Development of a robot-based gonioreflectometer

Based on INMS Lecture by Réjean Baribeau on 29 May 2008

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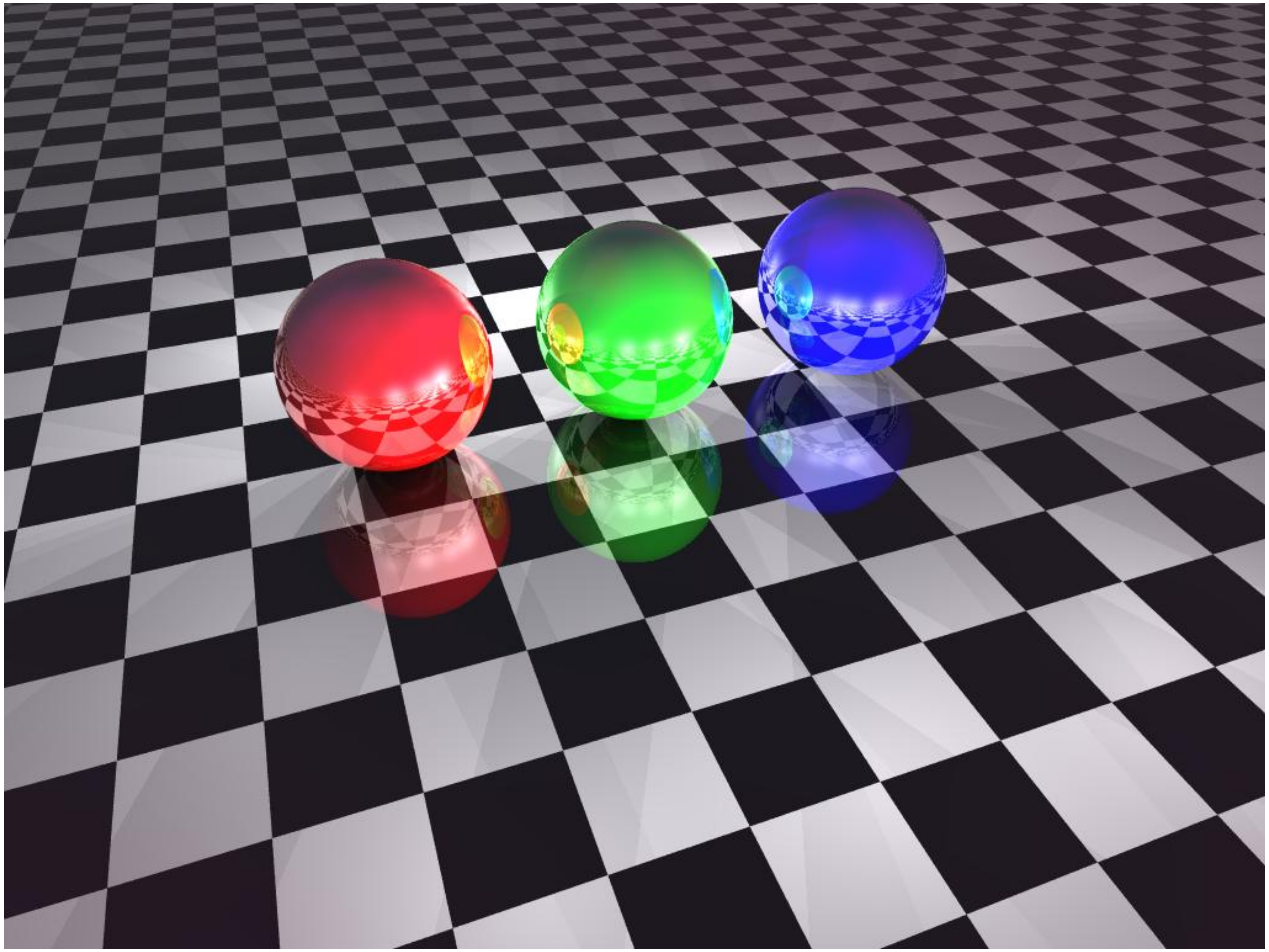
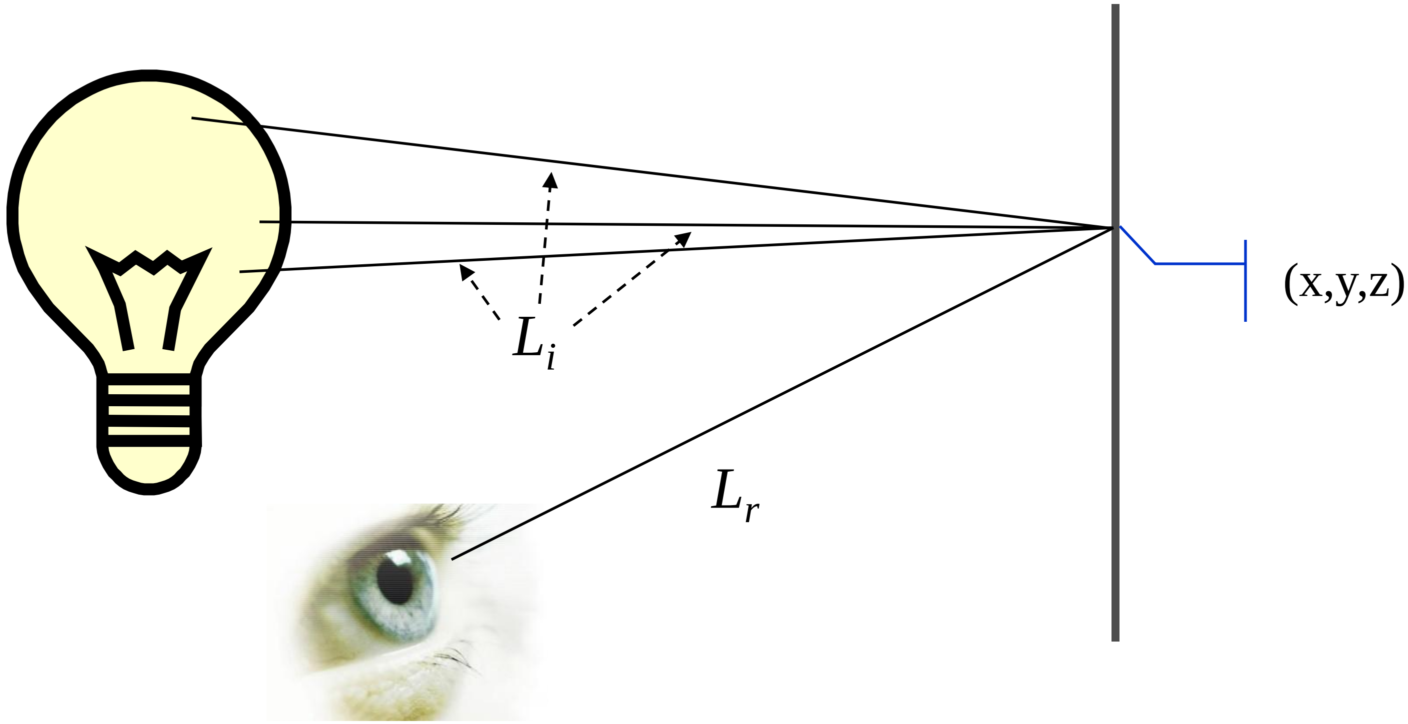
Outline

- Rendering a non-physical scene
- The concept of BRDF from rendering equation
- BRDF measurement from first principles
- The NRC robot-based gonioreflectometer
- A look at the applications

Computer rendering of a 3D scene

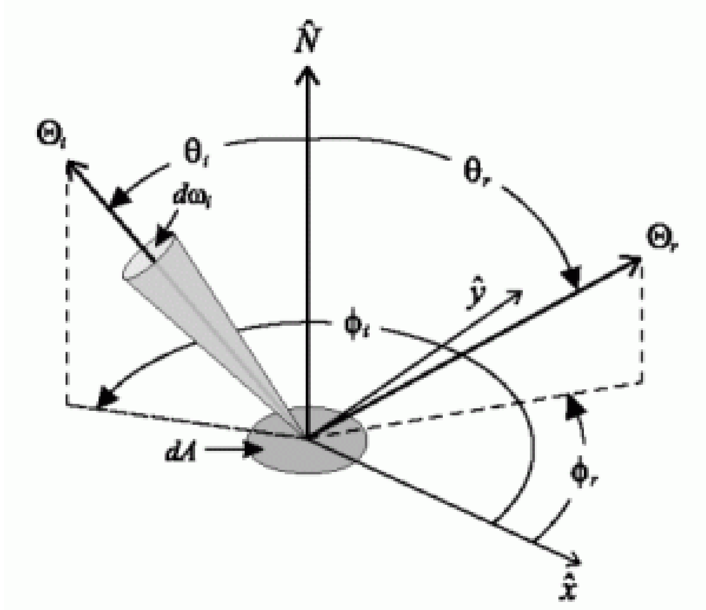


The rendering equation



$$L_r(\theta_r,\varphi_r;\lambda,x,y,z)=\int \underbrace{f_r(\theta_i,\varphi_i,\theta_r,\varphi_r;\lambda,}_{\text{Bidirectional Reflectance Distribution Function (BRDF)}} x,y,z)L_i(\theta_i,\varphi_i;\lambda,x,y,z)\cos(\theta_i)\,d\omega_i+\text{emittance}$$

BRDF geometry



$$L_r(\theta_r,\varphi_r;\lambda) = \int \underbrace{f_r(\theta_i,\varphi_i,\theta_r,\varphi_r;\lambda)}_{\text{BRDF}} L_i(\theta_i,\varphi_i;\lambda)\cos(\theta_i)\,d\omega_i + \text{emittance}$$

BRDF seen as a differential

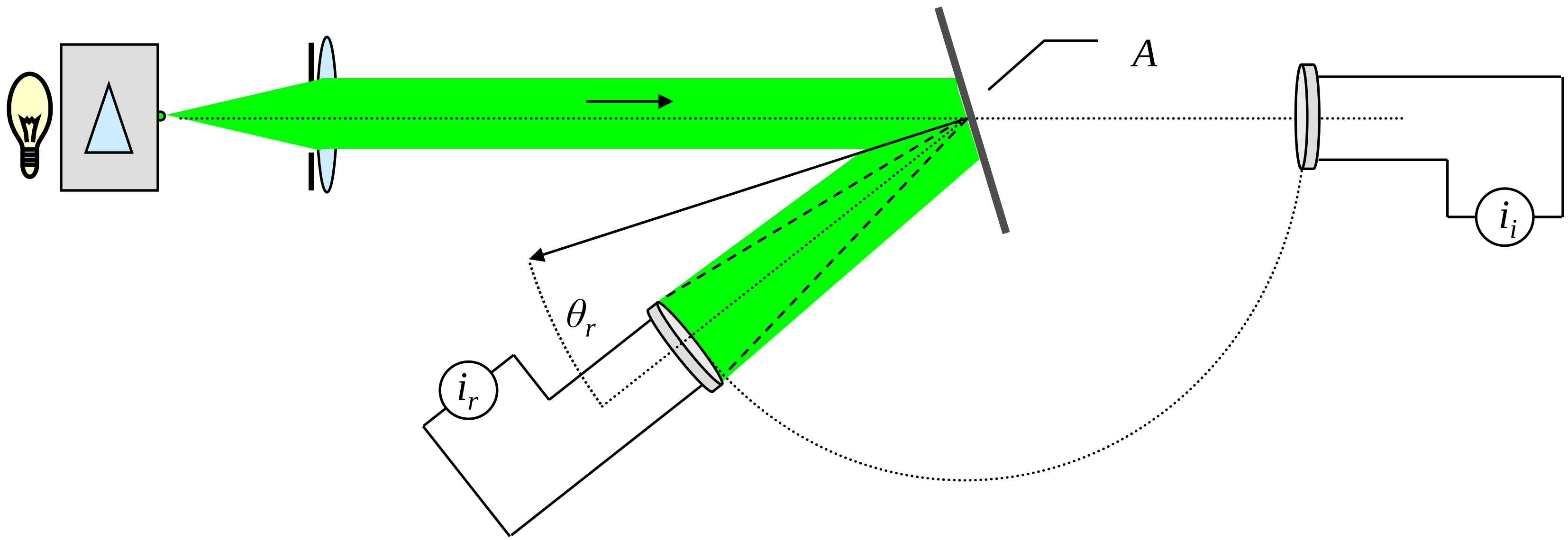
$$L_r(\theta_r,\varphi_r;\lambda) = \int f_r(\theta_i,\varphi_i,\theta_r,\varphi_r;\lambda)\underbrace{L_i(\theta_i,\varphi_i;\lambda)\cos(\theta_i)d\omega_i}_{dE_i}$$

$$L_r = \int \frac{dL_r}{dE_i} dE_i$$

$$f_r(\theta_i,\varphi_i,\theta_r,\varphi_r;\lambda) = \frac{dL_r}{dE_i}$$

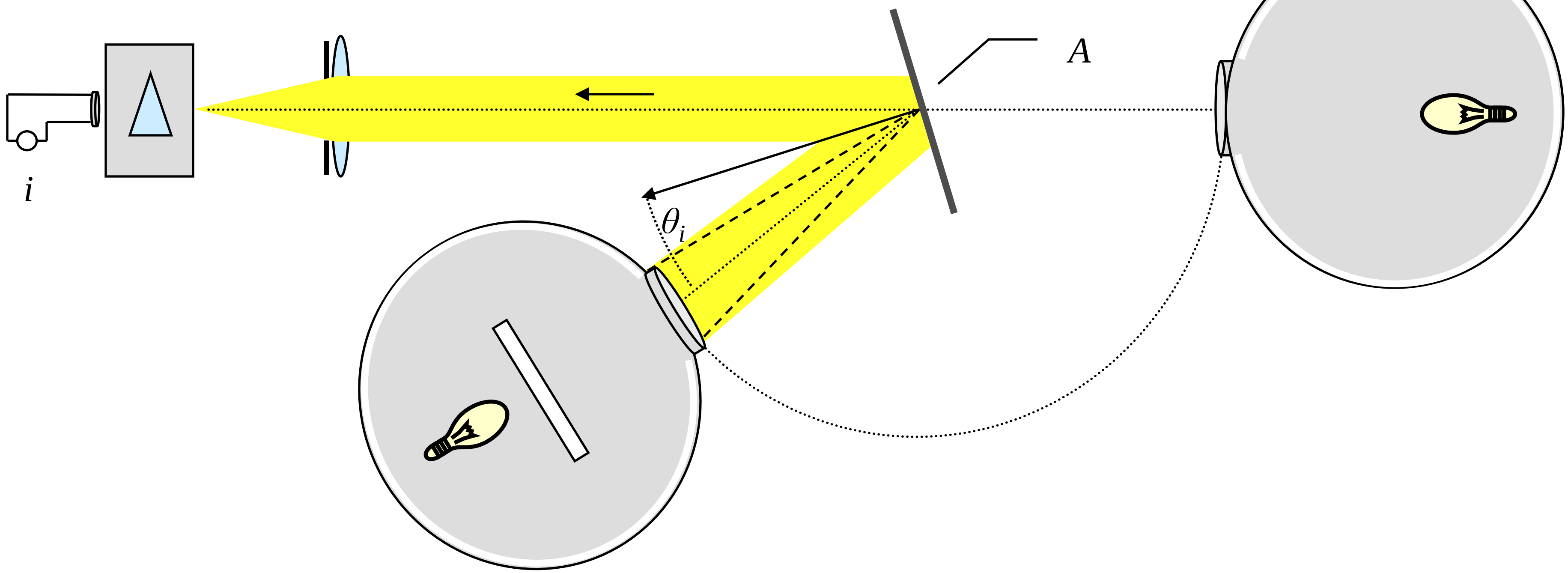
CIE definition

Measuring spectral BRDF from first principles: the monochromatic illumination approach



$$f_r = \frac{dL_r}{dE_i} \cong \frac{\Phi_r / \Omega A \cos\theta_r}{\Phi_i / A} = \frac{i_r}{i_i \Omega \cos\theta_r}$$

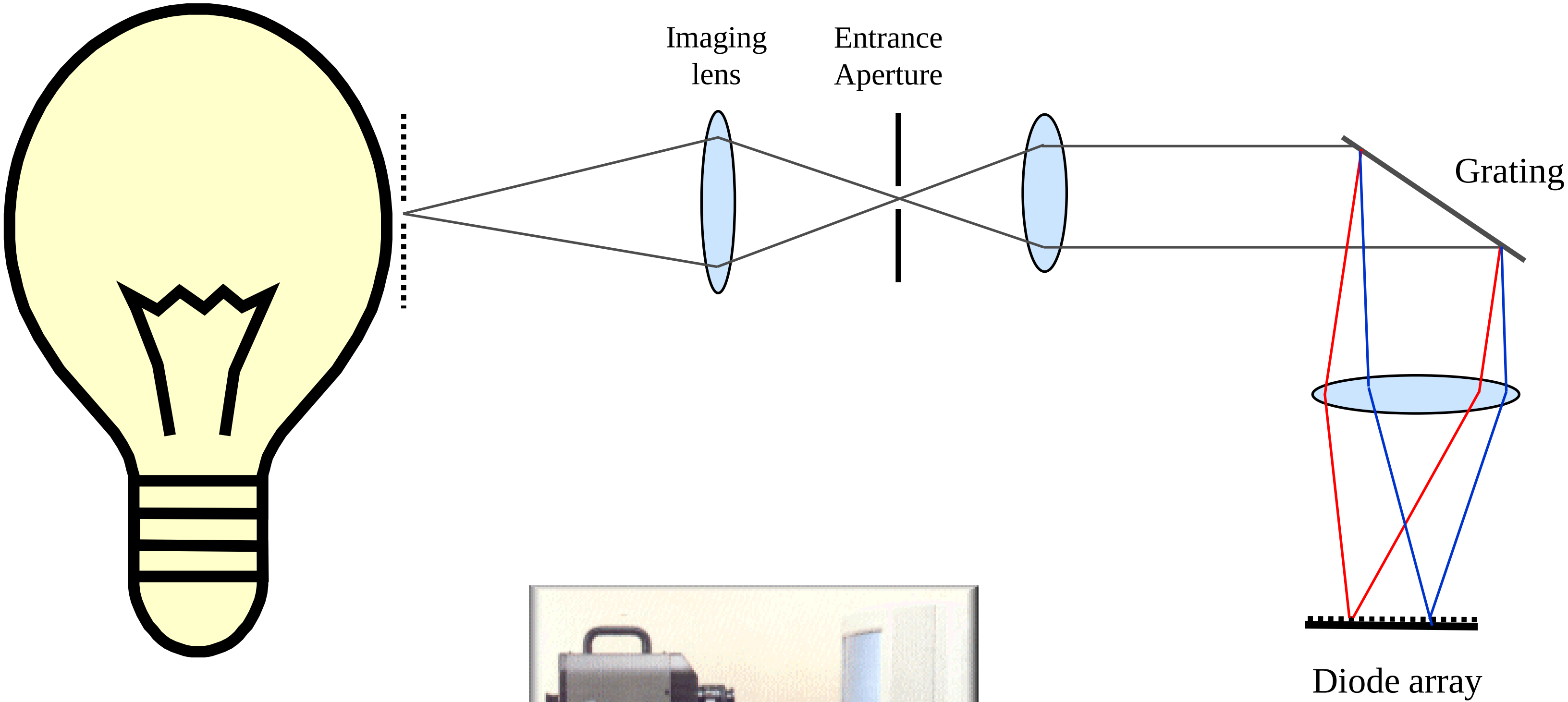
Measuring BRDF from first principles: illumination with white light

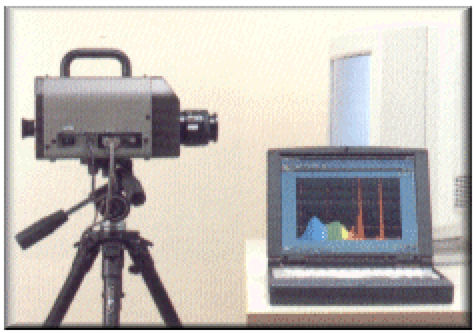


$$L_r = \int f_r L_i \cos\theta_i d\omega_i \cong f_r L_i \cos\theta_i \Omega$$

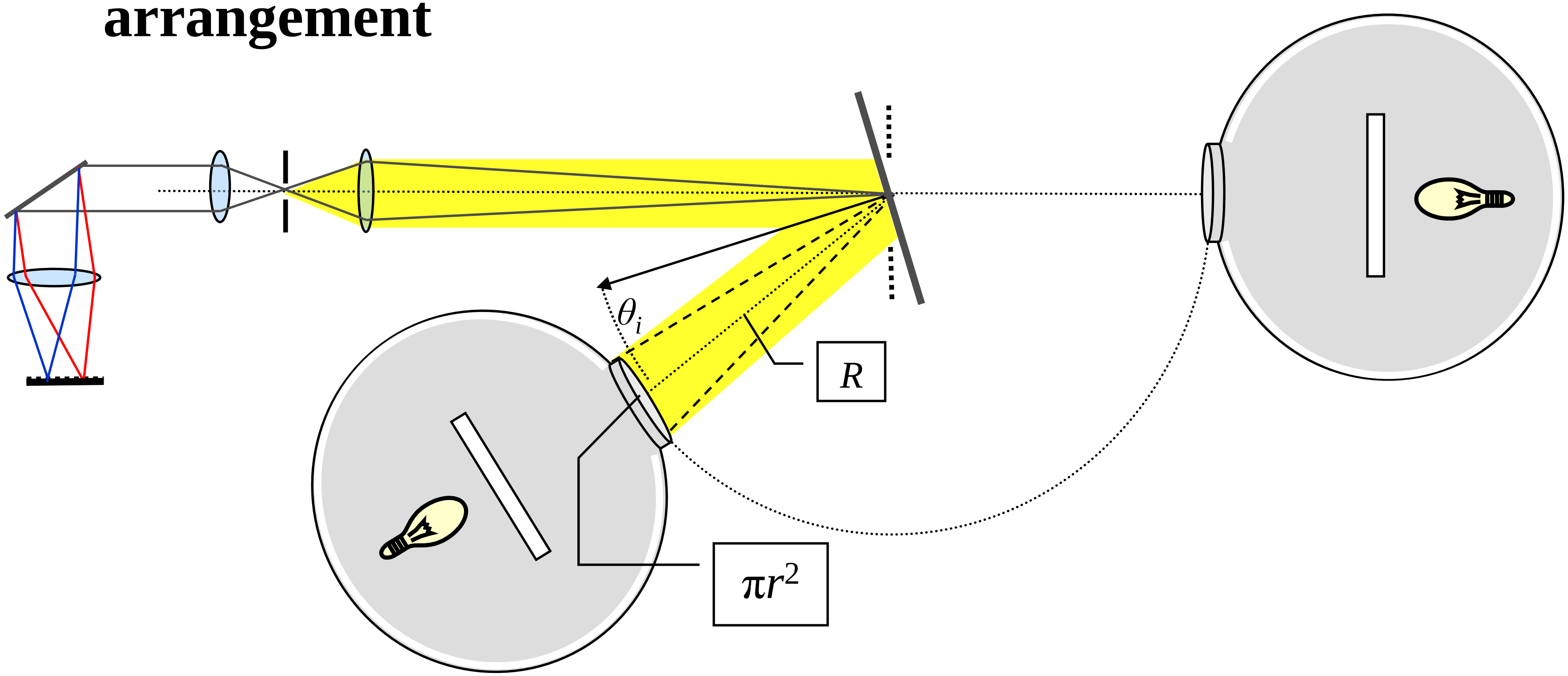
$$f_r = \frac{L_r}{L_i \cos\theta_i \Omega} = \frac{i_r}{i_i \cos\theta_i \Omega}$$

The diode array spectroradiometer



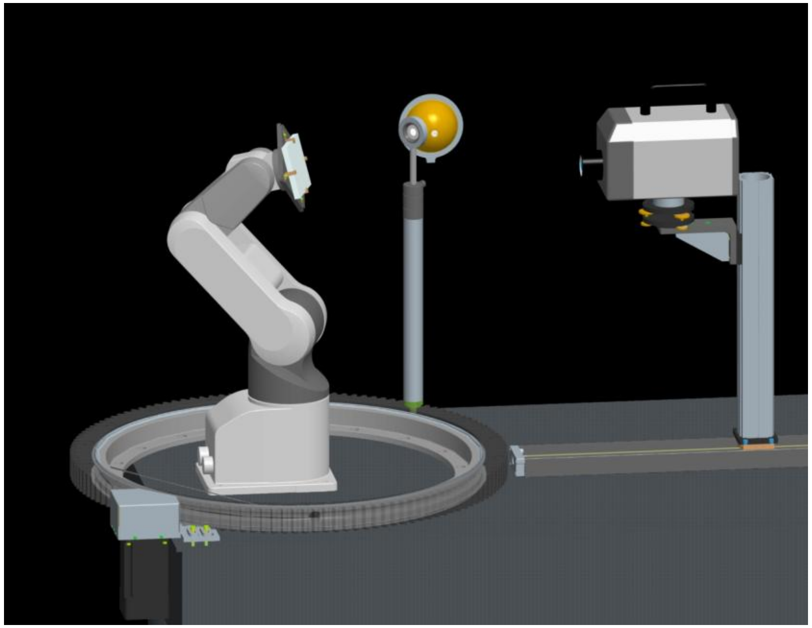


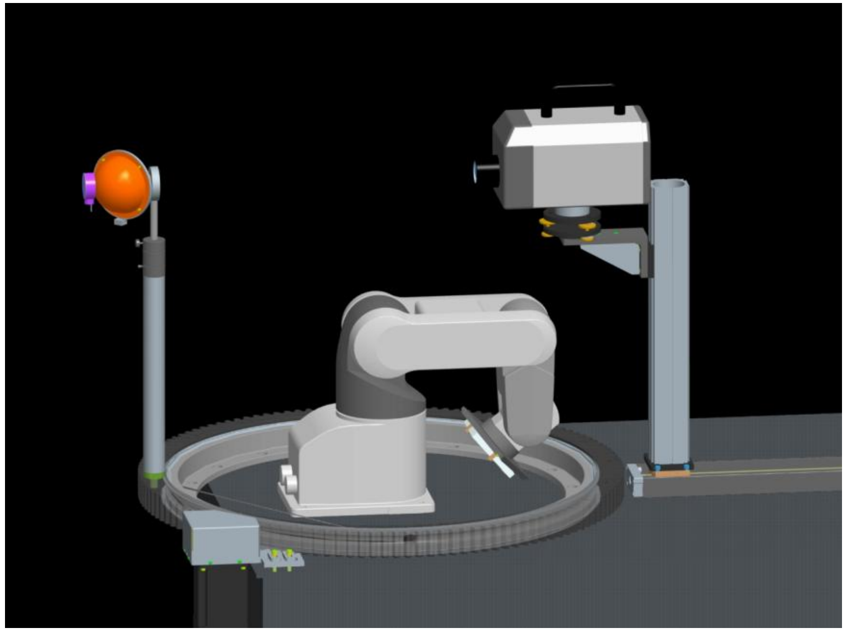
Measuring BRDF from first principles: the NRC arrangement



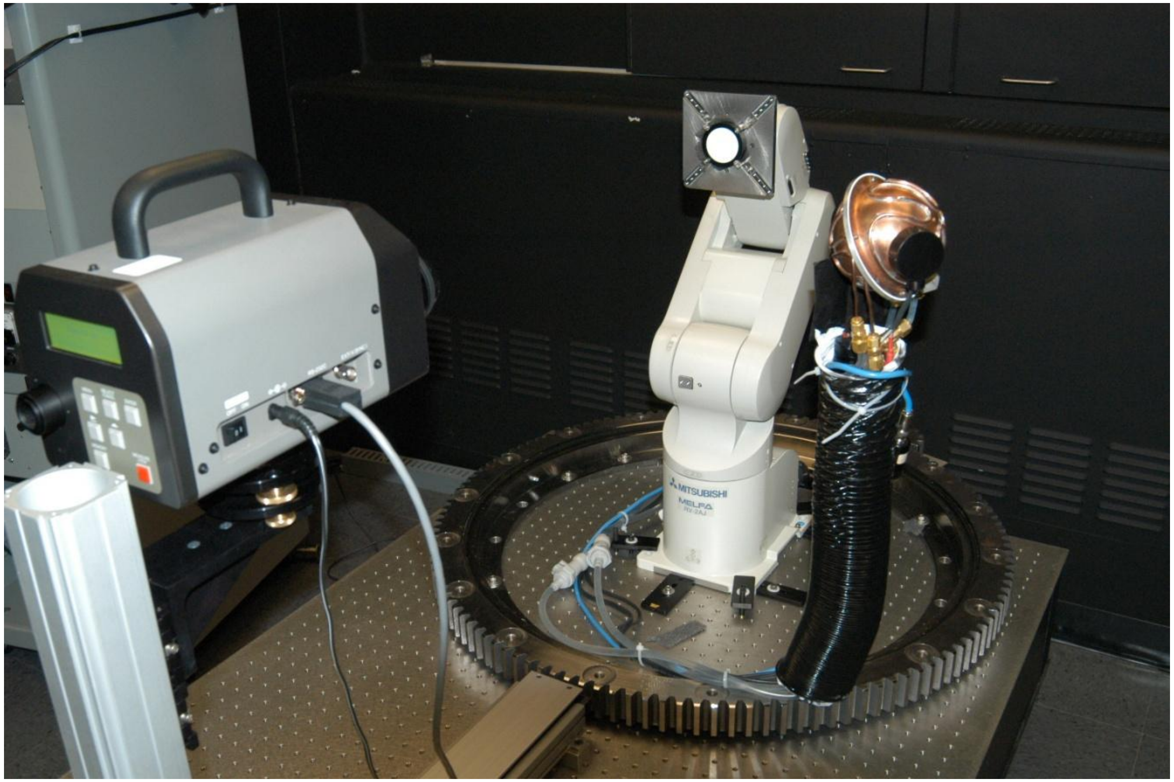
$$f_r = \frac{L_r}{L_i \cos\theta_i \Omega} = \frac{L_r}{L_i} \frac{1}{\cos\theta_i} \frac{R^2 + r^2}{\pi r^2}$$

The NRC system at the conceptual stage





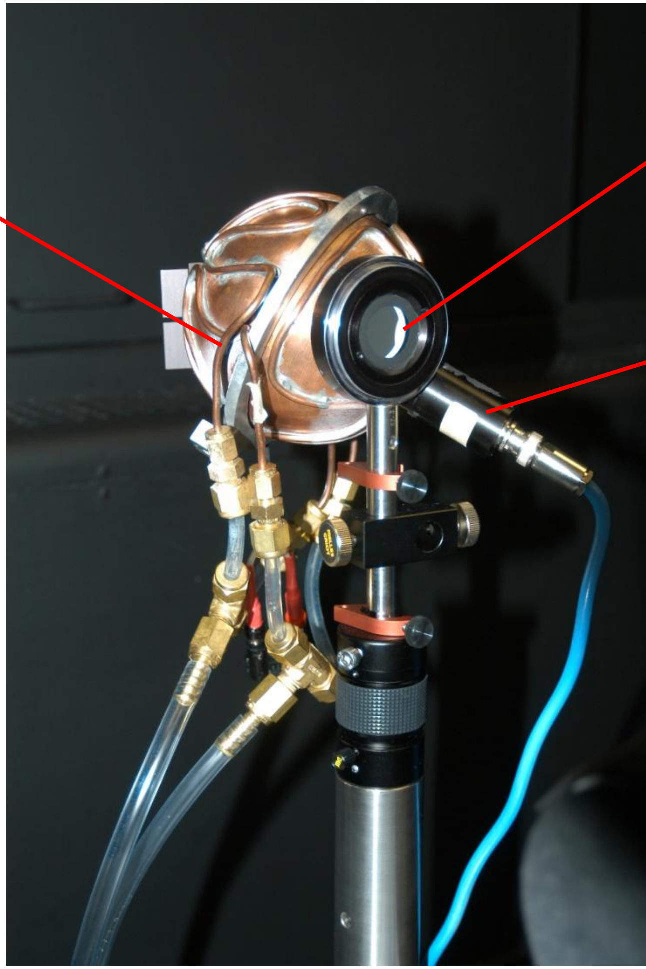
Laboratory setup



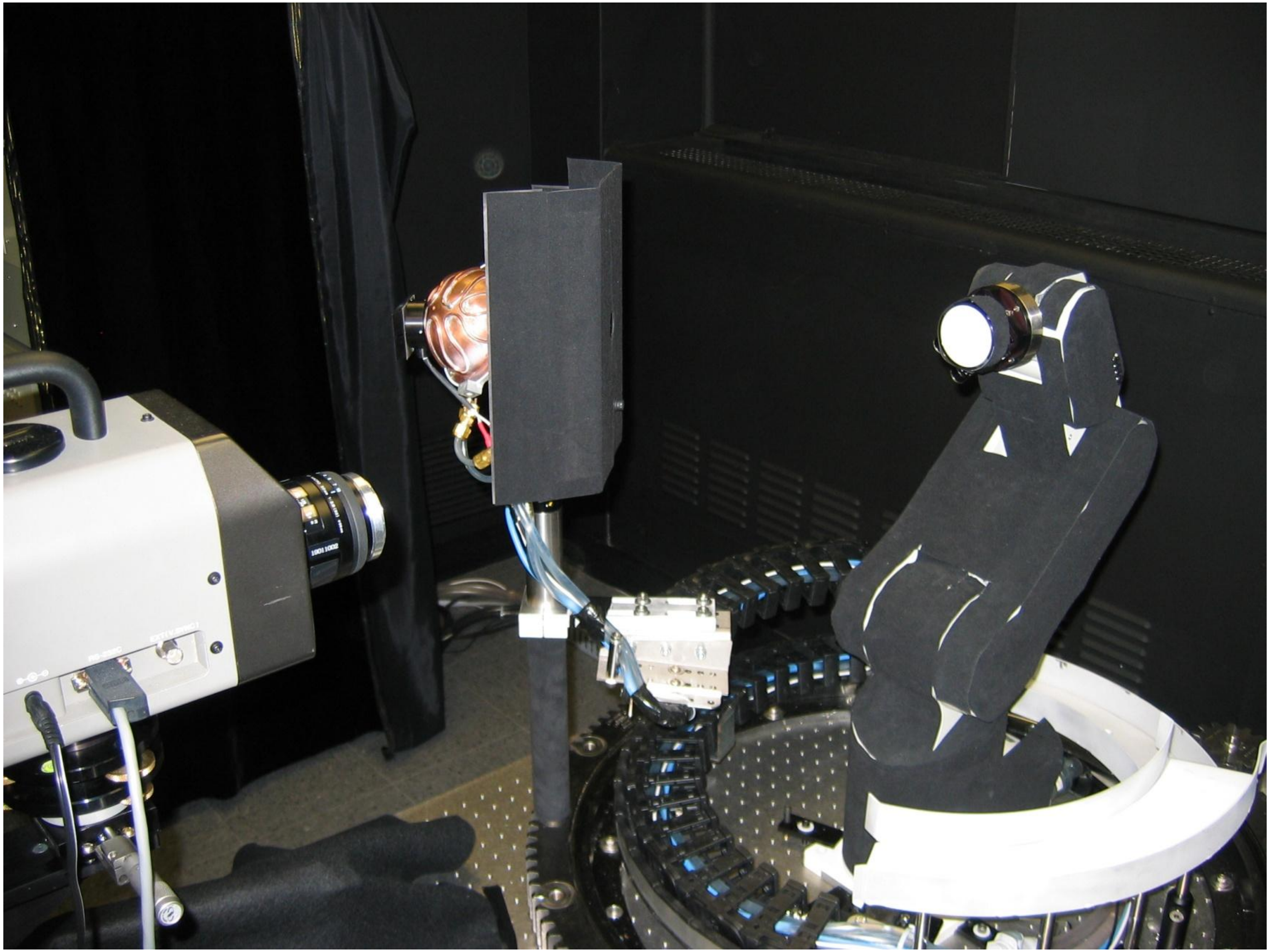
A closer look at the sphere

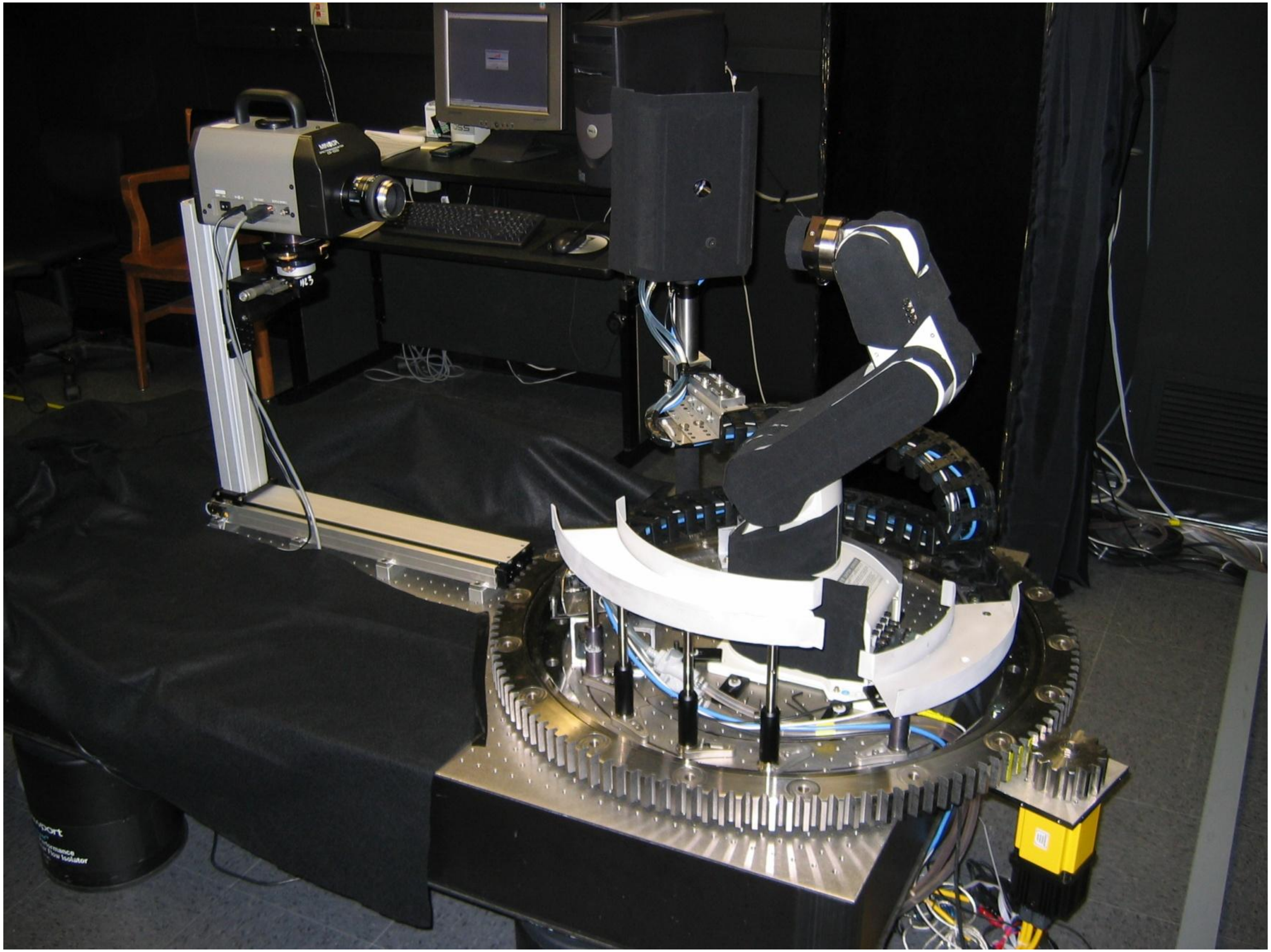
Water cooling

Precision
aperture

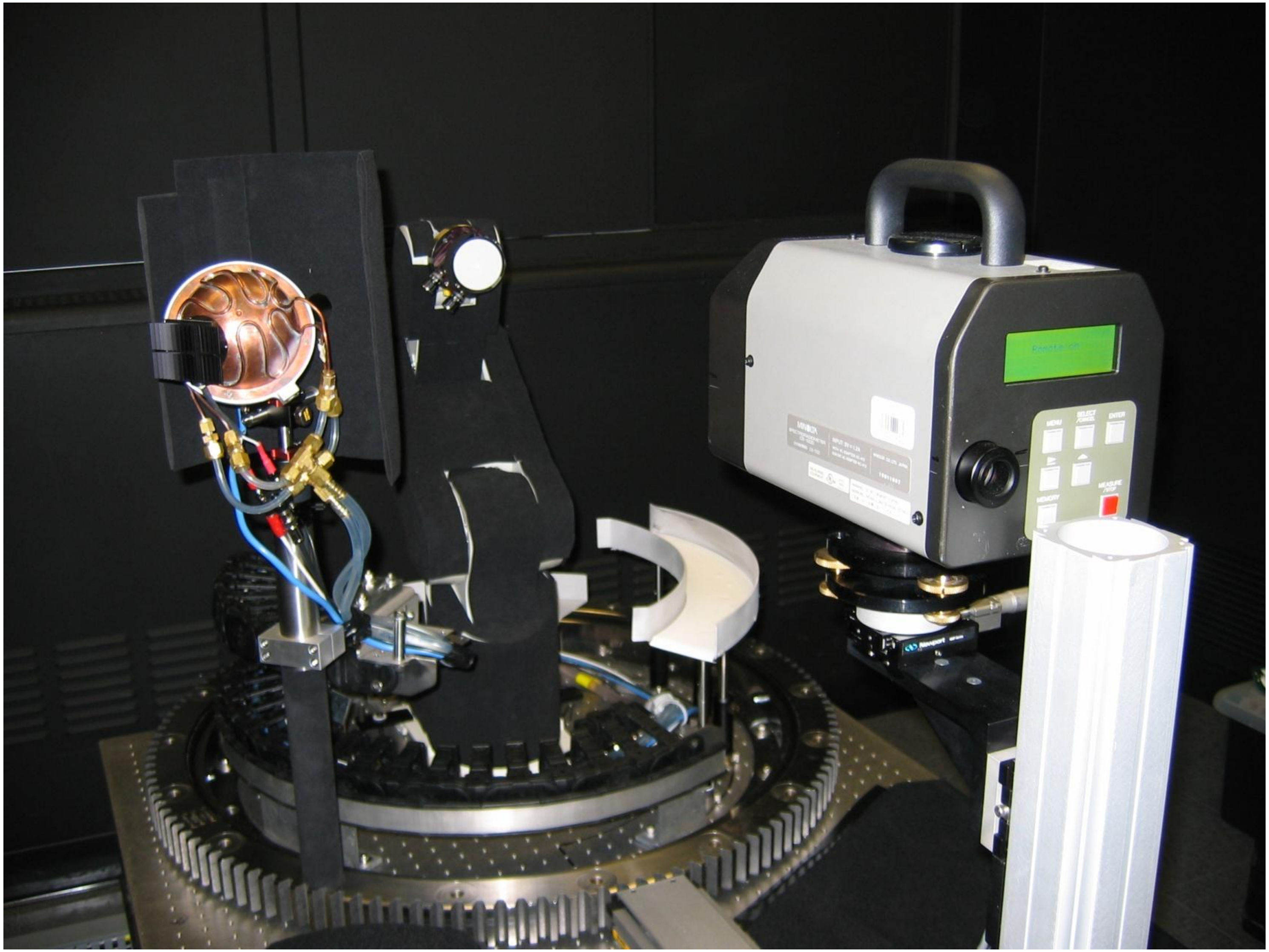


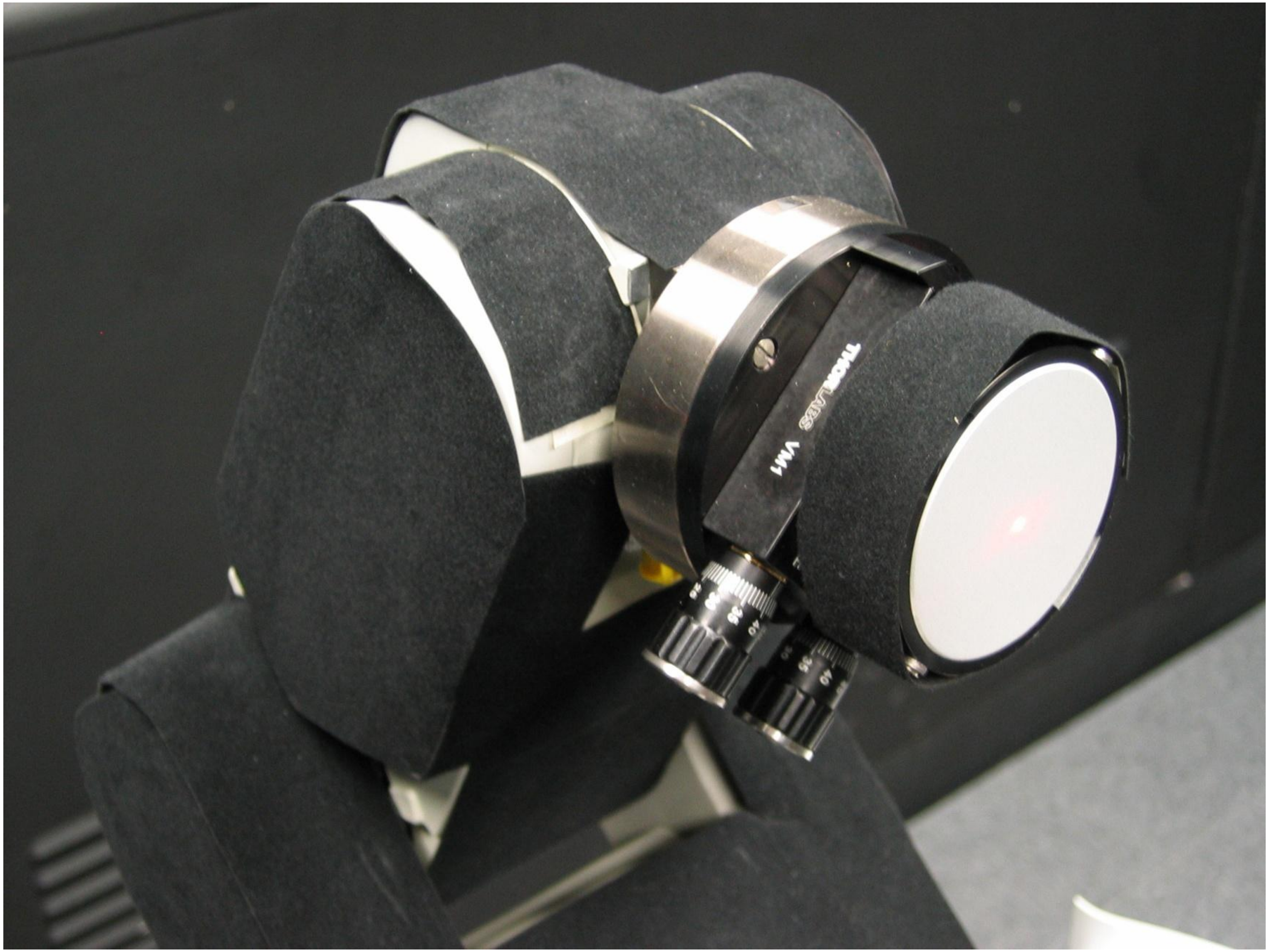
Monitoring
photodiode

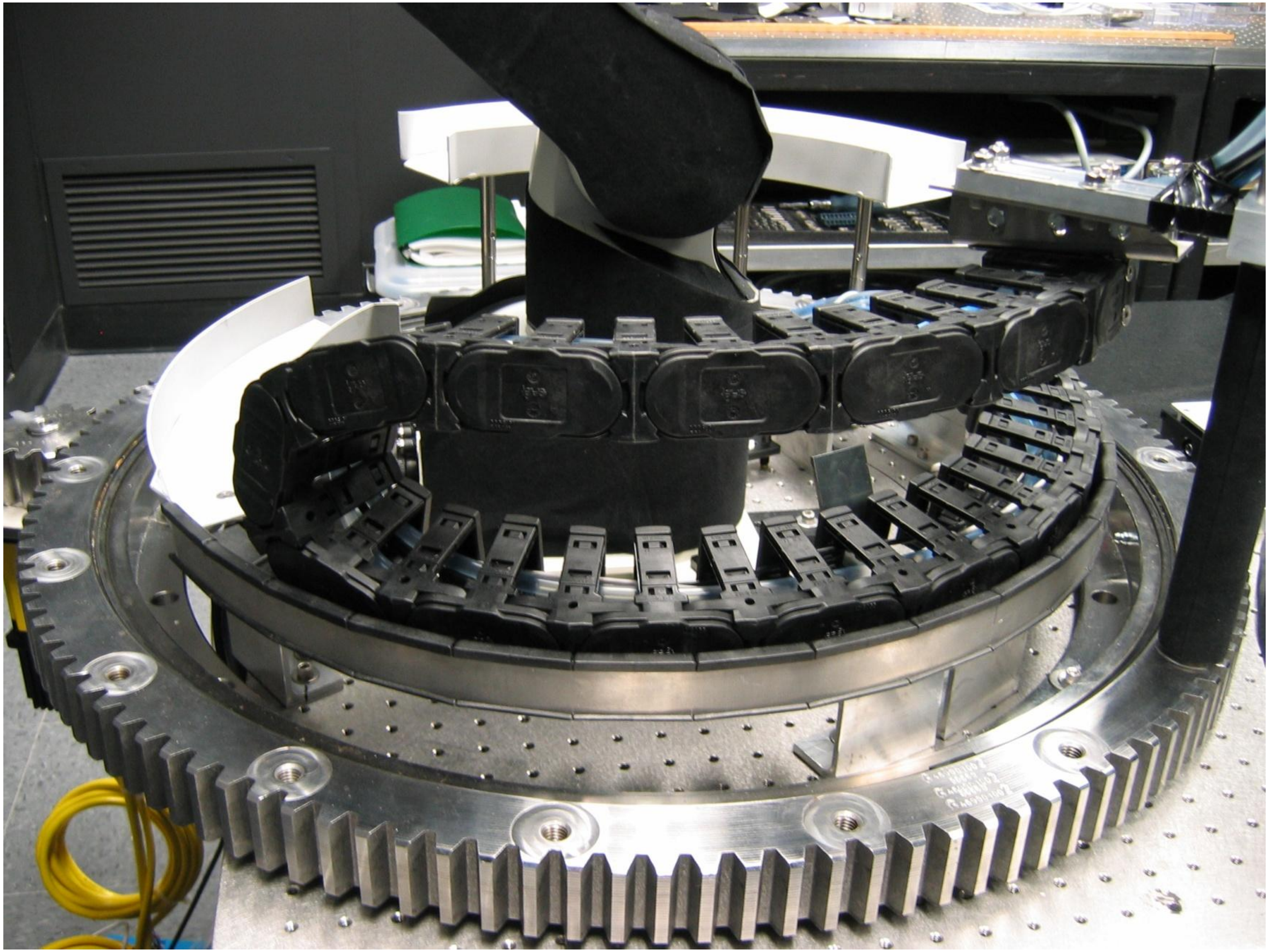





KOSS
SAMSUNG




VM1

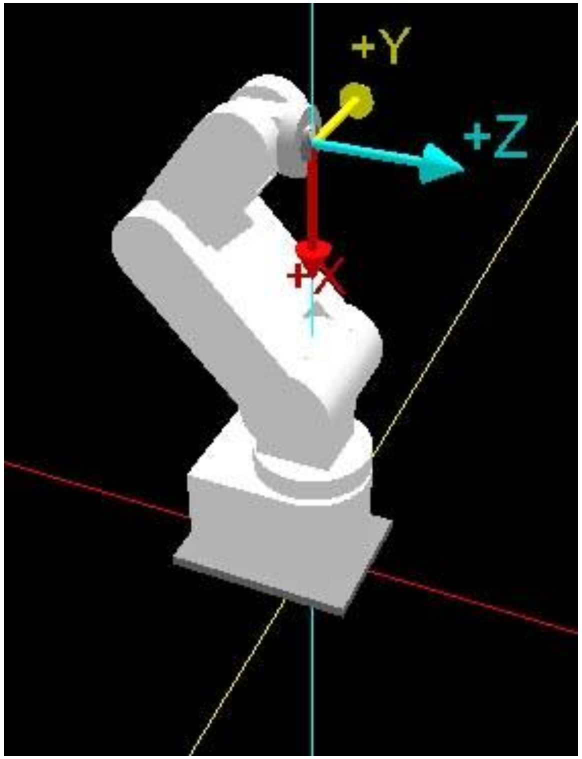


Some key parameter values

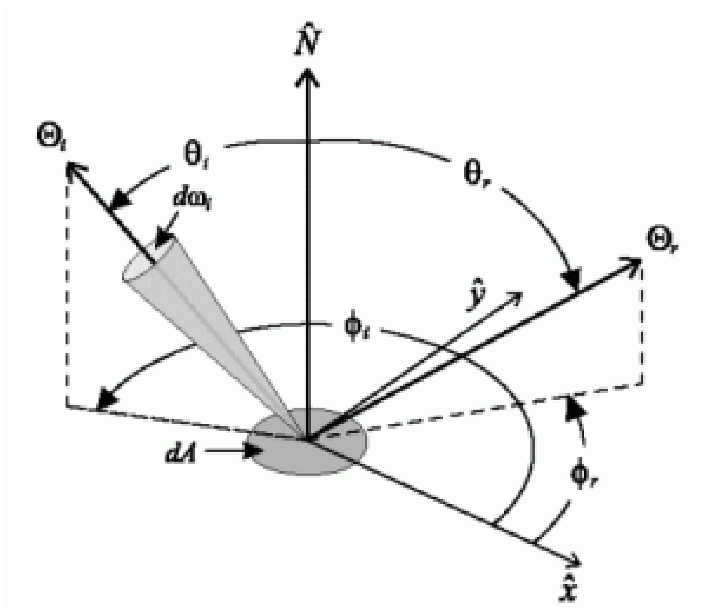
Table 1: Key parameter values

Parameter	Value
Aperture angle, irradiation	2.9°
Aperture angle, detection	1.6°
Spectroradiometer field of view	1°
Source-sample distance (*R*)	391.27 ± .03 mm
Source aperture radius (*r*)	10.000 ± .002 mm
Wavelength range	380nm-780nm
Wavelength interval	1nm
Wavelength accuracy	.2nm
Bandwidth	5nm

Using the robot as a goniometer



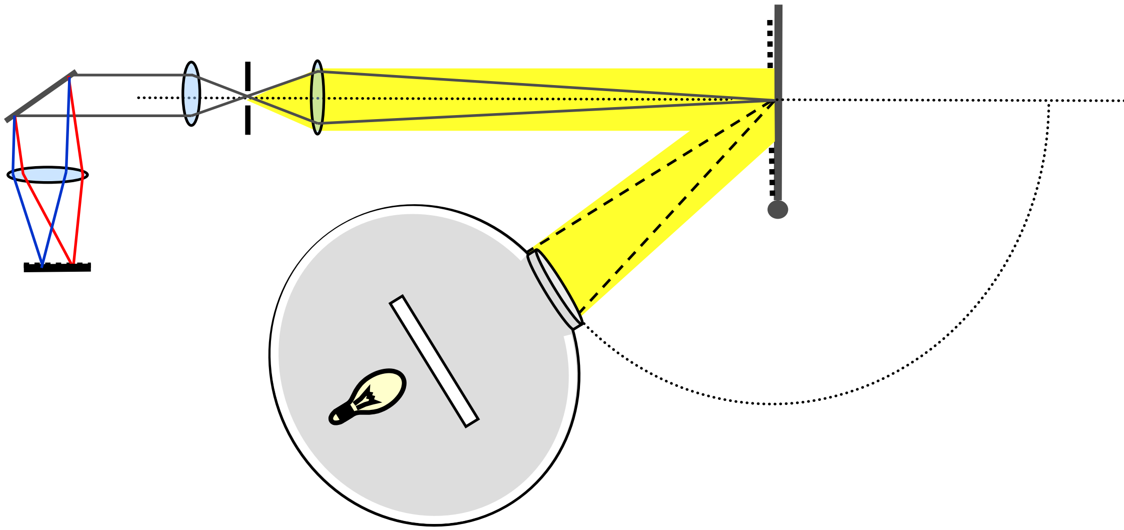
Robot space



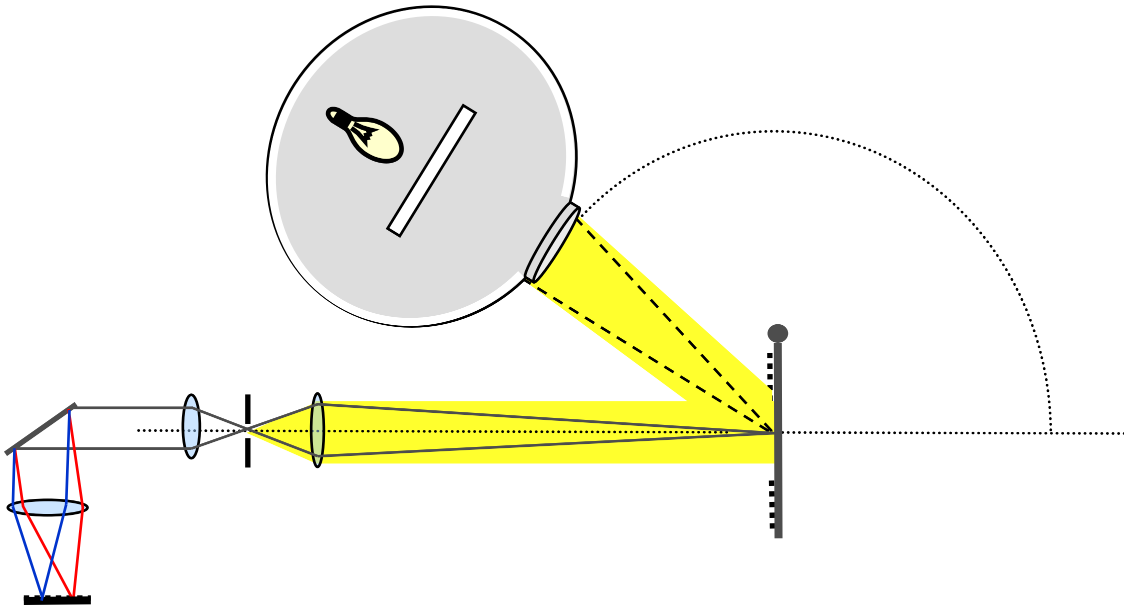
BRDF space

NRC · CNRC

Dual solution 1



Dual solution 2



Instrument Validation (in progress)

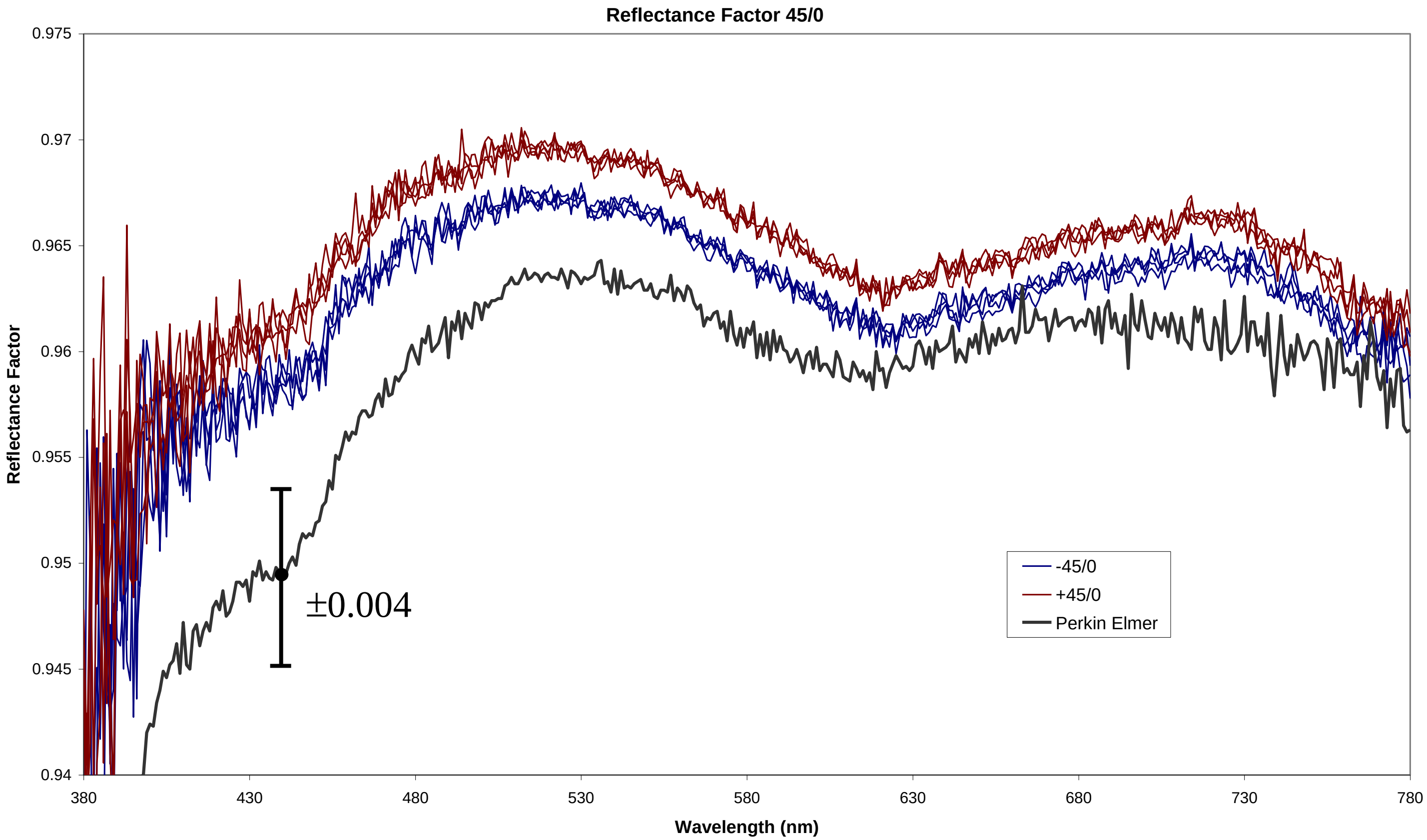
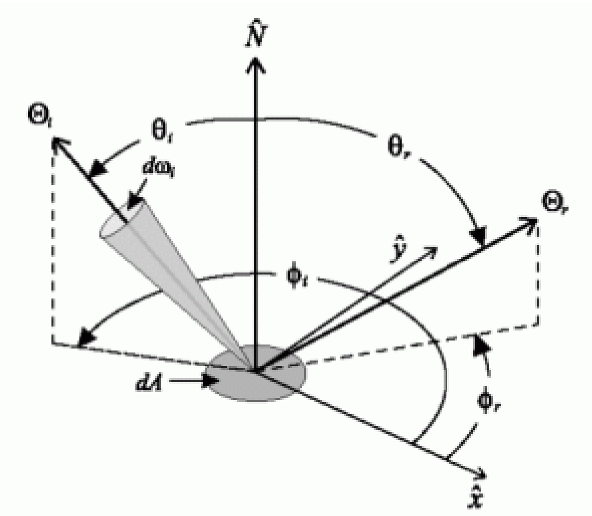
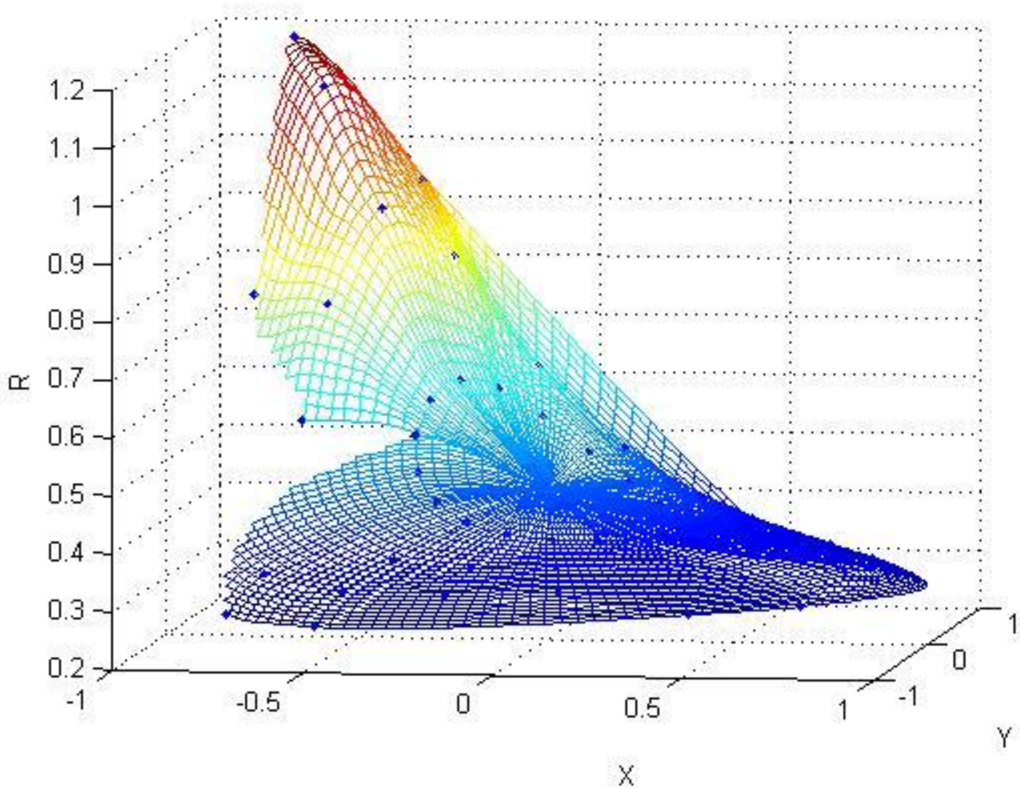


Figure 4. *Comparison of the 45/0 reflectance factor measured with the gonioreflectometer and with a spectrophotometer equipped with a 0/45 annular reflection accessory.*

First attempt at capturing a complete BRDF





- Sample: vapor-blasted aluminium
- Incidence angle: 45
- Reflection elevation angles: 0, 20, 40, 60, 80
- Reflection azimut angles: -180, -160, … 180
- λ = 532 nm
- Mesh grid: Delaunay interpolation

Applications

- Measuring gonioapparent materials (paints, surface structure,…)
- Reference materials (characterize, certify)
- Appearance modeling (compare theoretical with empirical)
- Remote sensing (compare remote with laboratory)

Gonioapparent material

Reference material: example from NIST

NIST SRM 2017 - Multi-Angle White Reflectance Standard

Details:

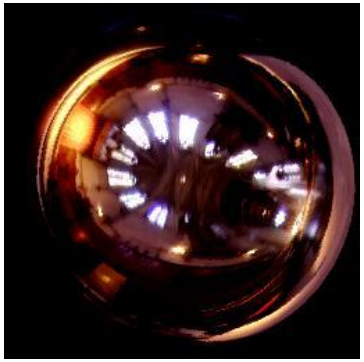
Description :	Multi-Angle White Reflectance Standard
Unit Price*:	$2,091.00

- Opal glass
- Certified measurements for
  - One angle of incidence (45)
  - Five in-plane angles of reflection (15   25   45   75   110   aspecular)
  - 360 nm, 370 nm, … 780 nm
- Certified for five years

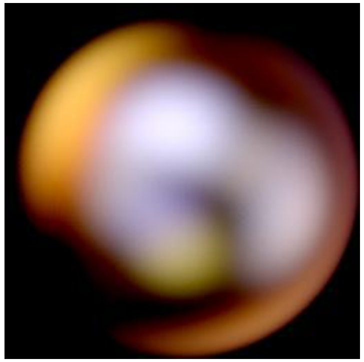
Appearance modeling

Smooth → Rough

Specular ↓ Diffuse



Mirror BRDF



Torrance-Sparrow BRDF

Lambertian BRDF

Oren-Nayar BRDF

Taken from Srinivasa Narasimhan instruction material on appearance modeling

Remote sensing (Mars simulant)

Figure 1. Wet (*left*) and dry (*right*) JSC Mars-1 simulant.

Source: PHOTOMETRIC SIGNATURES OF LIQUID WATER IN JSC MARS-1 REGOLITH SIMULANT. K. Gunderson, B. Lüthi, P. Russell and N. Thomas.

Conclusion

- The BRDF describes how reflecting objects redistribute radiance.
- We have built a primary instrument for BRDF measurement that uses:
  - A uniform light source for projection.
  - A diode array spectroradiometer for radiance measurement.
  - A five-axis robot and a rotation gear for angle control.
- Key features include:
  - Fast acquisition of the complete reflectance spectrum.
  - Automation to allow the unattended acquisition of a large number of points of a BRDF.
  - Expected accuracy of ~0.5% for white materials.
- Target applications:
  - Reference materials
  - Calibration targets for 2D and 3D remote sensors
  - Gonioapparent materials
  - Small displays, home theater screens etc.