (refractive index *n*) and the polarization of the incident light (Fresnel equations)
- Can be used for characterizing thin films -> complex refractive index, thickness.



Example - Thin film thickness

S. Pourjamal, H. Mäntynen, P. Jaanson, D. M. Rosu, A. Hertwig, F. Manoocheri, and E. Ikonen, “Characterization of thin-film thickness,” *Metrologia*, vol. 51, no. 6, pp. S302–S308, Dec. 2014.

SiO_2 on silicon wafer

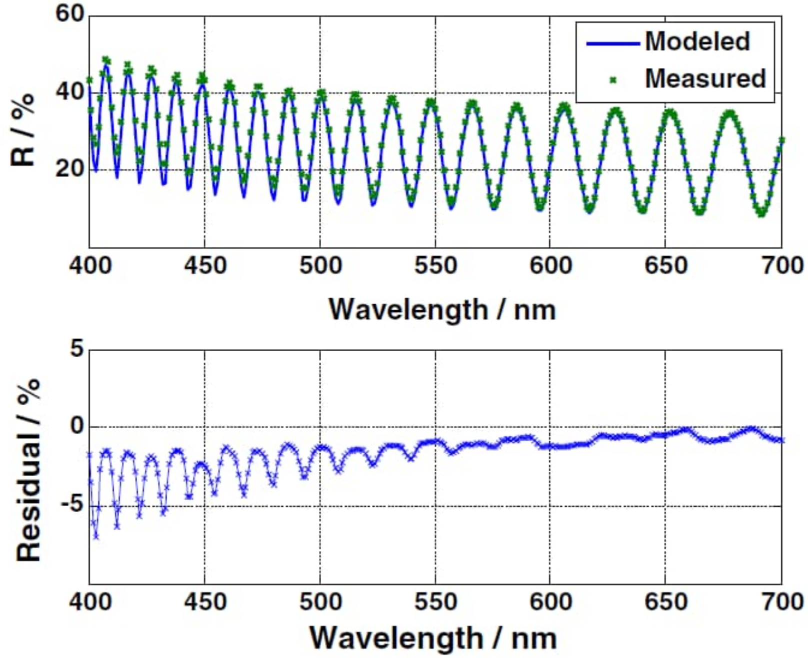


Figure 4. Reflectance data at the central spot of sample B at a 6° angle of incidence of s polarized light (upper figure) and absolute difference between the fit and the data (lower figure).

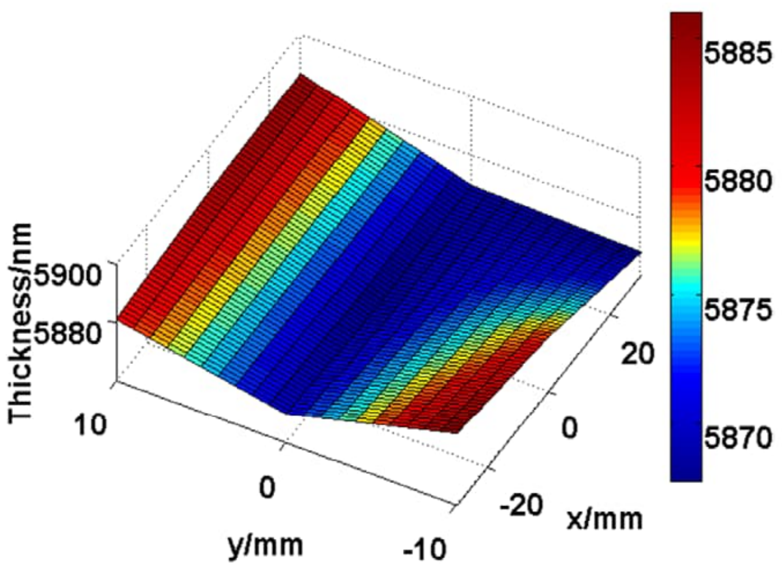
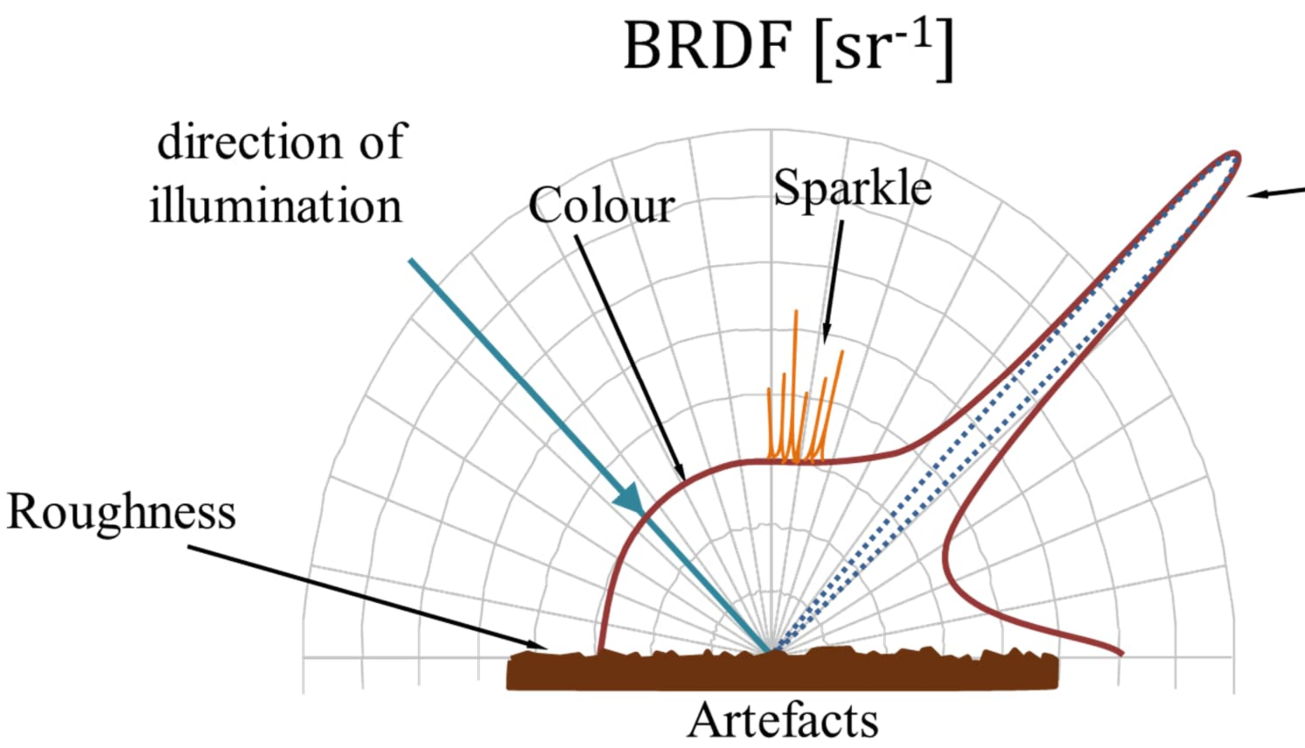
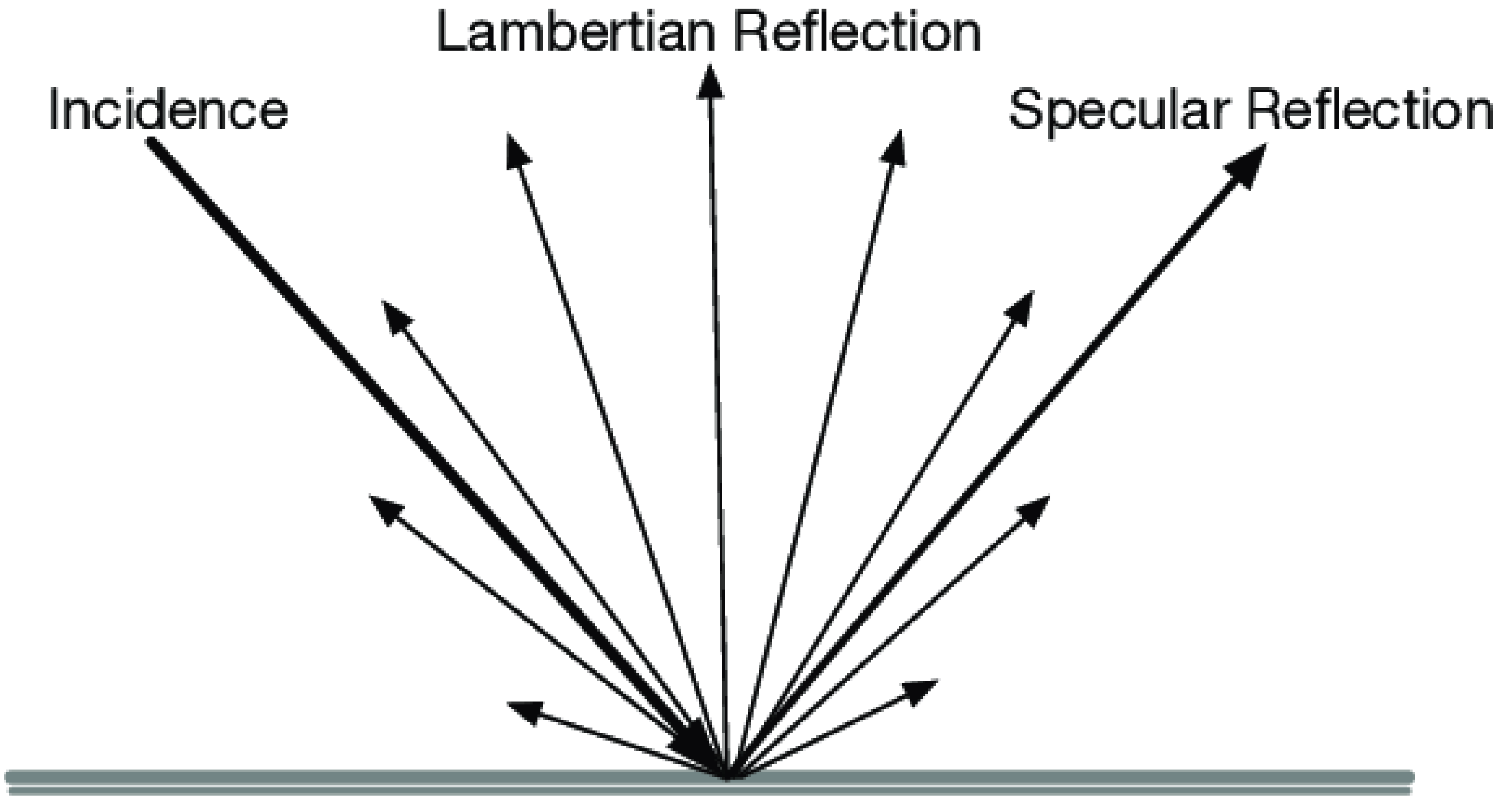


Figure 5. Spatial uniformity of the evaporated oxide layer thickness of sample B determined from spectral reflectance at a 6° angle of incidence.

BRDF (Bi-Directional Reflectance Distribution Functions)

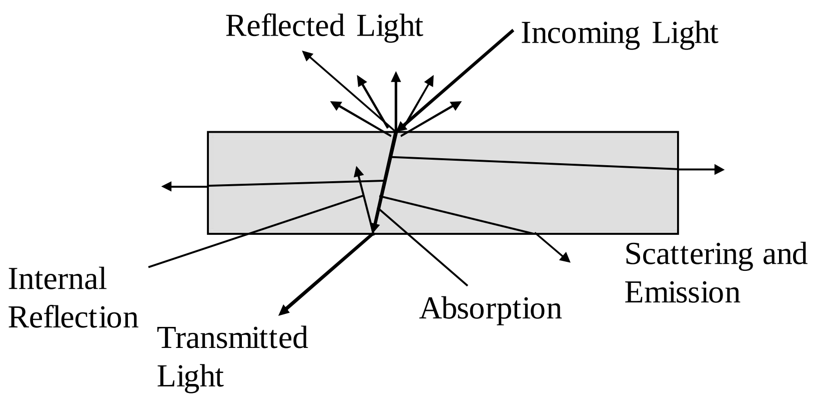


Lambertian reflection



What is BRDF?

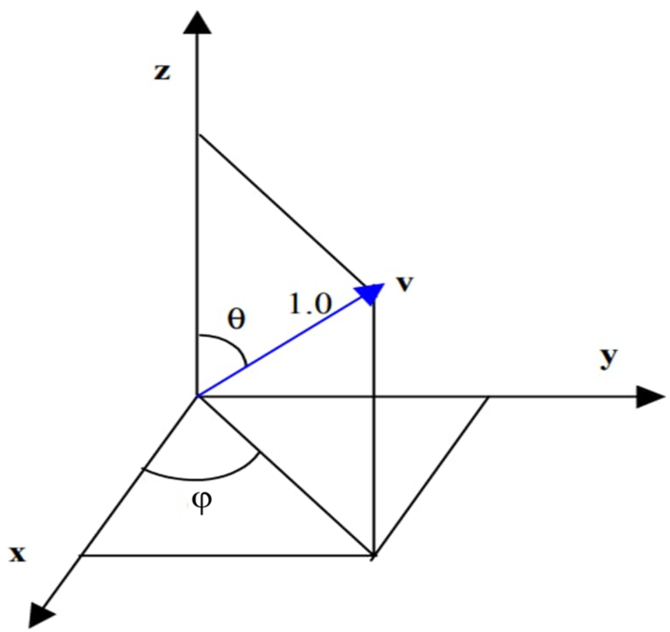
- Typical light-matter interaction scenario:



- 3 types of interaction: transmission, reflection, and absorption
- Light incident at surface = reflected + absorbed + transmitted
- BRDF describes how much light is reflected

What is BRDF?

Parametric definition: $BRDF_\lambda(\theta_i, \varphi_i, \theta_o, \varphi_o)$

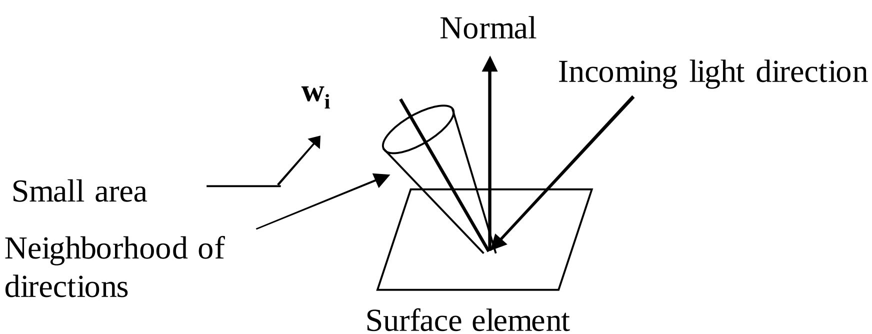


What is BRDF?

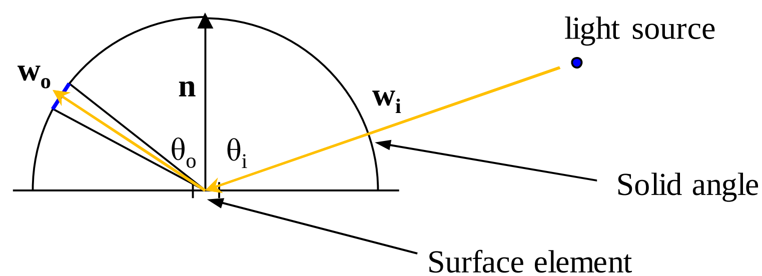
Definition:

- The ratio of the quantity of reflected light in direction w_o, to the amount of light that reaches the surface from direction w_i

3D



2D



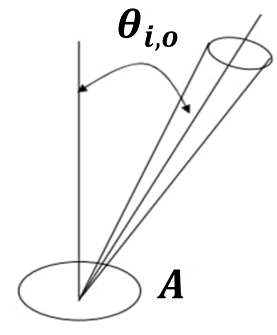
Definition of BRDF

General definition: $$BRDF = \frac{L_o}{E_i}$$

- In goniometric measurement, we use incident and detection power.

$$L(\theta)_o = \frac{\phi_o}{\cos(\theta_o)\, A\, W_o}$$

$$E(\theta)_i = \frac{\phi_i}{\cos(\theta_i)\, A}$$



$$\longrightarrow \quad BRDF = \frac{\phi_o \cos(\theta_i)\, A}{\phi_i \cos(\theta_o)\, A\, W_o}$$

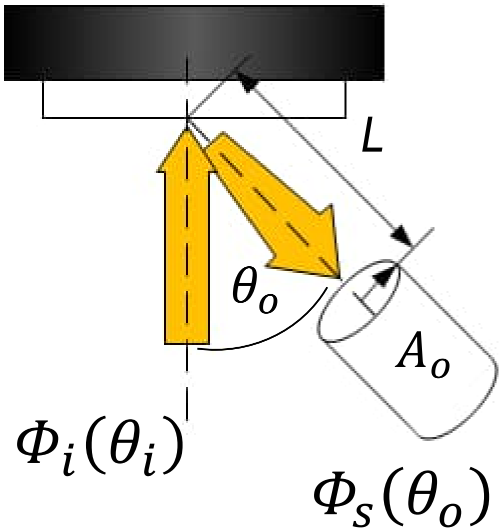
BRDF - goniometric

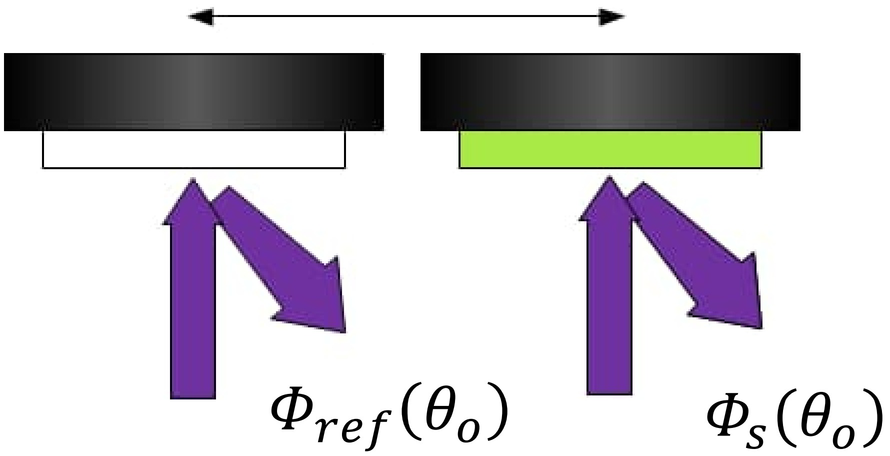
Radiance factor can be calculated:

$\theta_i = 0$

$$\beta(\theta_o, \theta_i) = \frac{\Phi_s(\theta_o)}{\frac{A_o}{L^2}} \cdot \frac{1}{\frac{\Phi_i(\theta_i)}{\pi}\cos(\theta_o)}$$

Solid angle





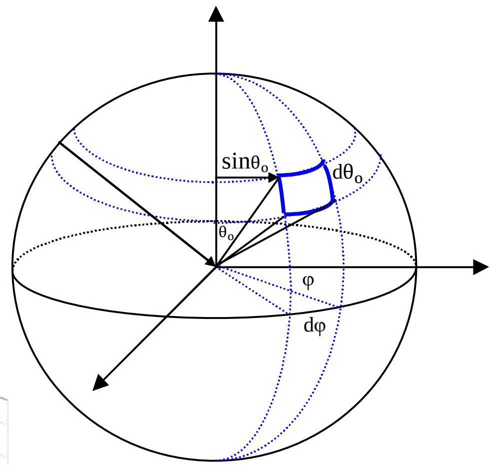
Relative goniometric

$$\beta_s(\theta_o) = \frac{\Phi_s(\theta_o)}{\Phi_{ref}(\theta_o)}\beta_{ref}(\theta_o)$$

Total diffuse reflectance - goniometric

For total BRDF →

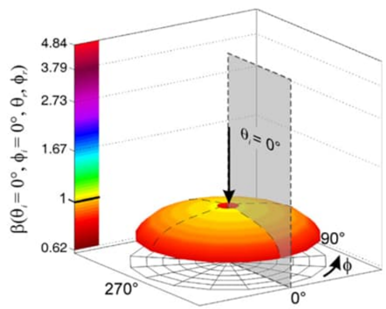
Unit sphere of radius 1



Differential surface area:

$$dA = (\text{heigth})(width)$$
$$dA = (d\theta_o)(sin\theta_0 d\varphi)$$
$$dA = sin\theta_0 d\theta_o d\varphi$$

Example:



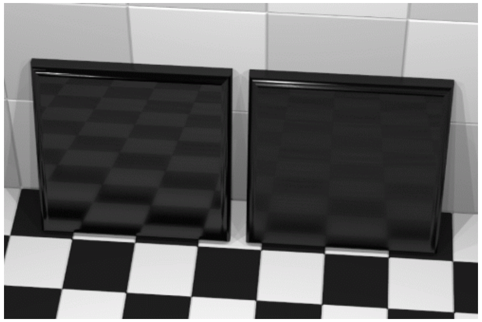
Total diffuse reflectance →

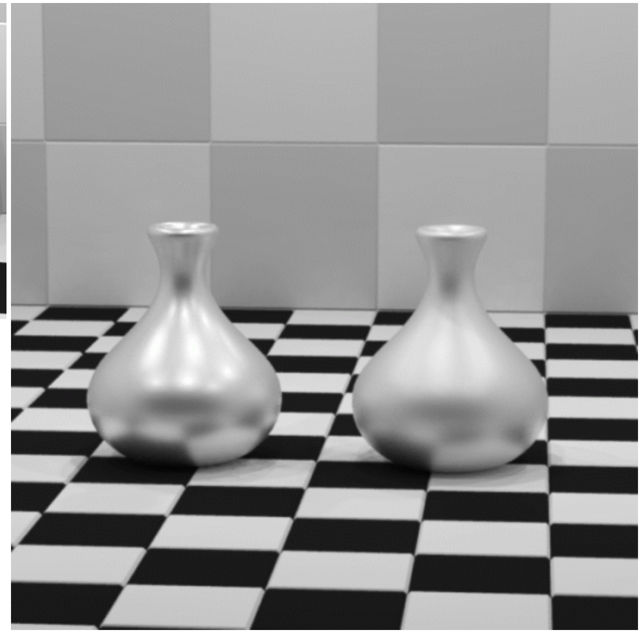
$$\rho(\theta_i) = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} \beta(\theta_o,\theta_i) cos(\theta_o) sin(\theta_o) d\theta_o d\varphi$$

$$\rho(\theta_i) = \int_0^{\frac{\pi}{2}} \beta(\theta_o,\theta_i) sin(2\theta_o) d\theta_o$$

$\theta_i = 0$

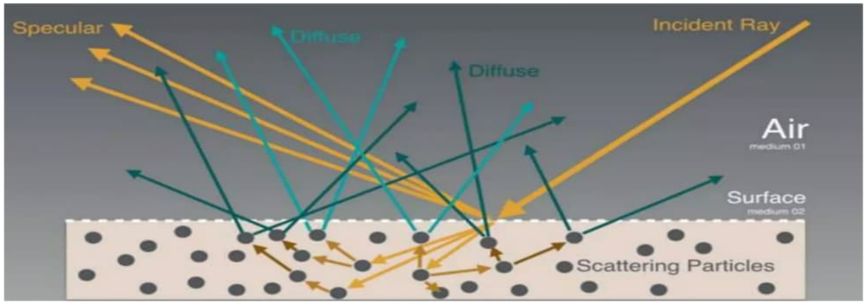
Examples





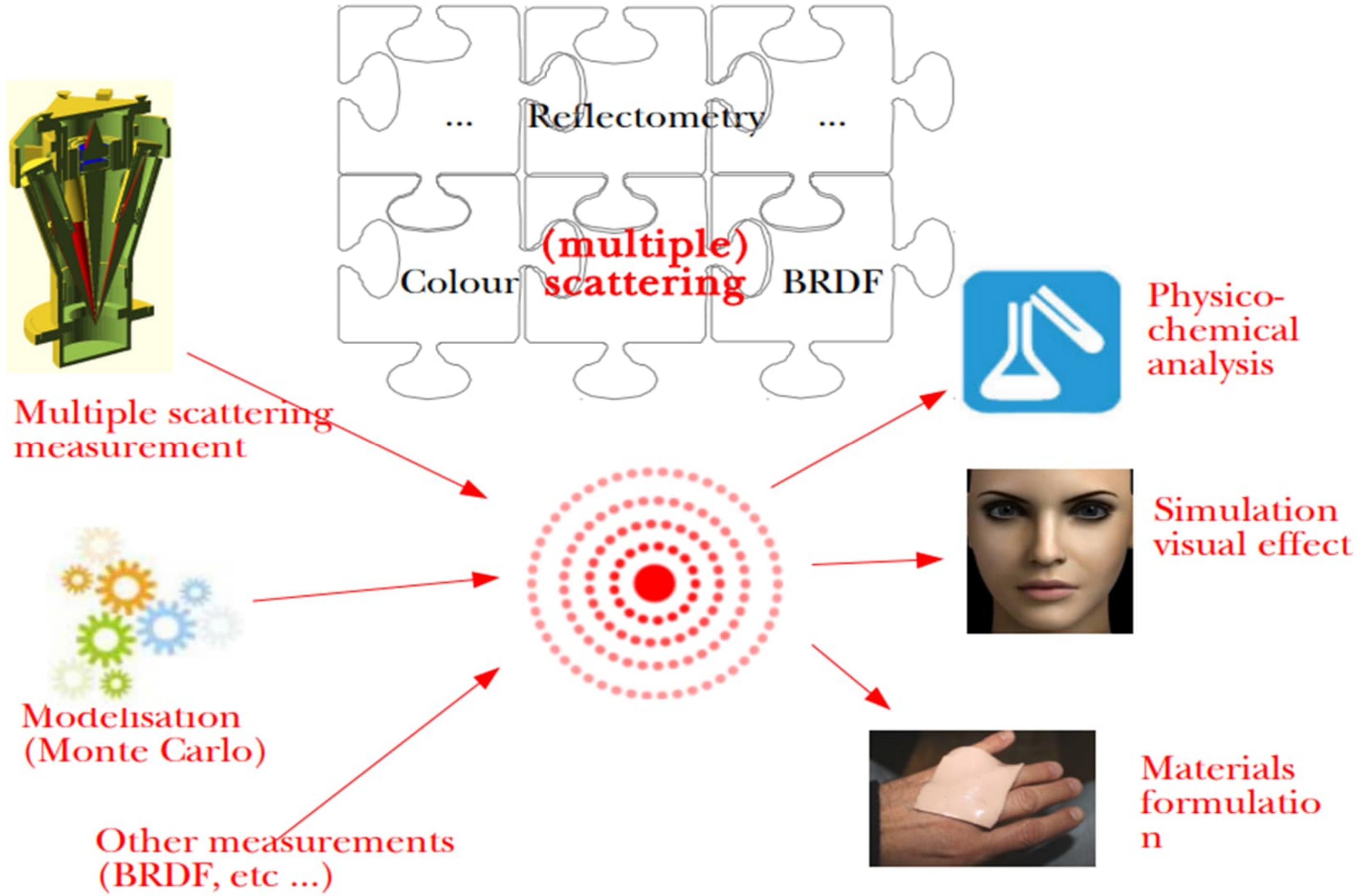
❖ How can we compute BRDFs for use in the general BRDF lighting equation?
  - Evaluate mathematical functions derived from analytical models.
  - Resample BRDF data acquired by empirical measurements of real-world surfaces.

Improvement for BRDF



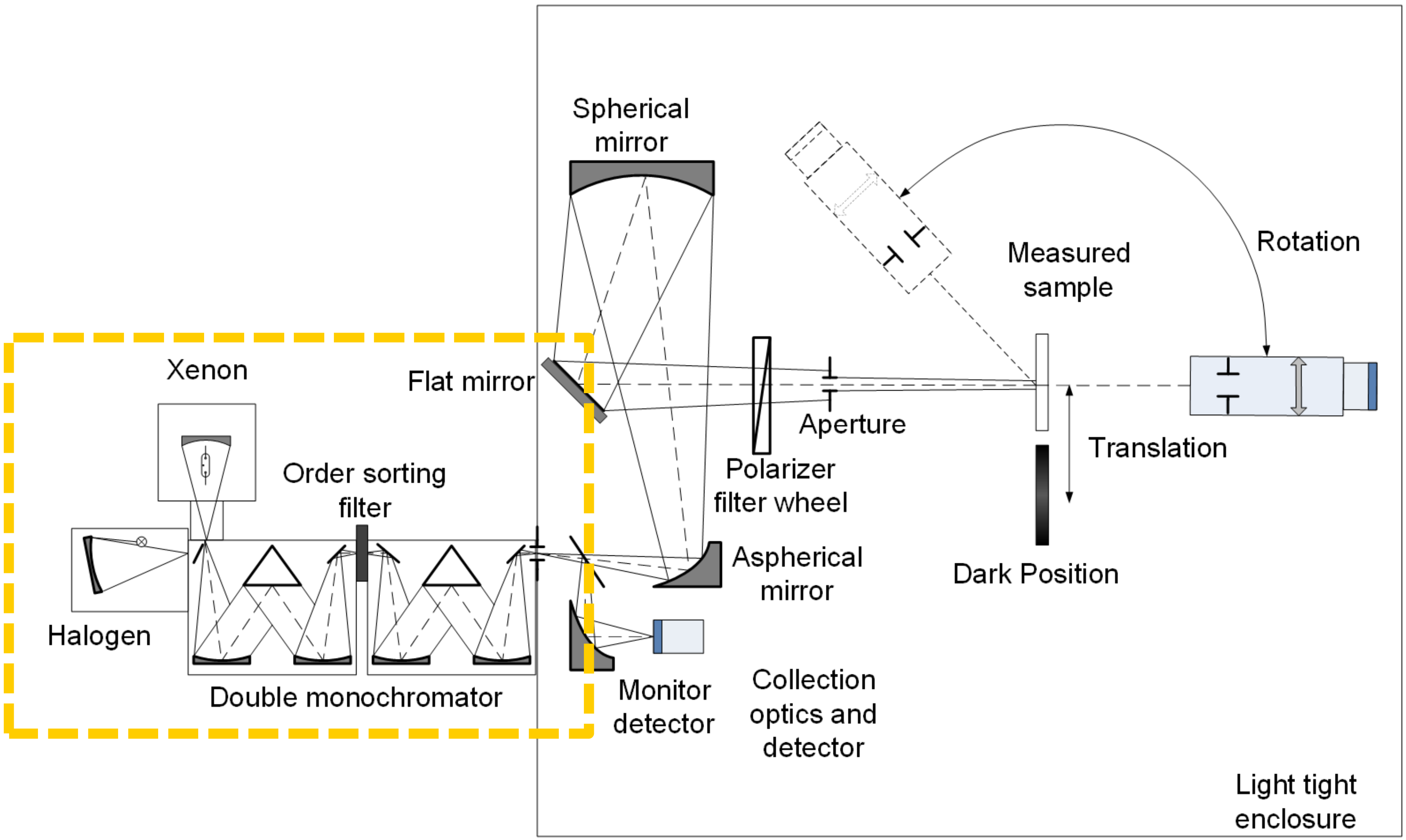
BRDF vs BSSRDF

Future of BRDF studies



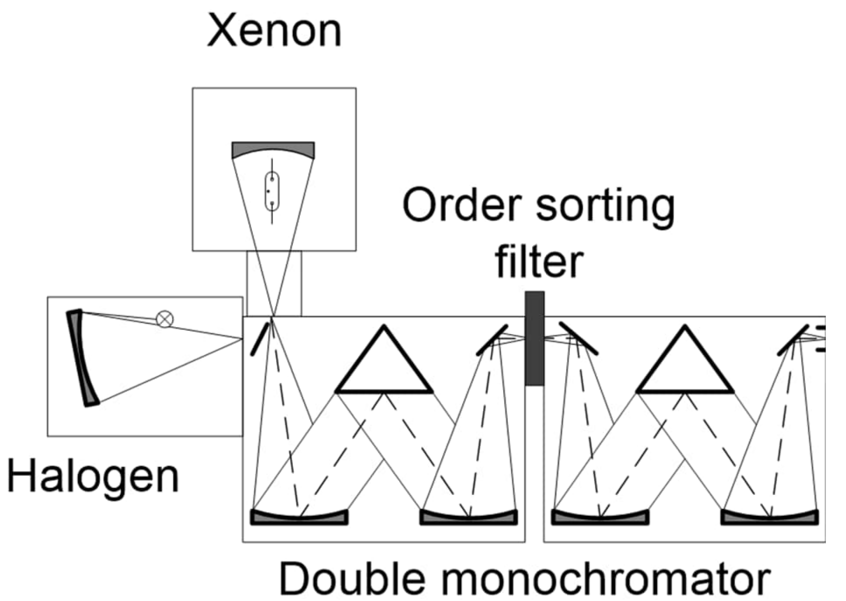
Gonioreflectometer

MRI Gonioreflectometer

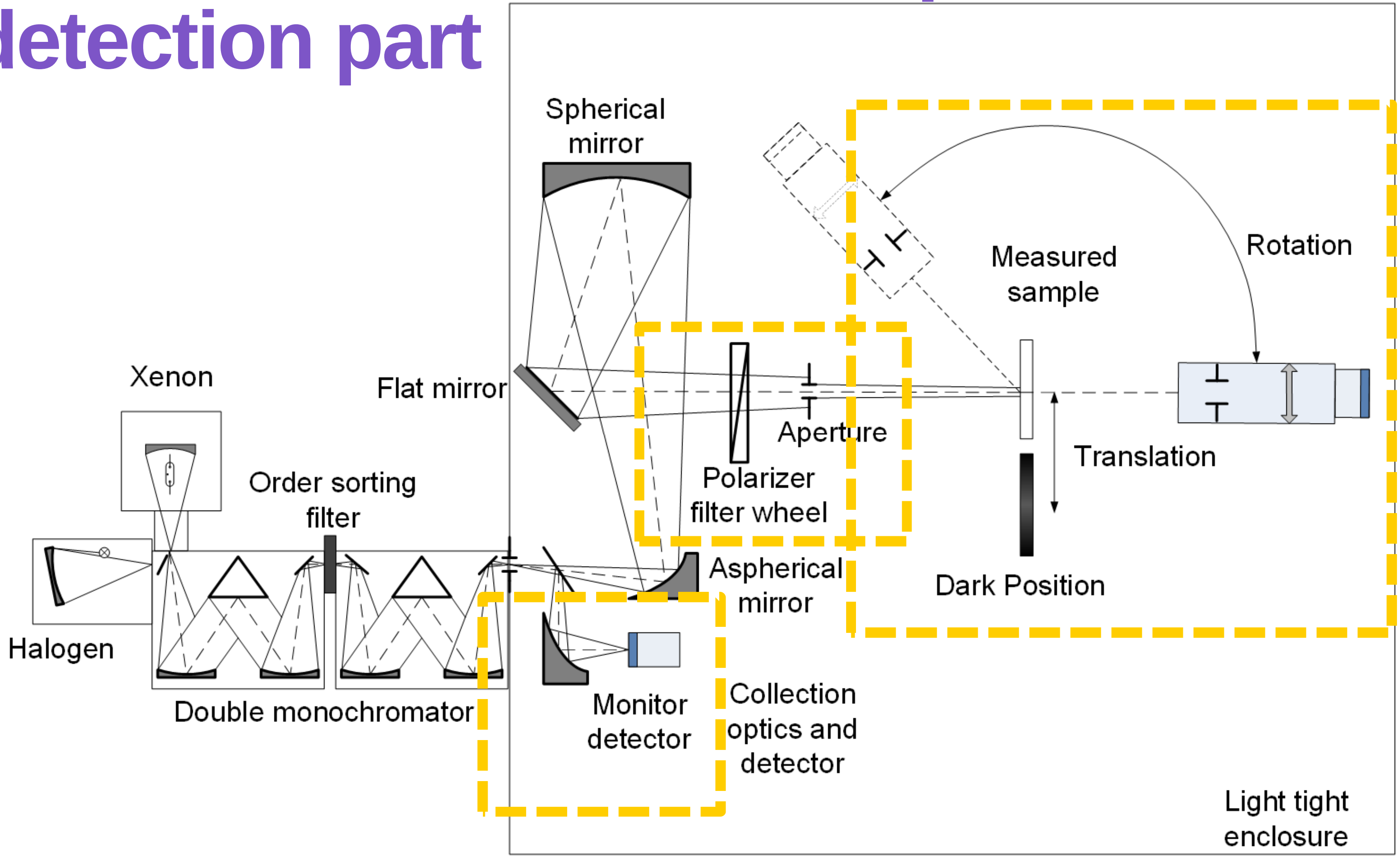


Gonioreflectometer illumination part

- **Xe lamp:**
  - Xenon
  - 450 W
  - 360-450 nm
- **Ha lamp:**
  - Quartz-tungsten-halogen
  - 50 W
  - 450-1650 nm

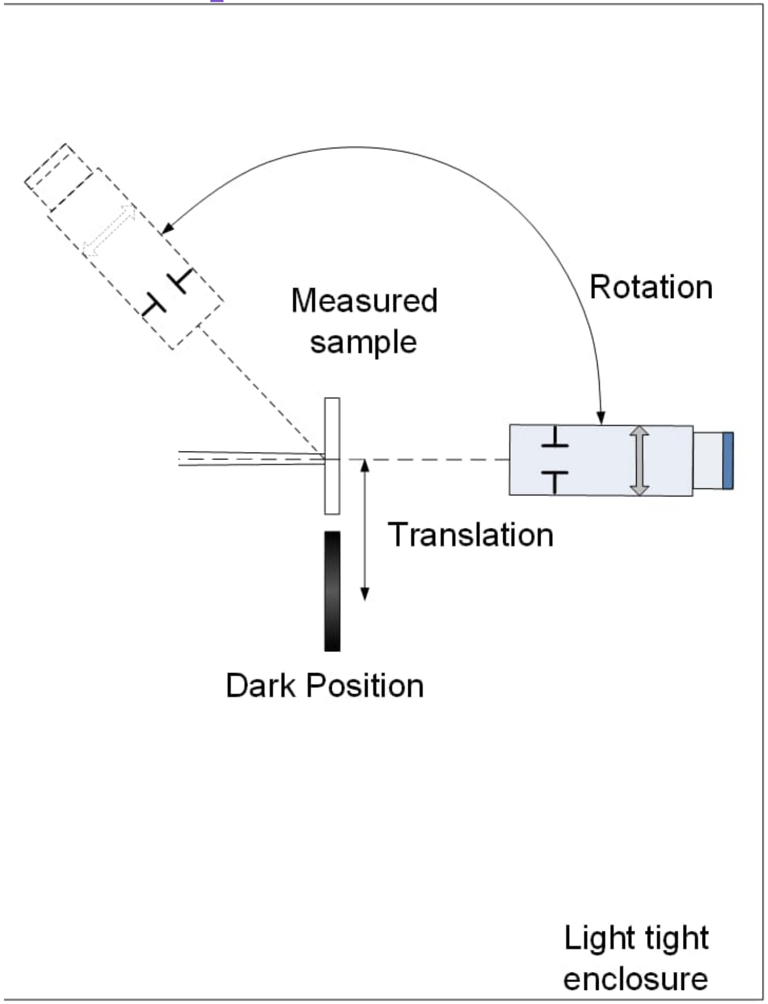


MRI Gonioreflectometer optics and detection part



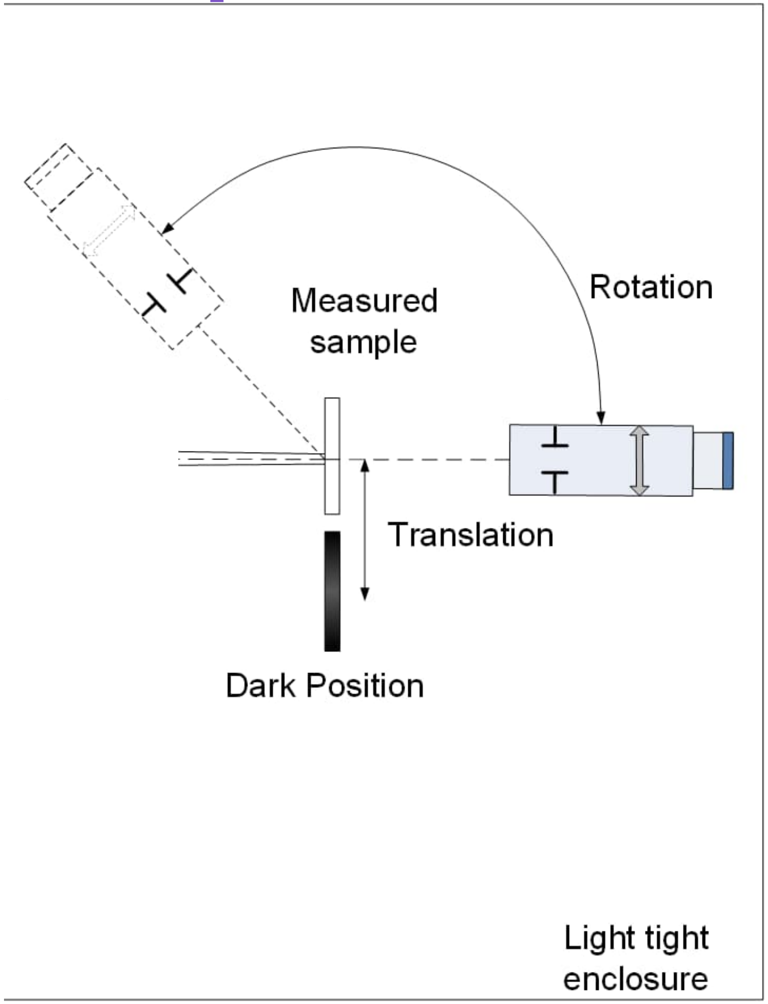
MRI Gonioreflectometer optics and detection part

- Variable beam size
- Sample translation stage:
  - Setting the incident angle
  - Full and dark signal measurements
- Viewing angles from -85 ° to 85 °
  - -10 ° to 10 ° blocked due to the detector



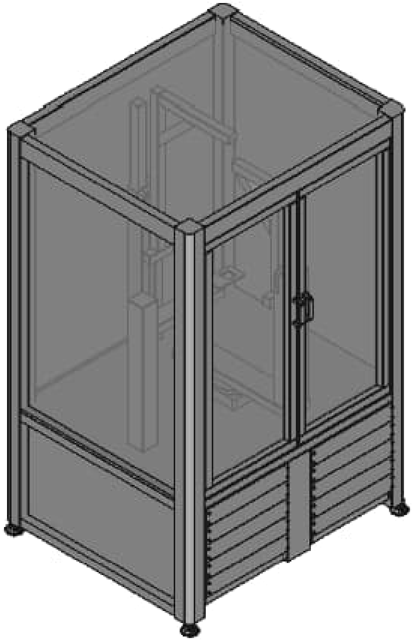
MRI Gonioreflectometer optics and detection part

- Sample-to-detector - aperture distance = 498.15 mm
- Aperture diameter = 25 mm^2
- Solid angle = 0.0022 sr^-1
- Detector diodes:
  - Silicon 10x10 mm
  - InGaAs 5 mm diameter
  - Underfilled

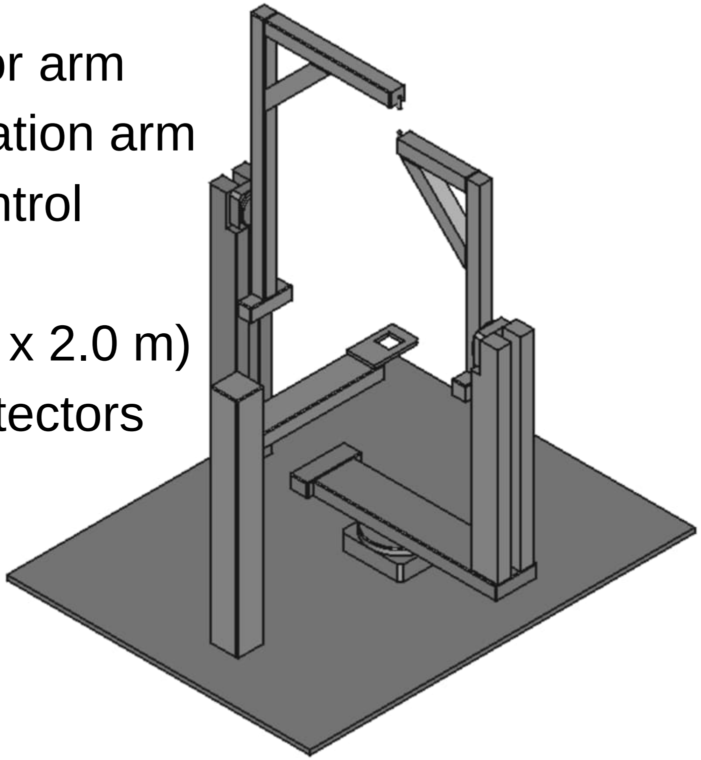


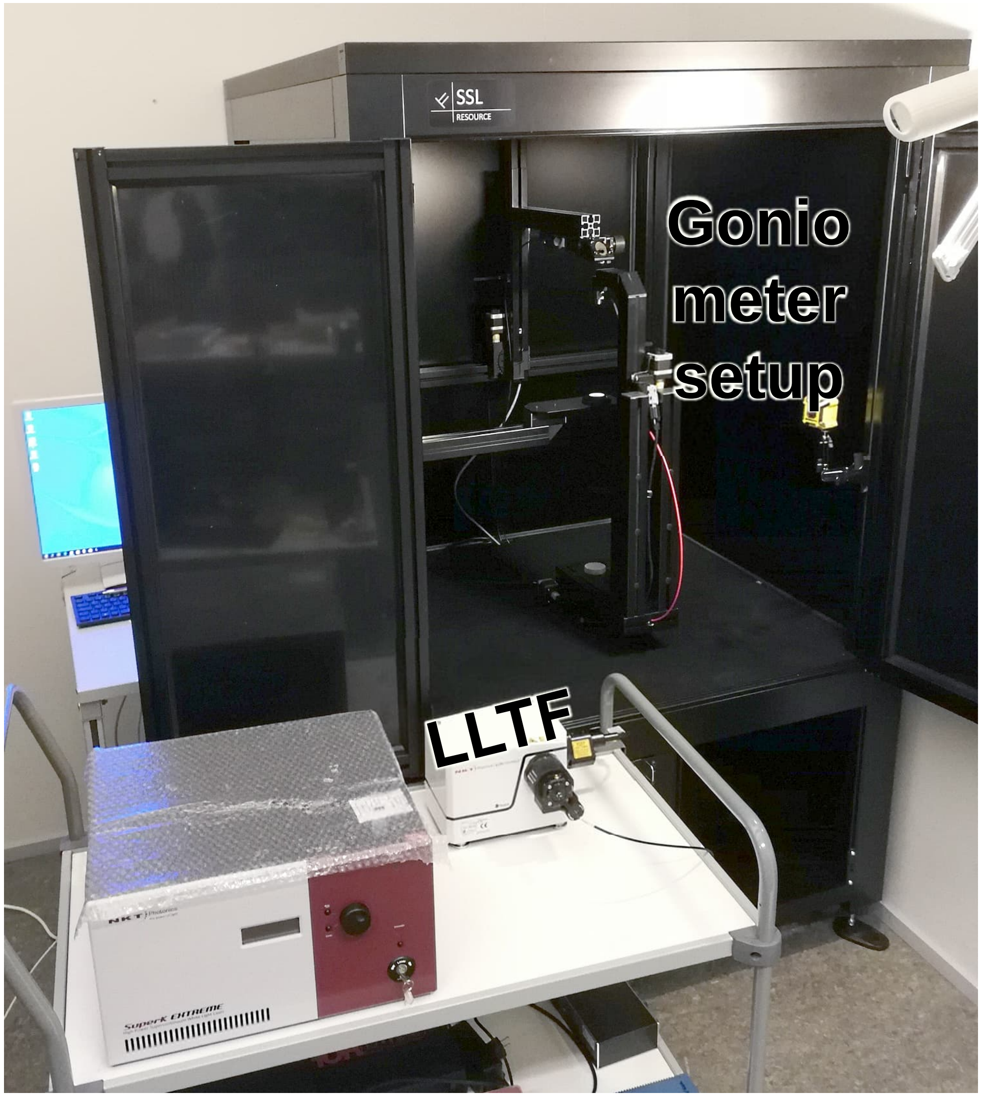
3D goniometer

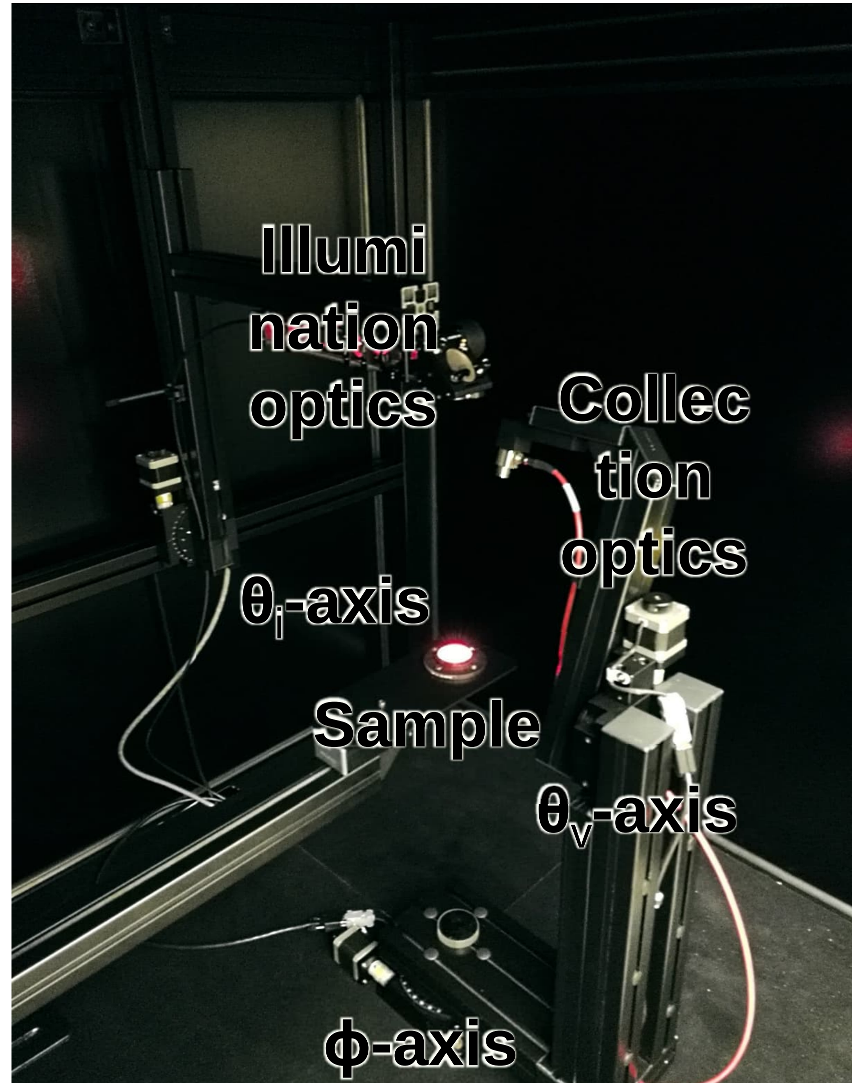
3D goniometer design



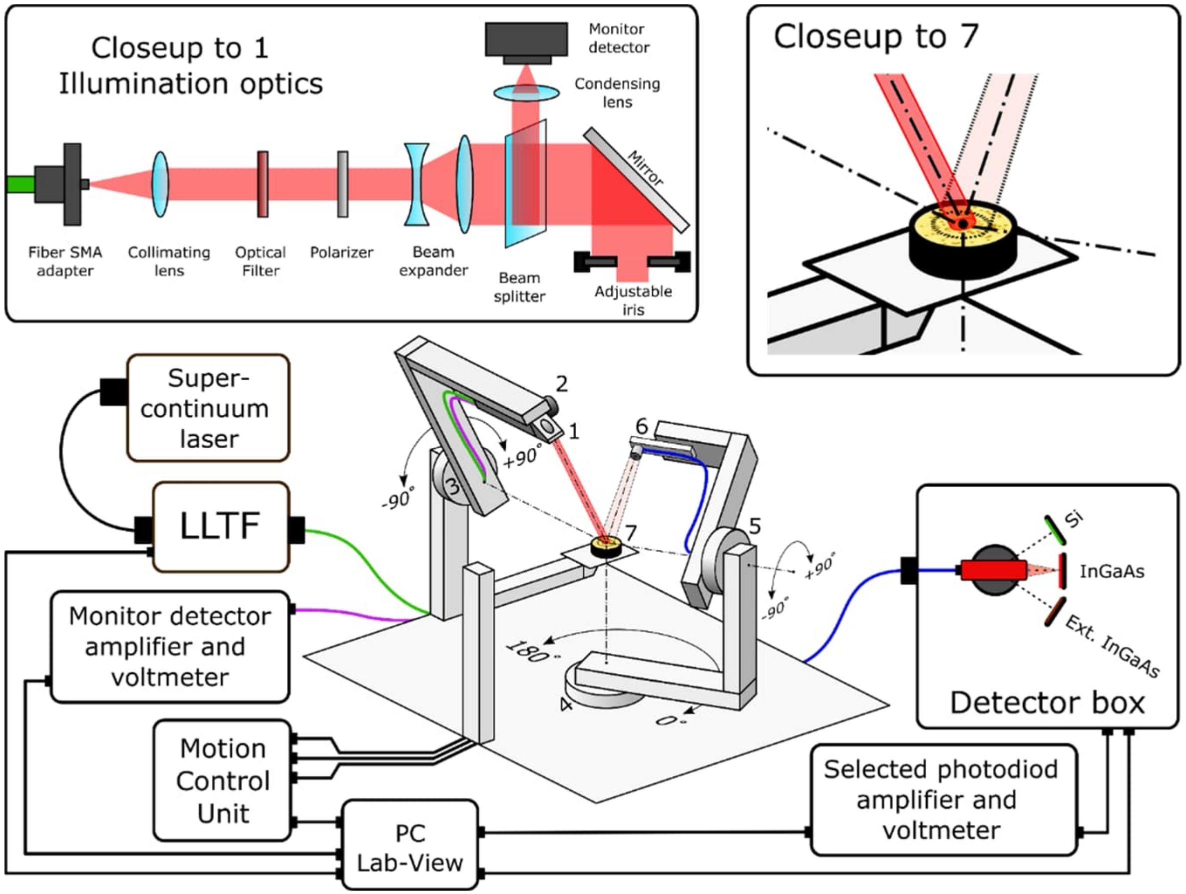
- 2-axis motorized detector arm
- 1-axis motorized illumination arm
- 3-axis stepper motor control
- Sample holder
- Dark box (1.1 m x 1.0 m x 2.0 m)
- Si, InGaAs, InGaAs+ detectors
- Detector optics
- Light source – NKT supercontinuum laser
- Light source optics




Gonio
meter
setup
LLTF
SSL
RESOURCE
SuperK EXTREME


Illumi
nation
optics
Collec
tion
optics
θ_i-axis
Sample
θ_v-axis
ϕ-axis

3D goniometer setup



Commercial Goniometer

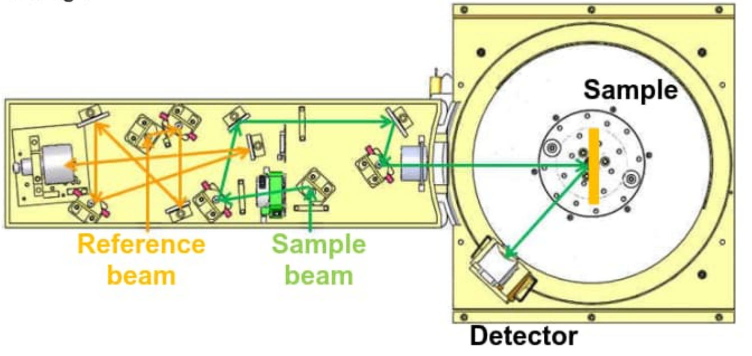
Cary 7000 UMS

What is a UMA?

UMA - Universal Measurement Accessory

Firmware driven

- Operates in normal double beam mode
- reduced slit height



Agilent Technologies

Agilent Restricted

Uncertainty

Uncertainty components

Source of uncertainty	Standard uncertainty		Uncertainty in Radiance factor/ %	
	VIS	NIR	VIS	NIR
Measurement noise	0.29%	0.10%	0.29	0.10
Instrument stability	0.13%	0.12%	0.13	0.12
Wavelength	0.1 nm	0.2 nm	0.15	0.26
Straylight (isochromatic)	0.14%	0.04%	0.14	0.04
Solid angle (due to sample-detector distance and detector aperture diameter)	0.15 mm 2 µm	0.15 mm 2 µm	0.06 0.02	0.06 0.02
Detector nonlinearity	0.04%	0.09%	0.07	0.13
Spatial nonuniformity	0.10%	0.06%	0.1	0.06
Illumination and viewing angles	0.10°	0.15°	0.02-0.3	0.04-0.4
Polarization	0.10 %	0.10%	0.1	0.1
Combined standard uncertainty			0.41-0.51	0.36-0.53

Type A

Measurements

400	0.311706	0.310599	0.312961
500	0.321732	0.321902	0.321831
600	0.322052	0.322093	0.322150
700	0.322283	0.322174	0.322156

Type A uncertainty (repeatability):

Instrument stability	0.13%

STDEV	Average*0.0013
0.00118	0.00041
0.00009	0.00042
0.00005	0.00042
0.00007	0.00042

Quadratic Sum →

Type A
0.0012
0.0004
0.0004
0.0004

Type B and total uncertainty

Measurements

vza	s-pol						vza	p-pol						vza	unpol			
	400	500	600	700				400	500	600	700				400	500	600	700
45	0.3210	0.3238	0.3239	0.3241			45	0.3181	0.3192	0.3191	0.3189			45	0.3195	0.3215	0.3215	0.3215

Type B (wavelength and polarization):

Wavelength	0.1 nm

Wavelength uncertainty			
400	500	600	700
0.000002	0.000001	0.0000002	0.0000002

Polarization	0.10 %

Polarization uncertainty			
400	500	600	700
0.00001	0.00001	0.00001	0.00001

Total uncertainty: $\sqrt{A^2 + B^2}$

↓

$$\sqrt{Pol^2 + Wav^2}$$

If K=2, then multiply to 2

Thank you!