Goniocolorimetry of diffusely reflecting and regularly reflecting surfaces

CNC/CIE CIE/USA (Ottawa), Oct. 3, 2011

Réjean Baribeau
Institute for National Measurement Standards
National Research Council Canada

Abstract

Paper #3

Goniocolorimetry of diffusely reflecting and regularly reflecting surfaces.

Réjean Baribeau

National Research Council Canada, Institute for National Measurement Standards

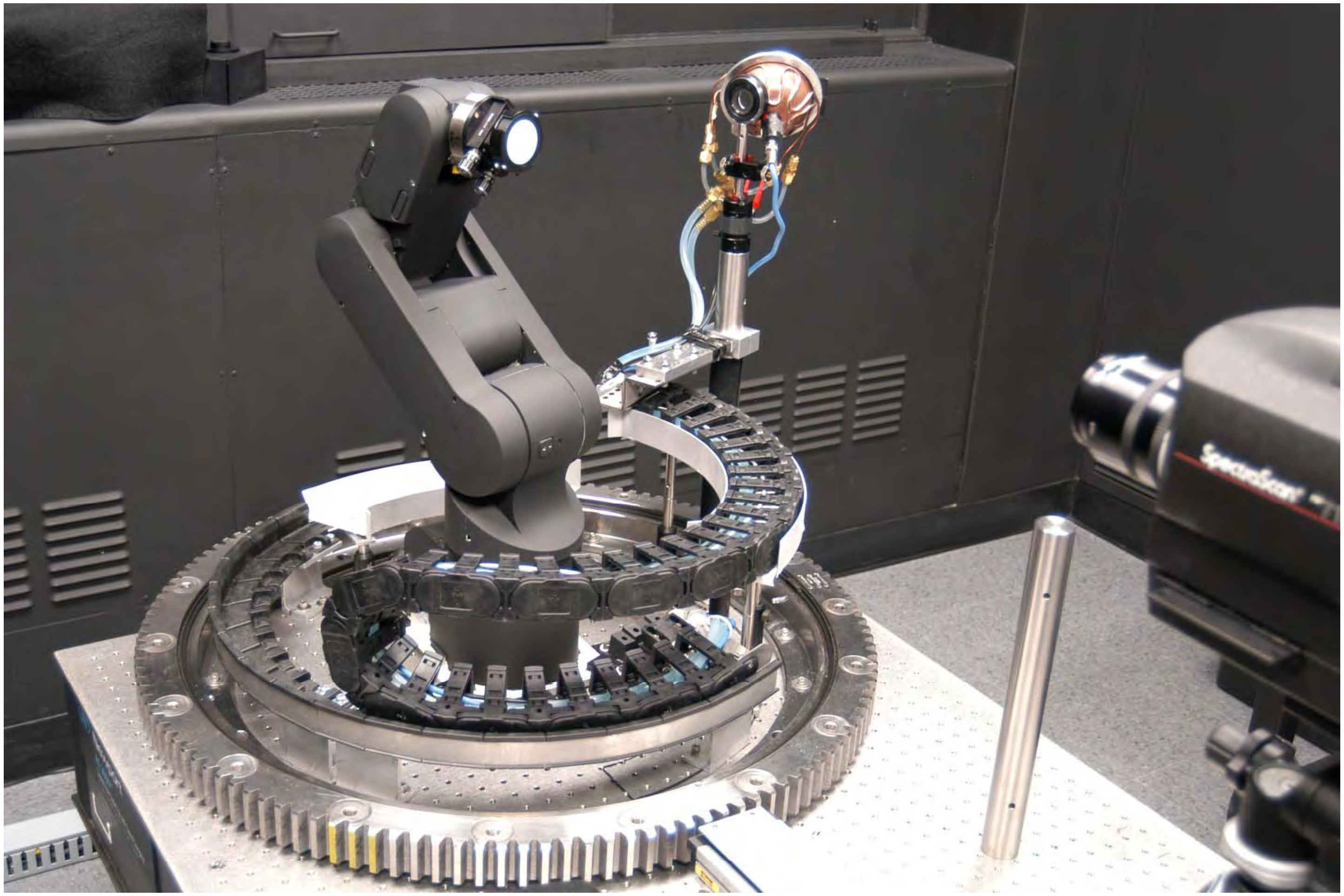
rejean.baribeau@nrc-cnrc.gc.ca

A new gonioreflectometer has been developed at the National Research Council of Canada to measure the angular variation of colours from reflecting surfaces. It incorporates a five-axis robot manipulator that holds the sample, a rotation stage that holds an extended uniform light source of precisely known emitting area, and an array spectroradiometer that measures the reflected radiance from the sample, which is compared to the radiance of the source itself to allow the calculation of the Bidirectional Reflectance Distribution Function (BRDF) from first principles. The BRDF is then used to predict the colour appearance for Standard illuminants such as daylight D65 . The system can be used for either diffuse or shiny samples, and in the later case the regular reflectance of the material is obtained. The system has the advantage of being very fast compared to other techniques thanks to the inherent diode array parallel processing. Examples of use will be given for two cases of iridescent samples: diffuse surfaces that incorporate interference pigments and shiny Atomic Layer Deposited thin films.

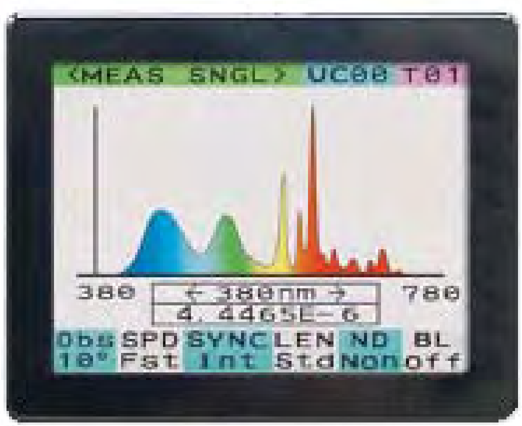
Goniocolorimetry

- Colour of a reflecting object varies with illumination and viewing angle
- The variation can be
  - Dramatic (special effect pigments, thin films)
  - Noticeable, or at least measurable (paper, $BaSO_4$)
  - Practically inexistent (PTFE)
- A complete description requires
  - Accurate 3D control of the illumination and viewing angles
  - Spectral measurement
- Goniocolorimetry consists in measuring the spectral BRDF and predicting the colour variations form it.

Overview of the instrument

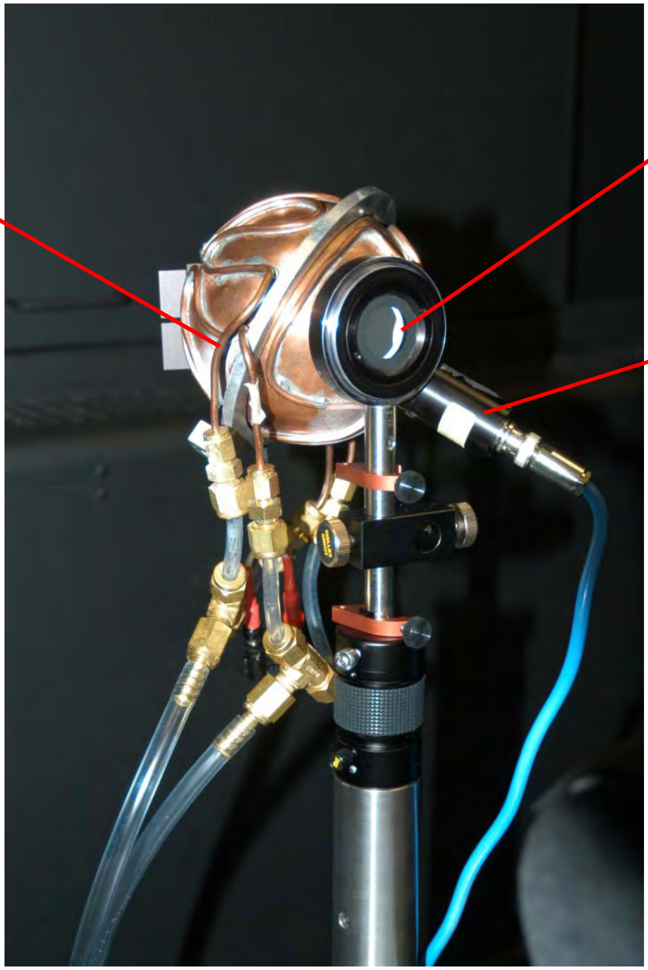


Spectroradiometer



Uniform light source

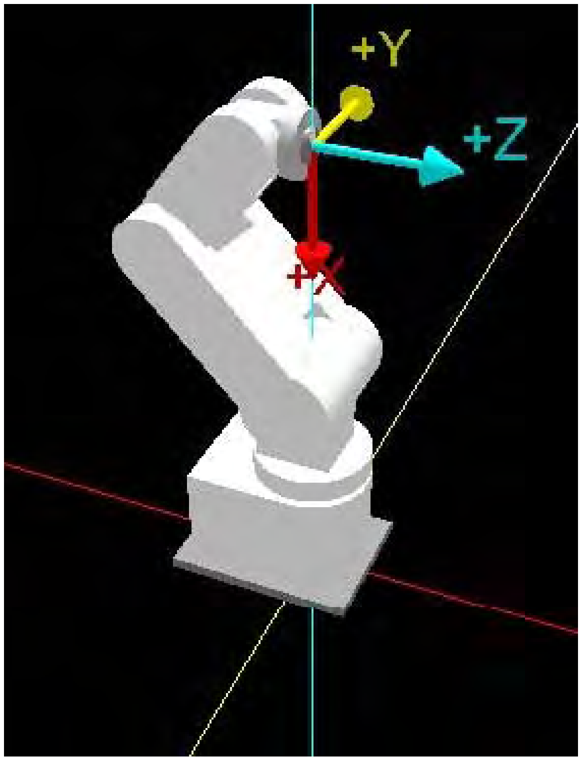
Water cooling



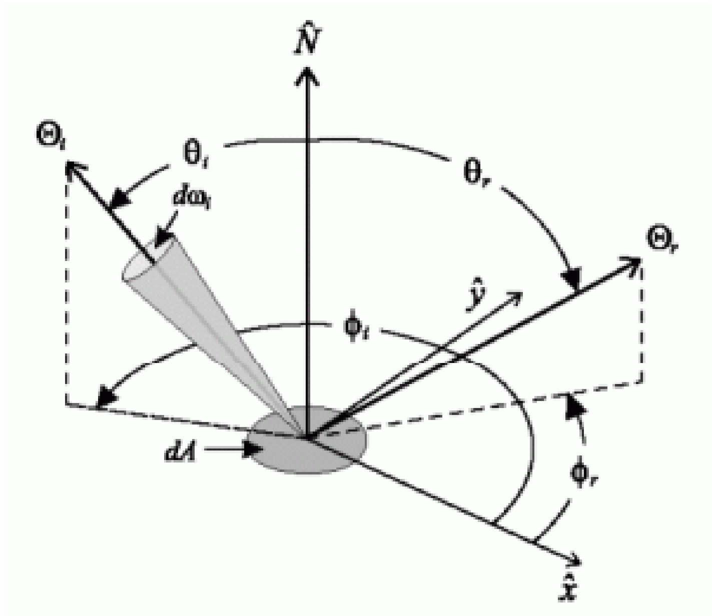
Precision aperture

Monitoring photodiode

The robot acts as a goniometer

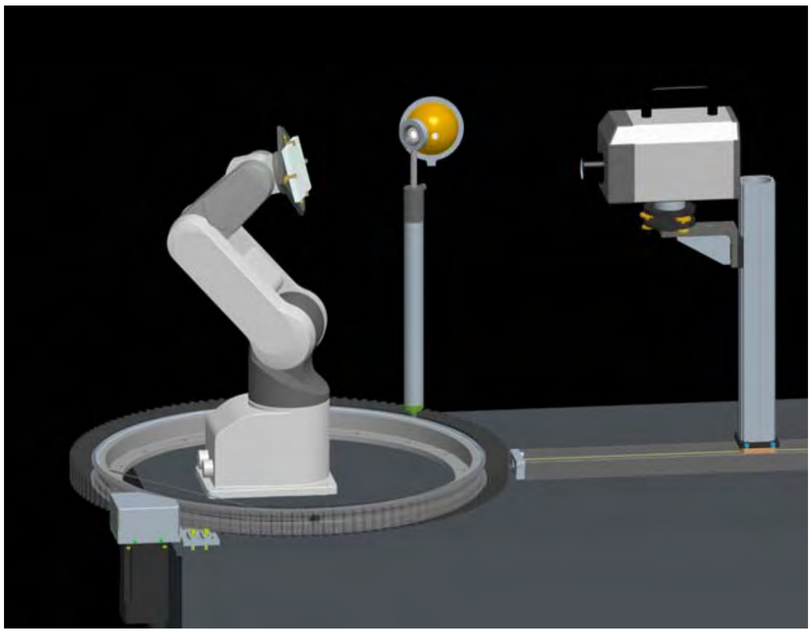


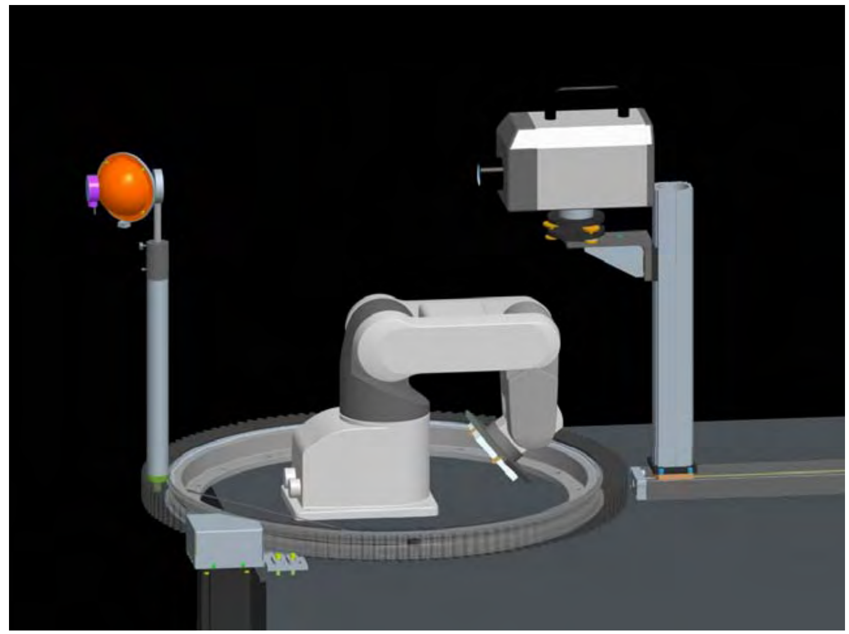
Robot space



BRDF space

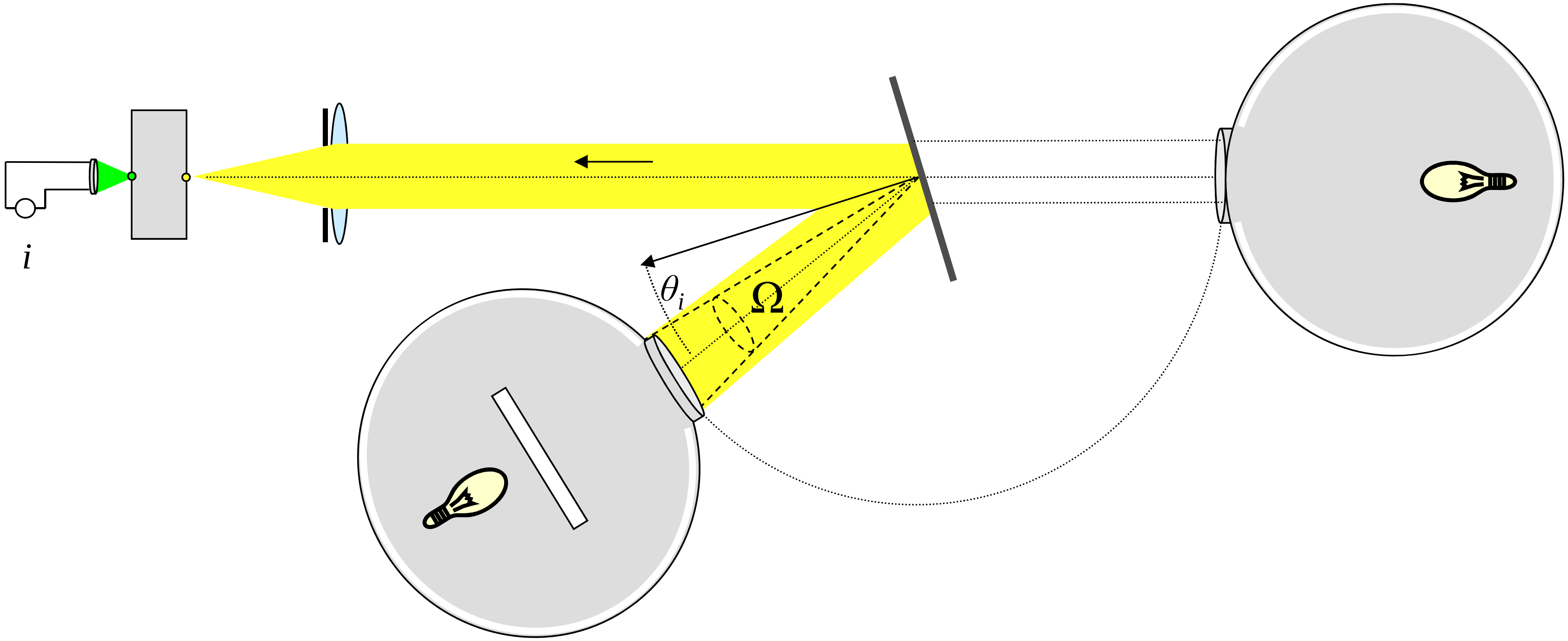
Calculation of the BRDF





$$f_r = \frac{L_{\text{sample}}}{L_{\text{sphere}}} \frac{1}{\cos\theta_i} \frac{1}{\Omega_{\text{sphere}}} \qquad \left[\text{sr}^{-1}\right]$$

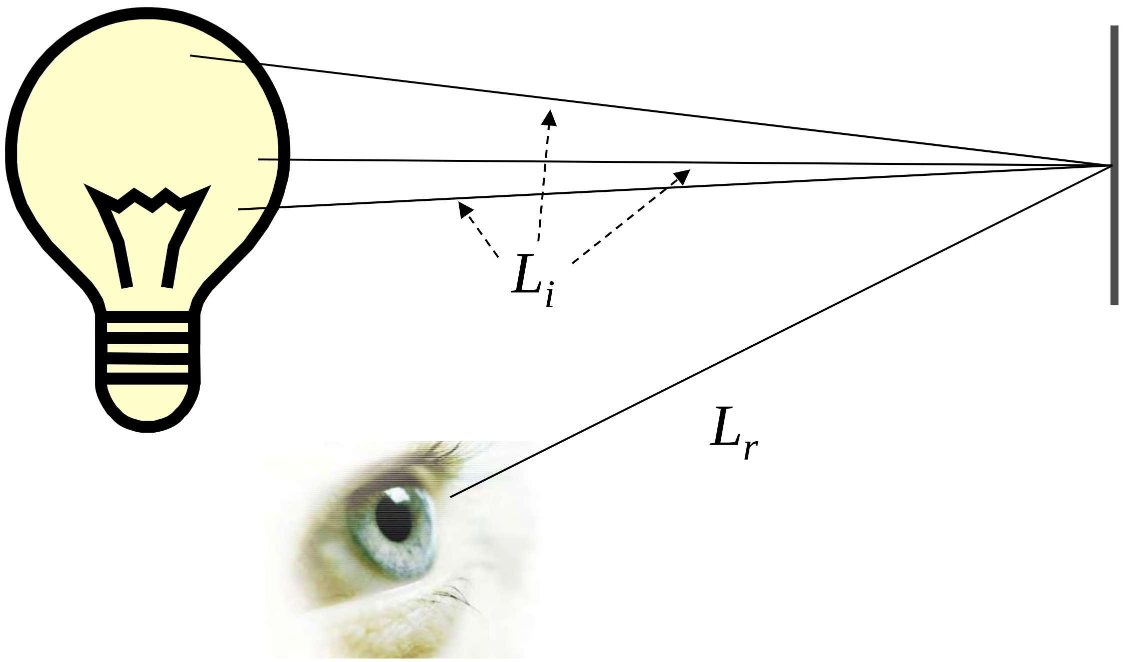
Measuring spectral BRDF from first principles



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

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

The rendering equation



$$L_r(\theta_r,\varphi_r;\lambda)=\int f_r(\theta_i,\varphi_i,\theta_r,\varphi_r;\lambda)L_i(\theta_i,\varphi_i;\lambda)\cos(\theta_i)d\omega_i$$

BRDF governs the appearance of materials

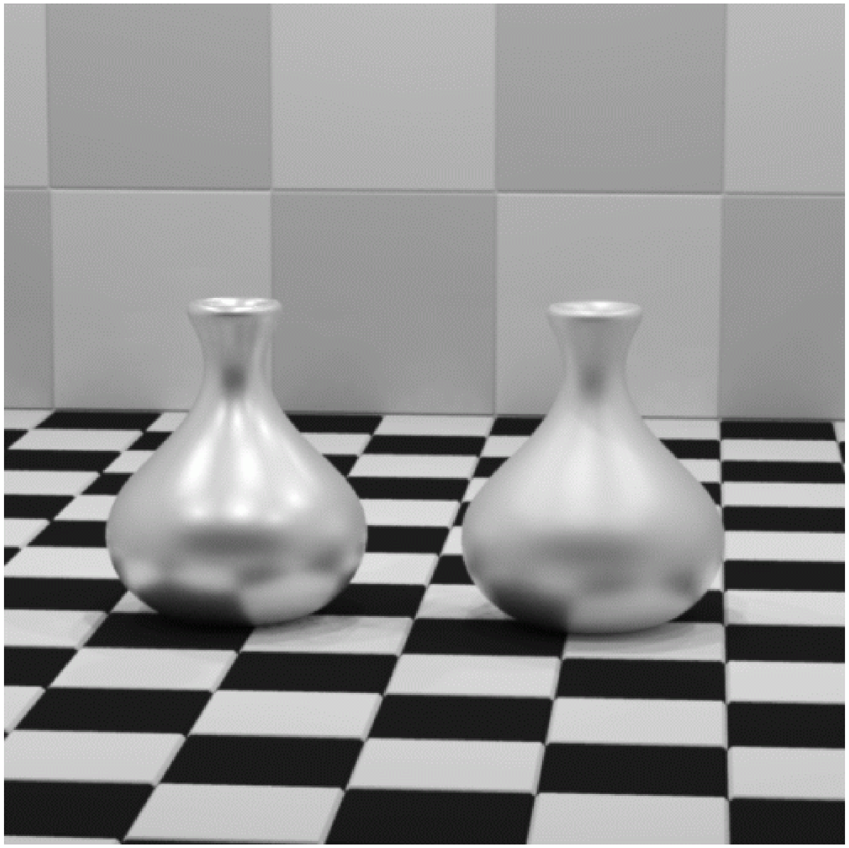
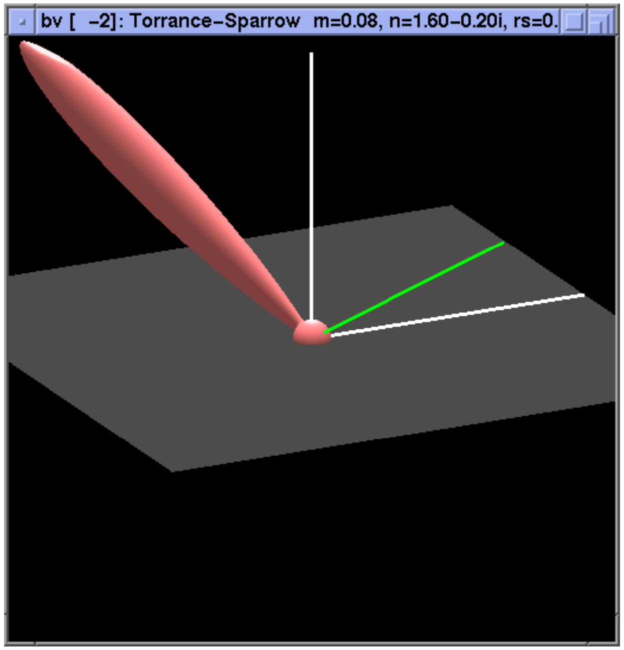
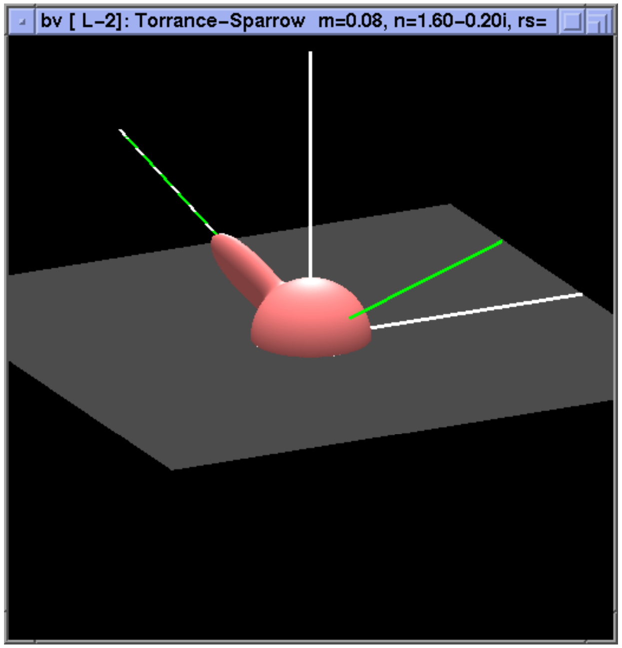


Image from NIST Information Technology Laboratory, Mathematical & Computational Sciences Division.

BRDF and surface finish



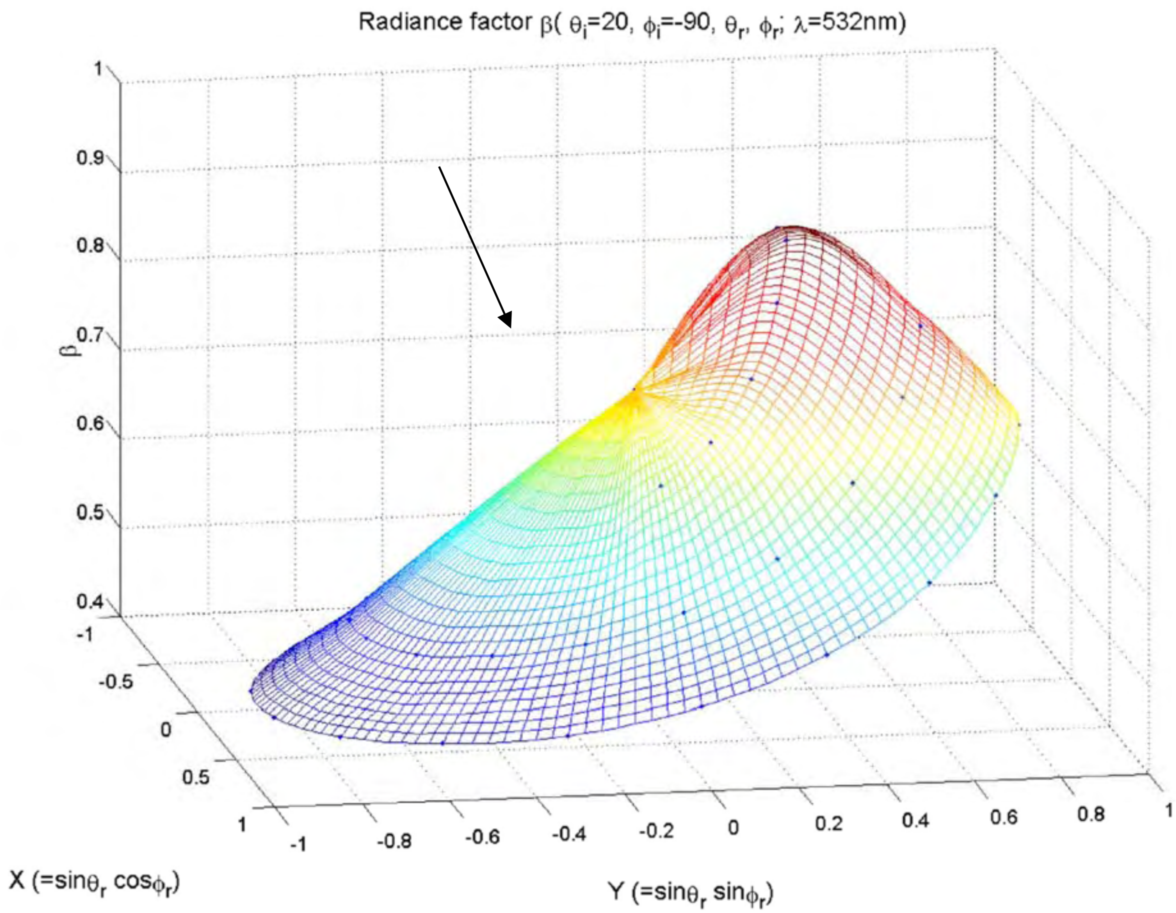
“glossy”



“semi-glossy”

Source: http://graphics.stanford.edu/~smr/cs348c/report.html

Reflection indicatrix of a vapor-blasted Al sample at λ=532 nm



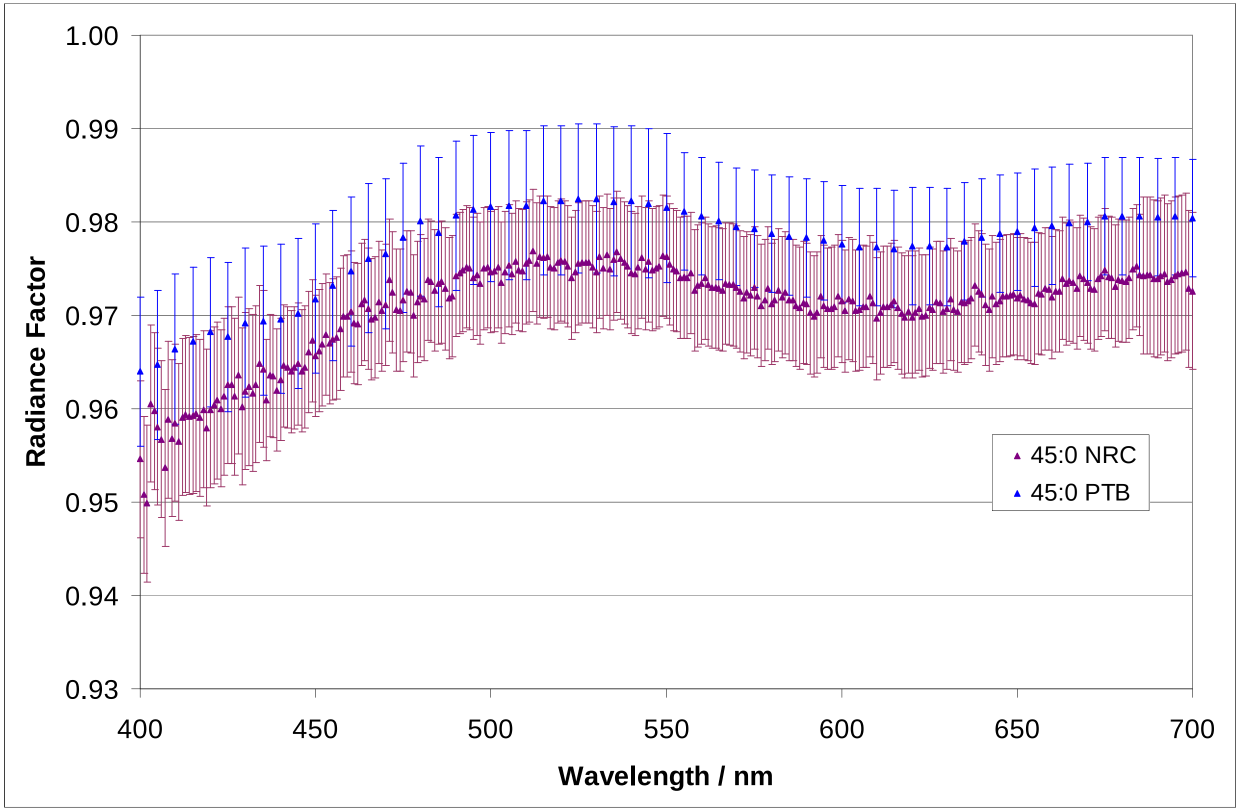
NRC · CNRC

Uncertainty budget for measuring white diffusing materials

Influencial factor	u	u(β)/β
Geometry		
Source-Sample distance	.2 mm	0.001
Source diameter	.002 mm	0.0002
Source non-uniformity		0.0006
Angle of incidence @ 45°	.1°	0.002
Detector		
Veiling flare		0.001
Spectral response		
400 nm - 435 nm		0.0025
435 nm - 685 nm		0.0015
685 nm - 700 nm		0.0025
Repeatability		
400 nm - 435 nm		0.002
435 nm - 685 nm		0.001
685 nm - 700 nm		0.002
Sample		
Uniformity		0.001
Expanded Uncertainty(k=2)		
400 nm - 435 nm		**0.0084**
435 nm - 685 nm		**0.0065**
685 nm - 700 nm		**0.0084**

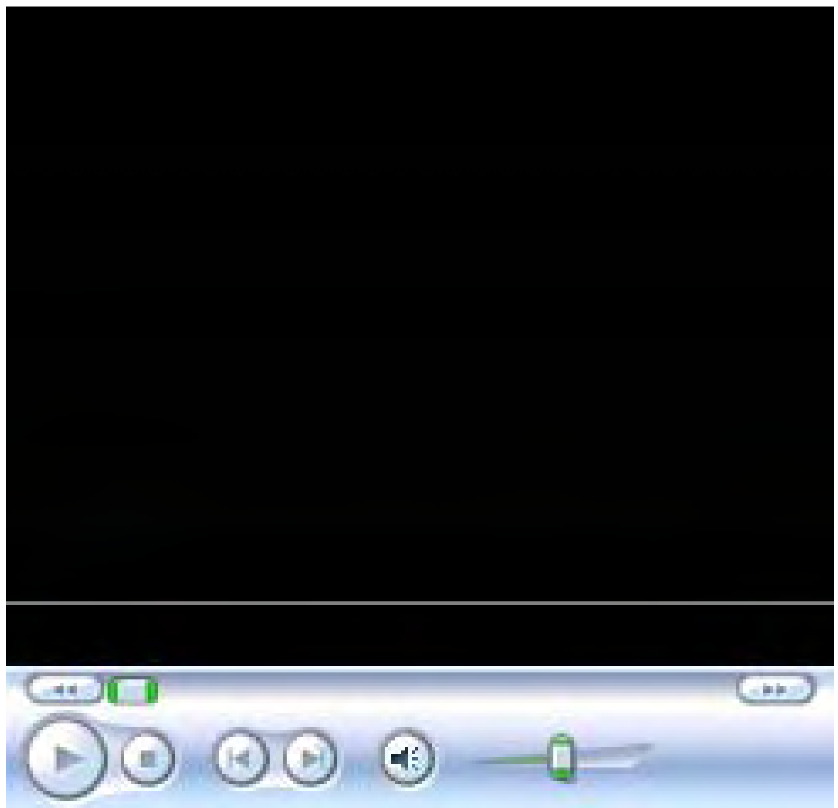
Table 1: NRC uncertainty budget.

Comparison with PTB

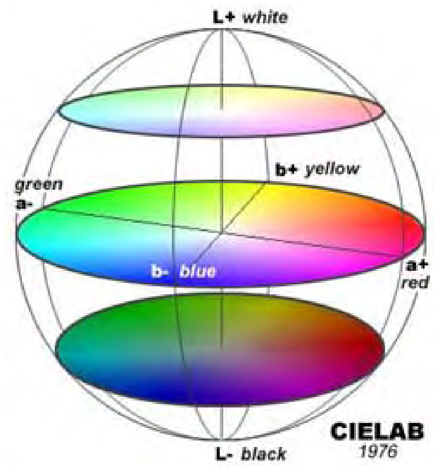


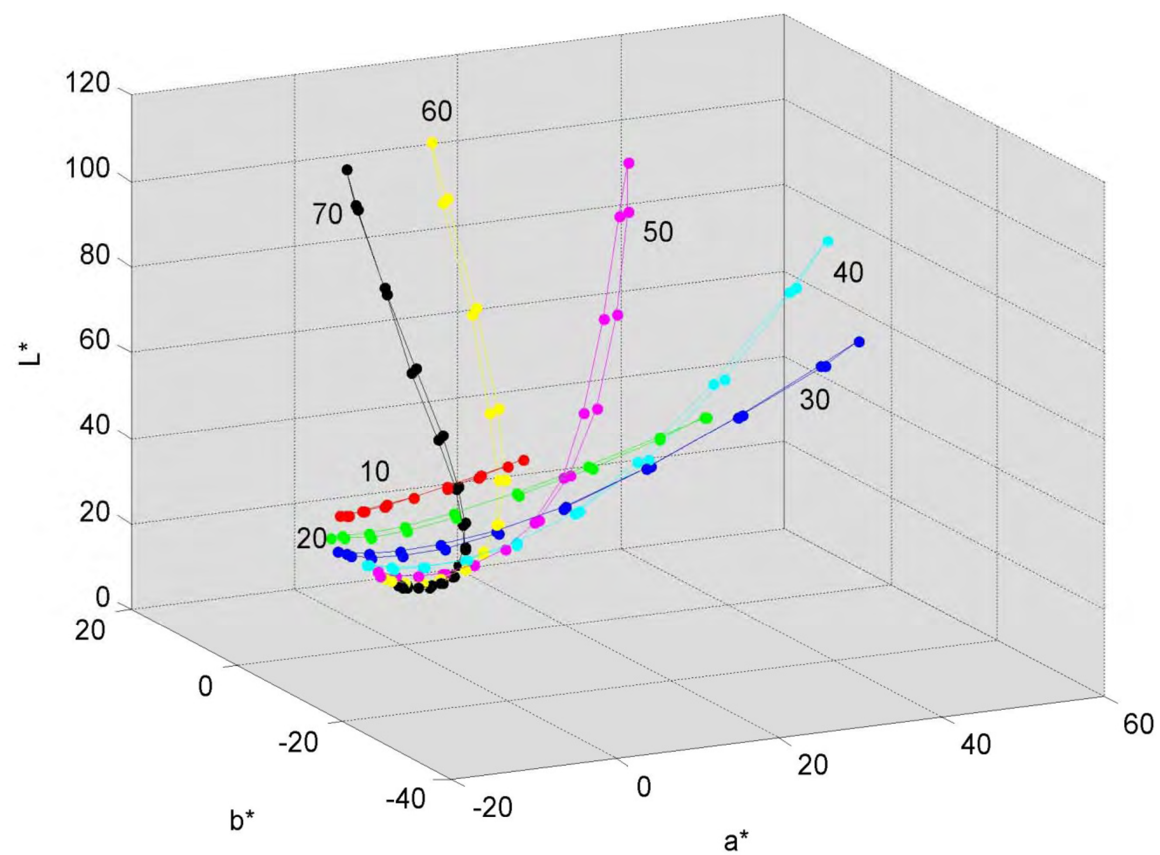
Comparison of the spectral radiance factors measured by NRC and PTB for an opal glass sample (NIST SRM-2017), for 45° incidence angle and 0° reflection angle.

Measurement of a ChromaFlare sample



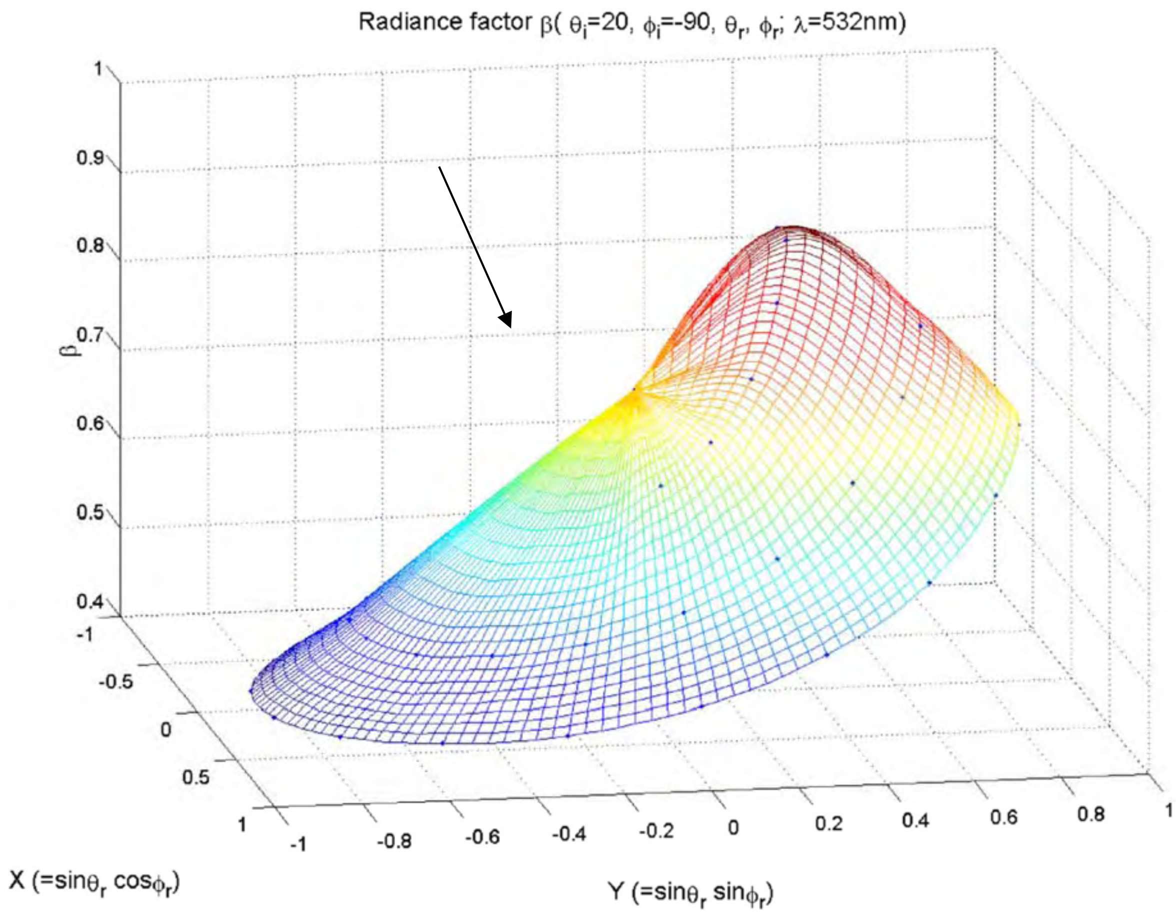
Colour variation as a function of angles





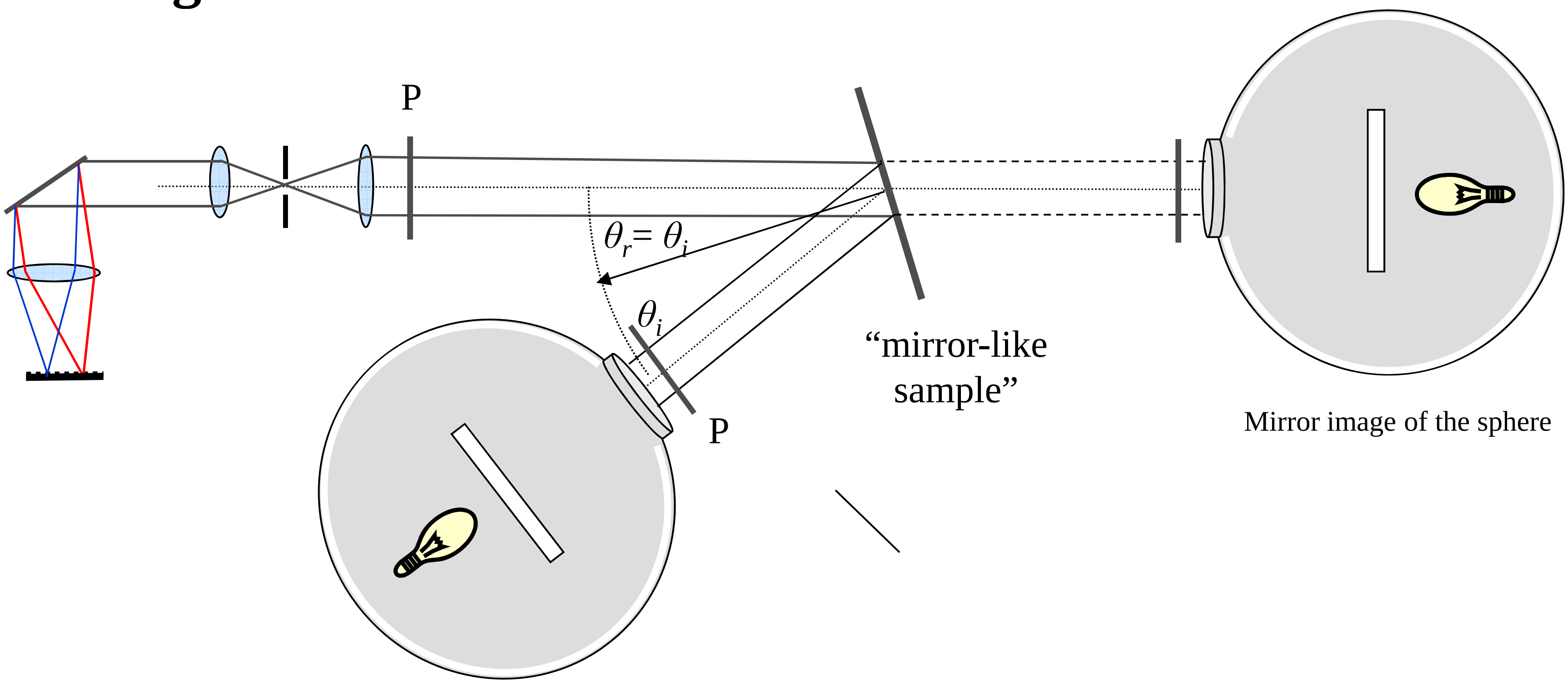
NRC · CNRC

Reflection indicatrix of a vapor-blasted Al sample at λ=532 nm



NRC · CNRC

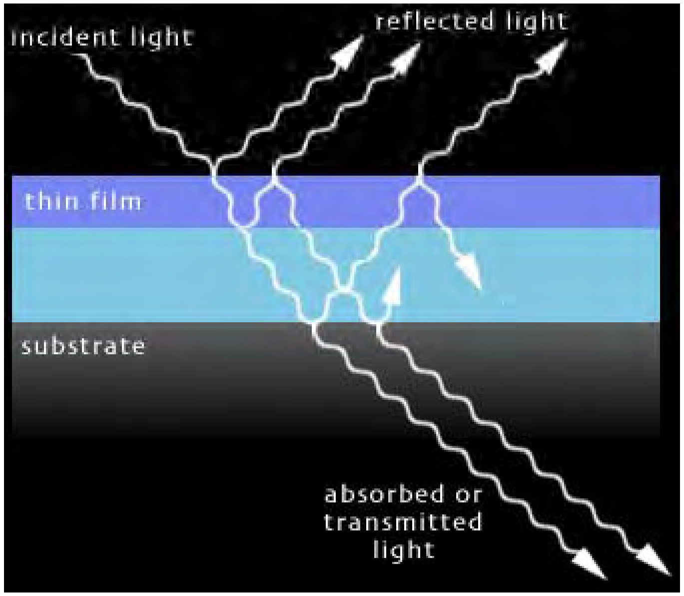
Regular reflectance measurement



$$\rho_r(\theta_i, \lambda) = \frac{L_{\text{mirror image}}}{L_{\text{direct}}}$$

Iridescence from thin films

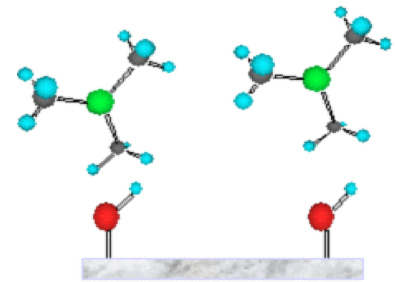
Reflection on thin films

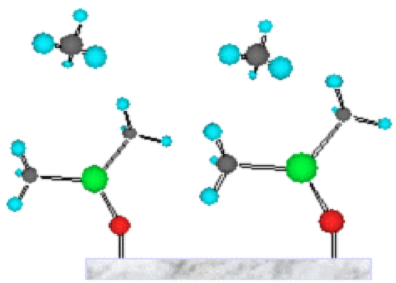


Source: http://www.tufts.edu/as/tampl/projects/micro_rs/theory.html

Atomic Layer Deposition

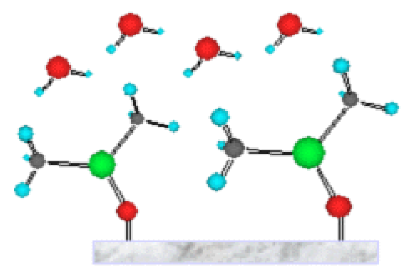
A vapour is introduced over a surface where it reacts chemically, anchoring itself.

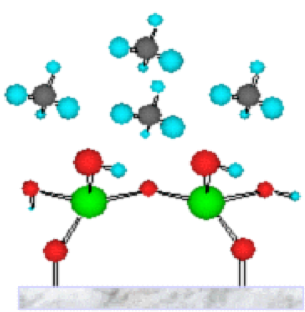




Due to specific chemical design, only one layer forms. This is the key to ALD.

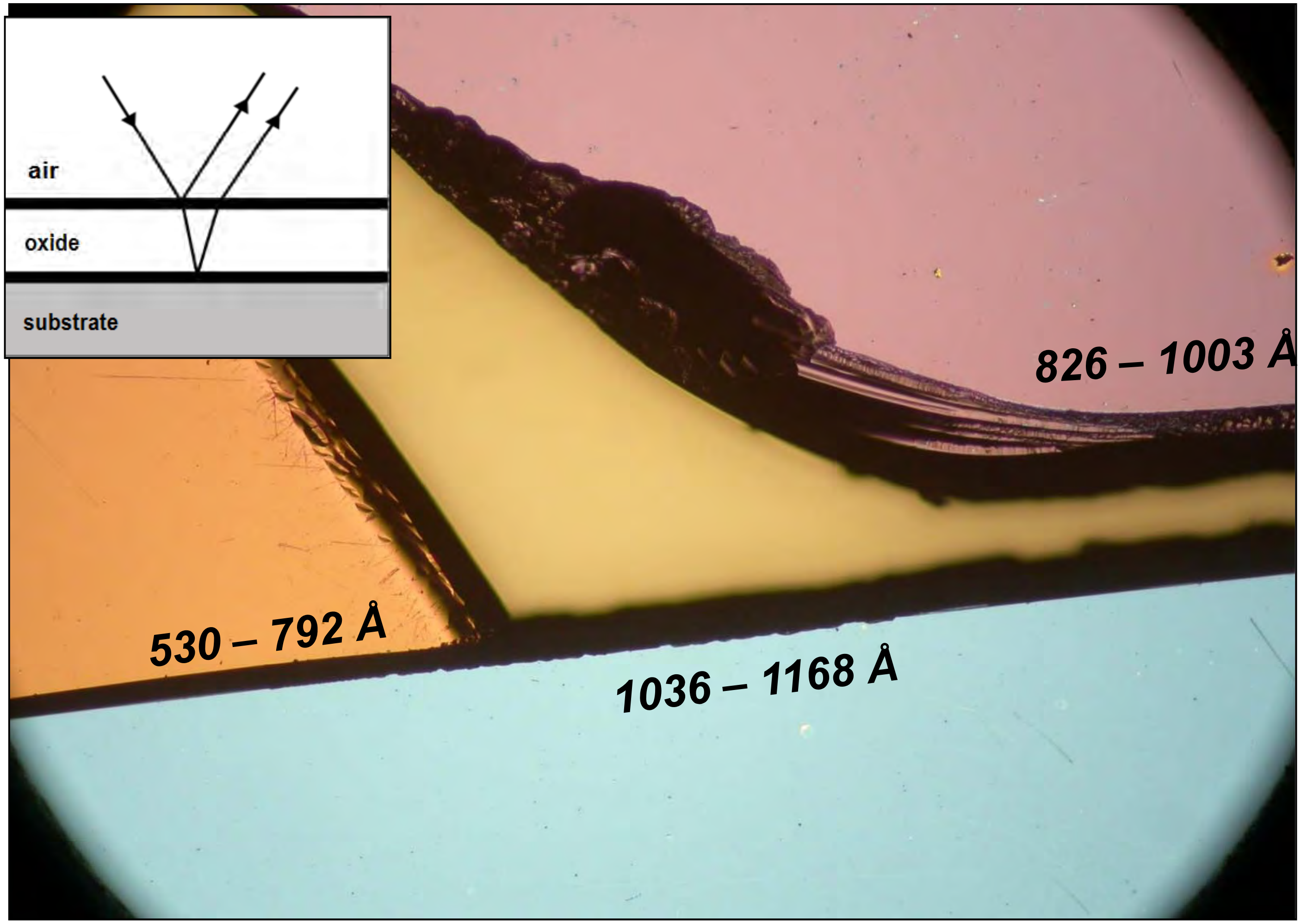
After removing excess chemical from the gas phase, a second vapour is introduced

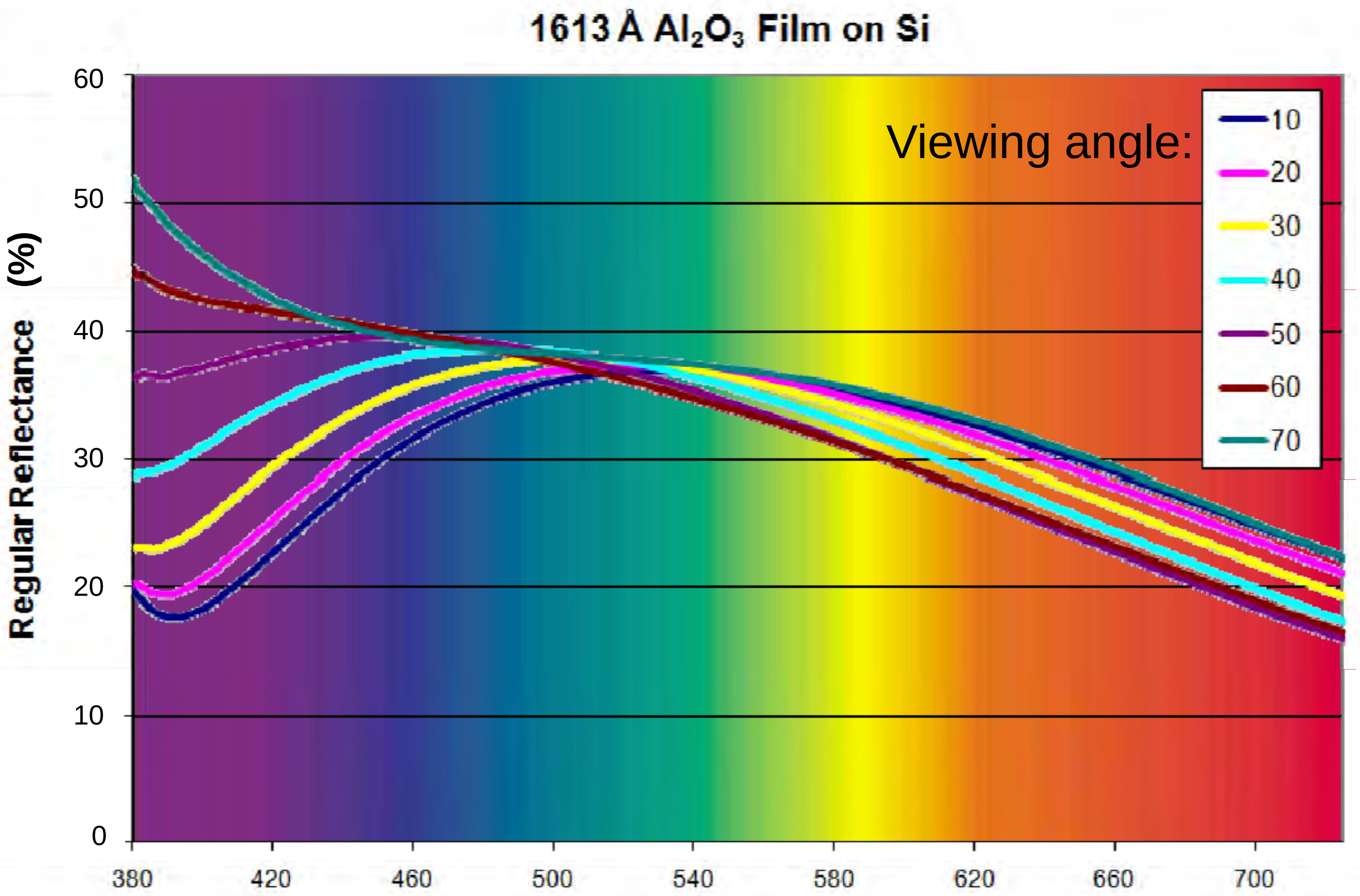




It reacts with the monolayer to produce a one ”molecule” thick layer of target material.

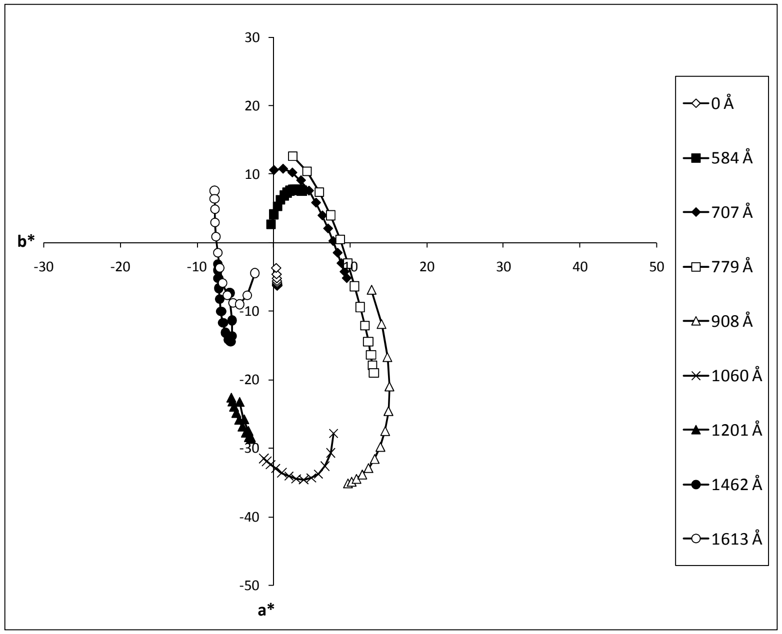
Interference colors from thin films



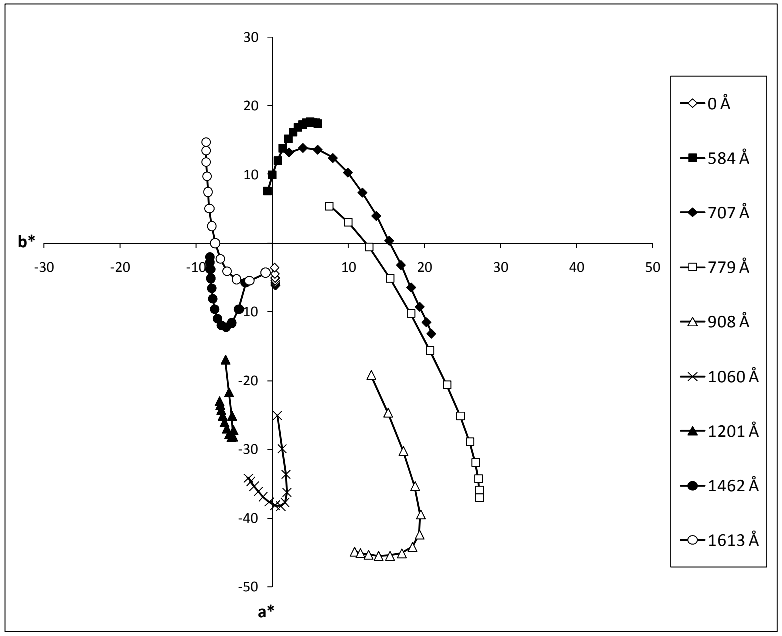

1613 Å Al_2O_3 Film on Si
Regular Reflectance (%)
0
10
20
30
40
50
60
380
420
460
500
540
580
620
660
700
Viewing angle:
10
20
30
40
50
60
70

NRC · CNRC

Measured vs. predicted colours



Fresnel theory



Measured

Summary

- A system has been built to measure colour variations with illumination and viewing angles.
- Applicable to
  - Diffusely reflecting objects (in-plane and out-of-plane BRDF)
  - Specular objects (regular reflectance).
- The accuracy is comparable to what exist at other NMIs.
- The instrument is fast and particularly suited for iridescent materials.