Variable-Radius Source Method to Separate Specular Component from Haze Peak

2005 CORM

May 11 & 12, 2005
Boulder, Colorado

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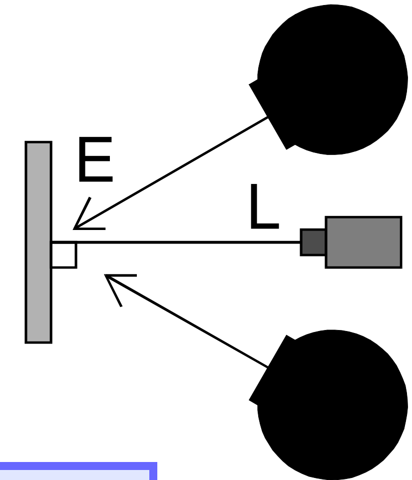
Oversimplified Models — Possible Ambiguity

Lambertian ("Diffuse") component assumption:

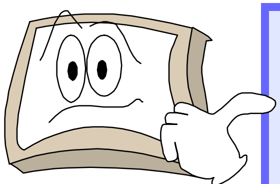
Display surface measured as if it were matte paint:



β = luminance factor, q = luminance coefficient ($=\rho_d/\pi$)

E = illuminance, L = observed luminance

$$L = qE = \frac{\beta}{\pi}E. \quad (\text{Recall}: \ \beta_{d/\theta} = \rho_{\theta/d})$$

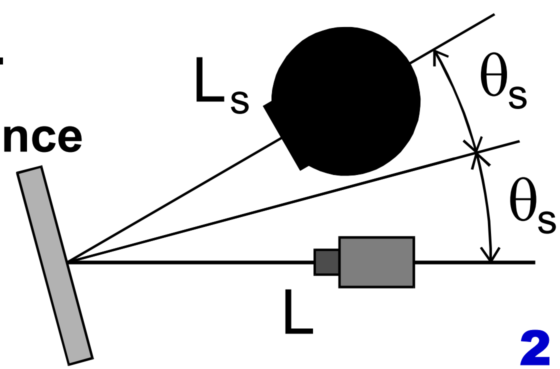


Note

Strictly speaking this equation is for a Lambertian material; "diffuse" means scattered out of specular direction and is <u>not</u> limited to Lambertian materials.

Specular component assumption:

Display surface treated as if it were a mirror.



ρ_s = specular reflectance, L_s = source luminance

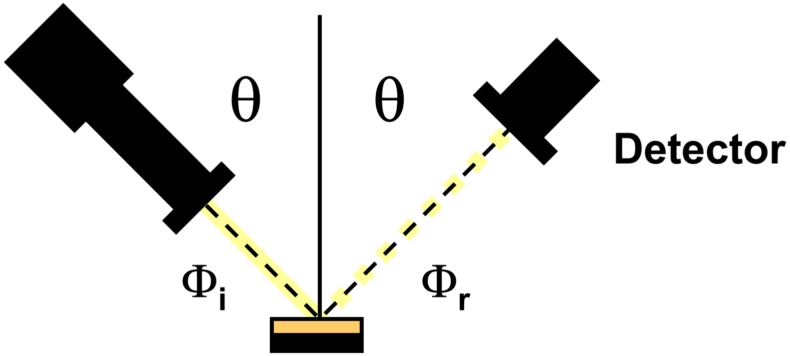
$$L = \rho_s L_s$$

Specular Reflectance ρ_s:

(CIE: Regular Reflectance ρ_r)

Ratio of the specularly (regularly) reflected flux to the incident flux for a given geometry of source and detector:

$$\rho_s = \left. \frac{\Phi_r\,(\text{specular})}{\Phi_i} \right|_{\substack{\text{Apparatus} \\ \text{Geometry}}}$$



CIE 17.4: 845-04-60 “**regular reflectance** (ρ_r) unit: 1

Ratio of the regularly reflected part of the (whole) reflected flux to the incident flux.”

CIE 17.4: 845-04-45 “**regular reflection; specular reflection**

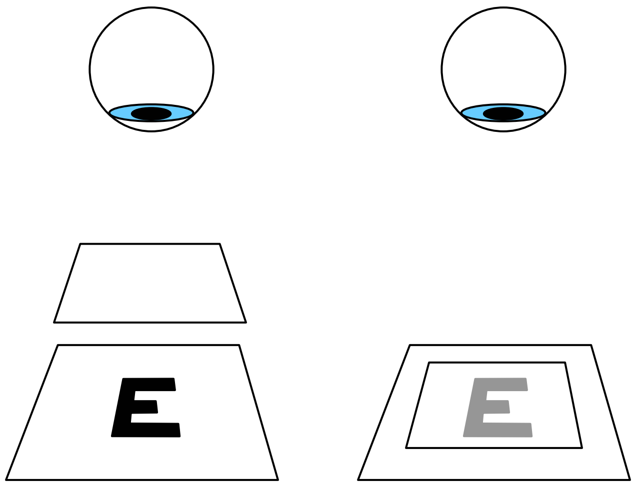
Reflection in accordance with the laws of geometrical optics, without diffusion.”

Oversimplified Model: Easy to Measure, Robust, IF OK

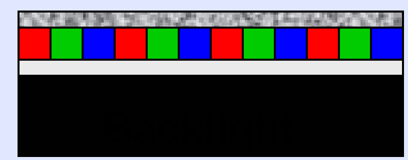
Unfortunately, many FPDs are not well characterized by just these two components — an oversimplified model.

FPDs Can Permit Diffusing Surface Near Pixels

Like wax paper over printing...



Some FPDs allow diffusing surface close to pixels.



Legibility depends upon distance of strong diffusion layer from surface containing information

Problem: Simple Models Inadequate for All Surfaces

Neither Lambertian nor specular models may work!

Three-Component Model of Reflection

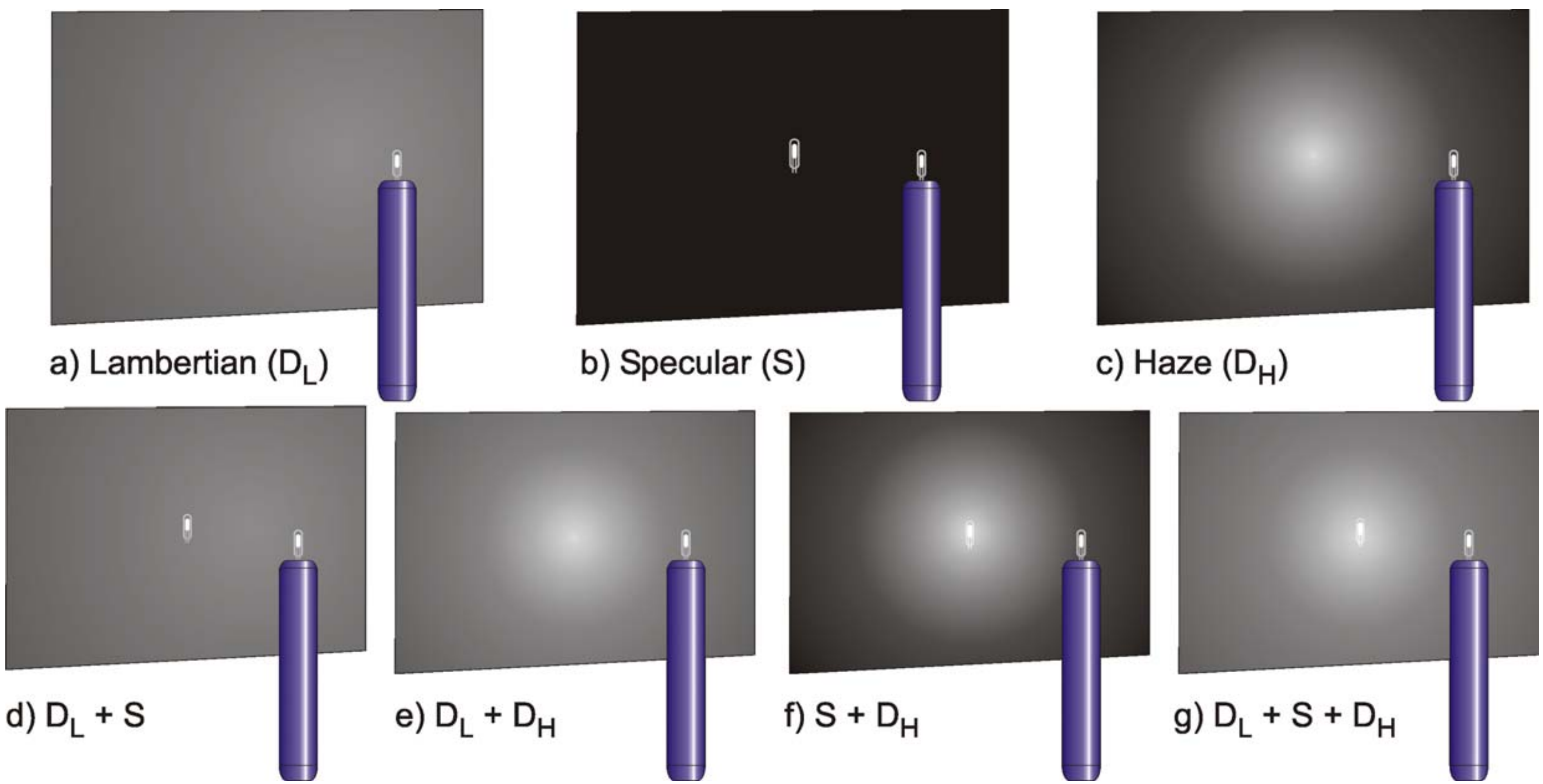
1. SPECULAR (producing a distinct virtual image of the source)

2. & 3. DIFFUSE (has TWO components):

2. LAMBERTIAN (like matte paint) & 3. HAZE (fuzzy ball in specular direction)

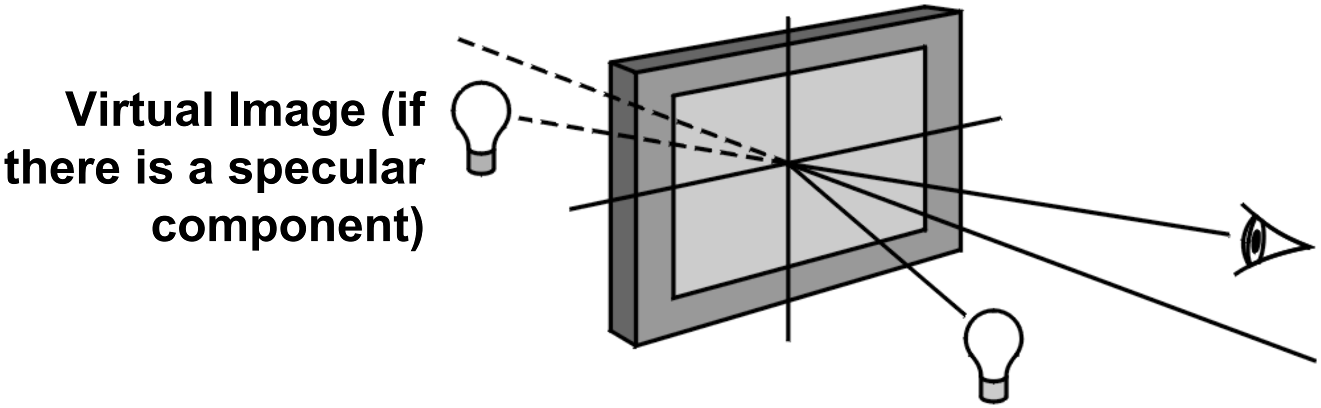
Reflectance can be thought of as having three components:

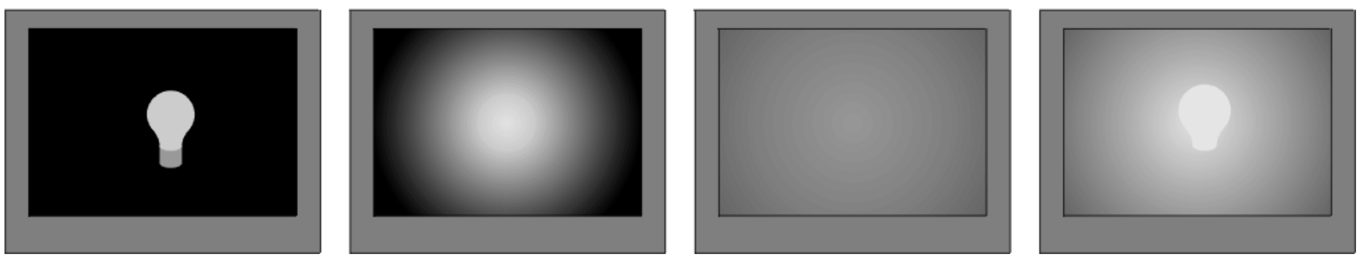
$\rho = \rho_L + \rho_s + \rho_H$, where the diffuse reflectance is $\rho_d = \rho_L + \rho_H$.



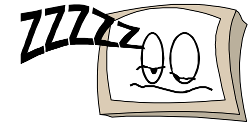
Three Component Model, Cont.

Specular, Lambertian, Haze





Specular Only	*Haze Only*	*Lambertian Only*	*All Three*

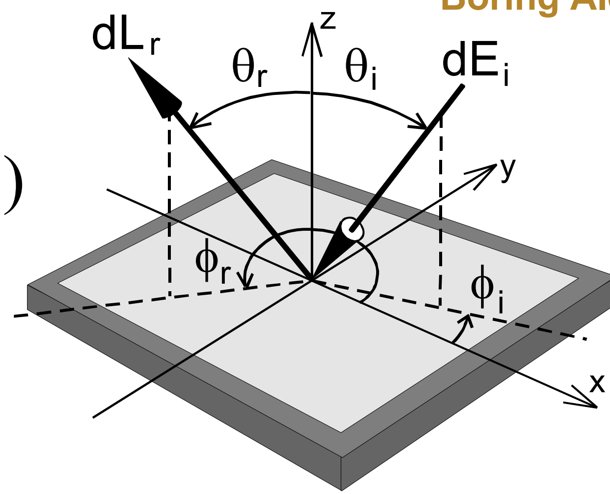


Boring Alert

BRDF — Three Components:

Bidirectional Reflectance Distribution Function

A generalization of $L = qE$.



$$dL_{\mathrm{r}}(\theta_{\mathrm{r}},\phi_{\mathrm{r}}) = B(\theta_{\mathrm{i}},\phi_{\mathrm{i}},\theta_{\mathrm{r}},\phi_{\mathrm{r}};\lambda,p)\,dE_{\mathrm{i}}(\theta_{\mathrm{i}},\phi_{\mathrm{i}})$$

We will drop the wavelength λ and polarization p dependence.

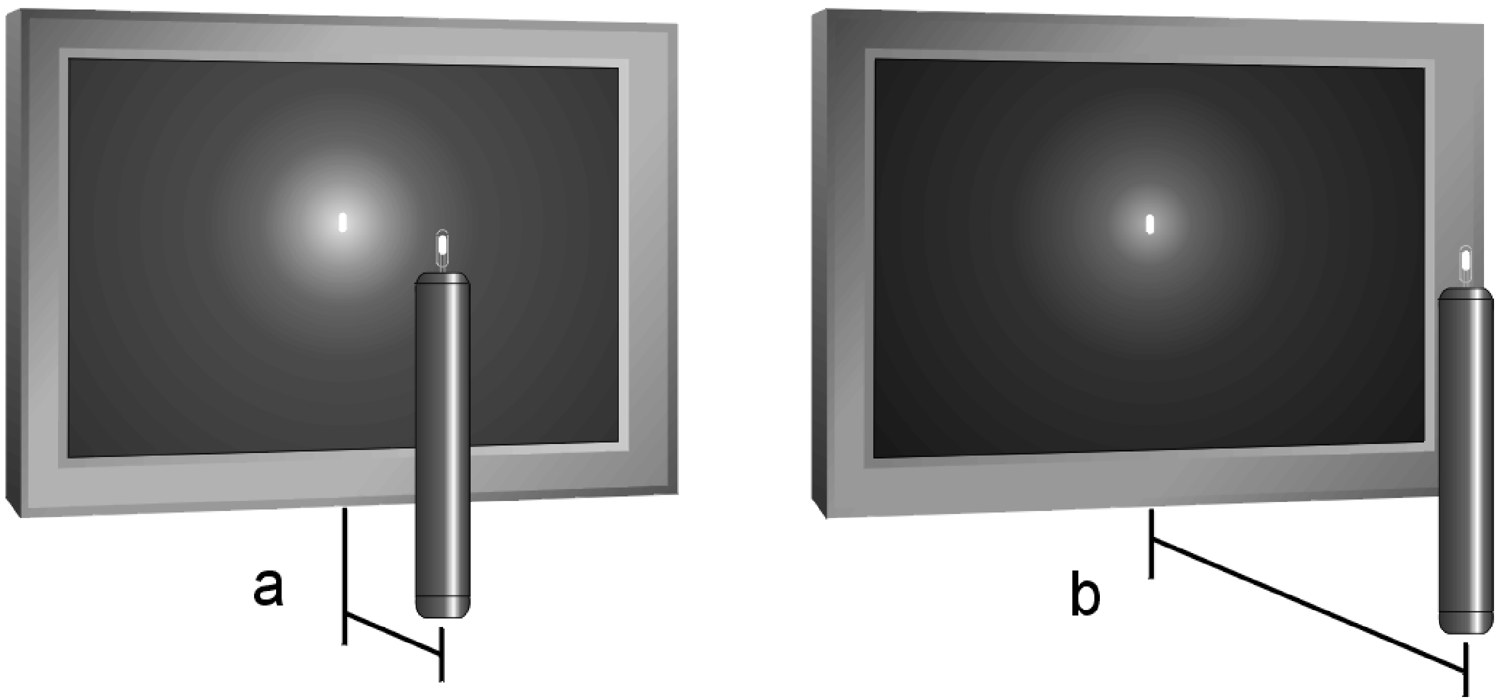
$$B = D_{\mathrm{L}} + S + D_{\mathrm{H}} \quad \begin{cases} D_{\mathrm{L}} = q = \rho_{\mathrm{L}}/\pi & \Rightarrow \text{Lambertian (perfectly diffuse)} \\ S = 2\rho_{\mathrm{s}}\,\delta(\sin^2\theta_{\mathrm{r}} - \sin^2\theta_{\mathrm{i}})\,\delta(\phi_{\mathrm{r}} - \phi_{\mathrm{i}} \pm \pi) & \Rightarrow \text{Specular} \\ D_{\mathrm{H}} = H(\theta_{\mathrm{i}},\phi_{\mathrm{i}},\theta_{\mathrm{r}},\phi_{\mathrm{r}}) & \Rightarrow \text{Haze (diffuse)} \end{cases}$$

$$L_{\mathrm{r}}(\theta_{\mathrm{r}},\phi_{\mathrm{r}}) = qE + \rho_{\mathrm{s}}L_{\mathrm{s}}(\theta_{\mathrm{r}},\phi_{\mathrm{r}} \pm \pi) + \int_0^{2\pi}\int_0^{\pi/2} H(\theta_{\mathrm{i}},\phi_{\mathrm{i}},\theta_{\mathrm{r}},\phi_{\mathrm{r}})L_{\mathrm{i}}(\theta_{\mathrm{i}},\phi_{\mathrm{i}})\cos(\theta_{\mathrm{i}})\,d\Omega.$$

***dE*, element of illuminance**

Three Component Model, Cont.

Like the Lambertian component, the haze is proportional to the illuminance; but like the specular component, it follows the specular direction.



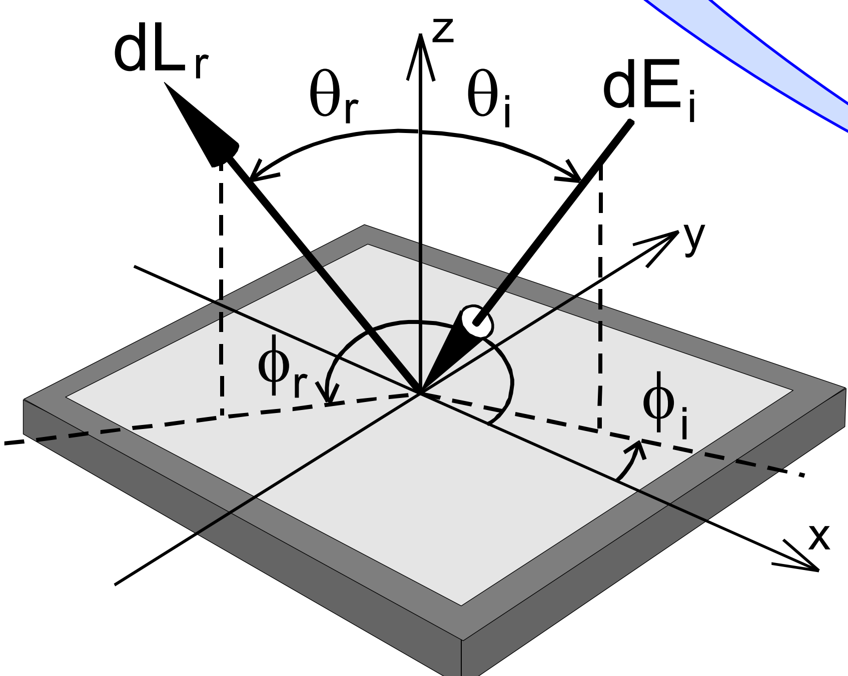
The luminance of the specular component remains constant with change in distance. The peak of the haze changes with distance (according to illuminance). Because the haze peak adds to the specular image, it can appear that the specular image is changing its luminance, but that is not the case. Look carefully at the specular image, you will see it is not changing its luminance when you separate the specular image from the haze peak.

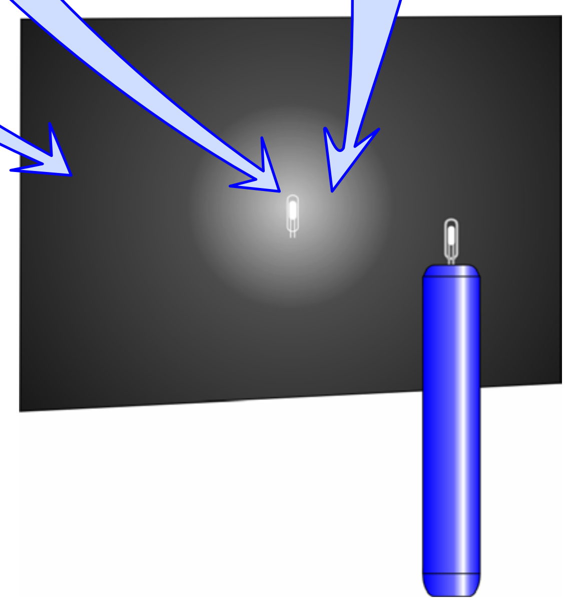
Three Component Model, Cont.

Observed Luminance **=** ***Lambertian Component*** **+** ***Specular Component*** **+** ***Haze Component***

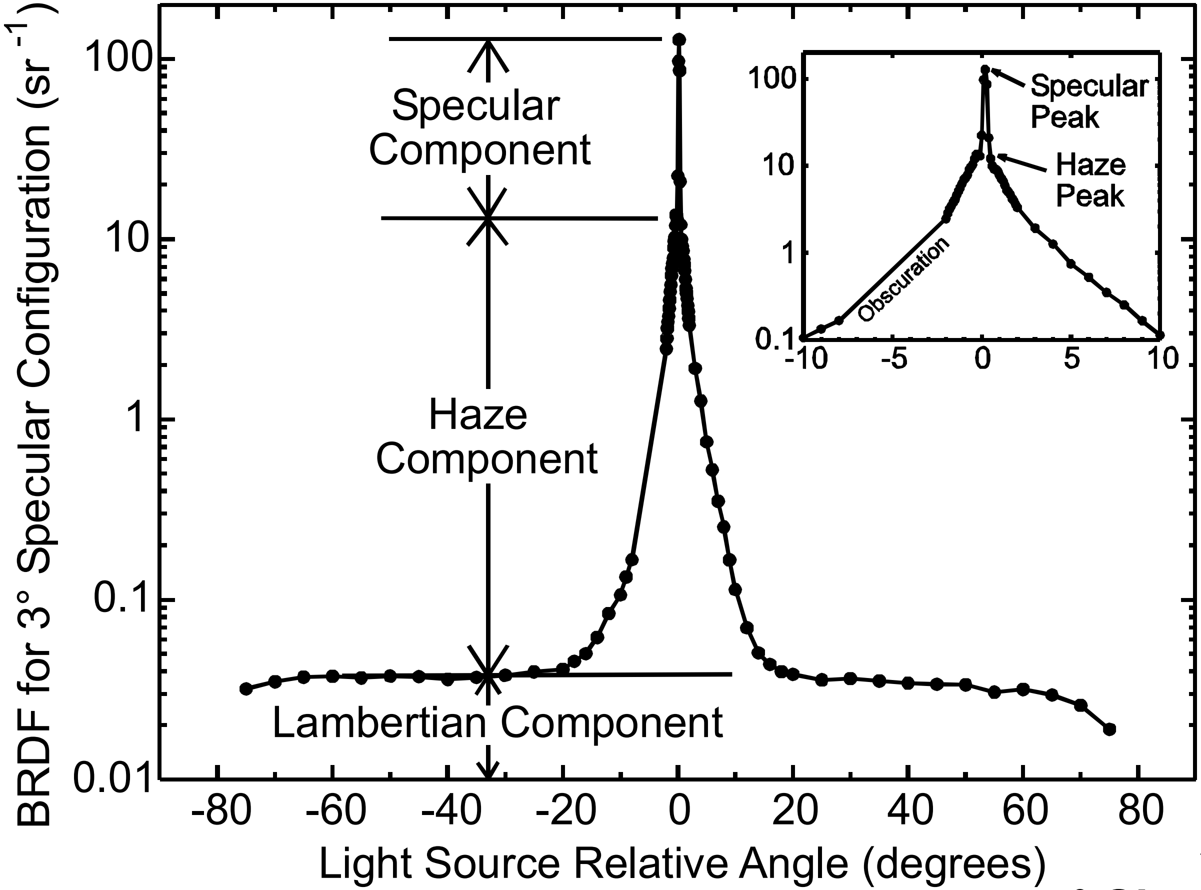
$$L_r(\theta_r, \phi_r) = qE + \rho_s L_s(\theta_r, \phi_r \pm \pi) + \int_0^{2\pi} \int_0^{\pi/2} H(\theta_i, \phi_i, \theta_r, \phi_r) L_i(\theta_i, \phi_i) \cos(\theta_i) d\Omega.$$

Background gray — **Distinct image** — **Fuzzy ball**





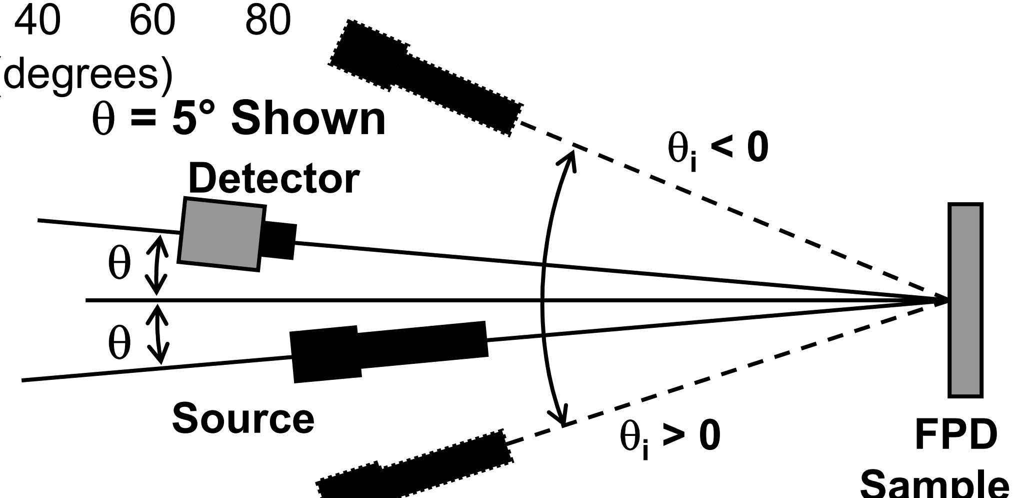
Three Component Model, Cont.



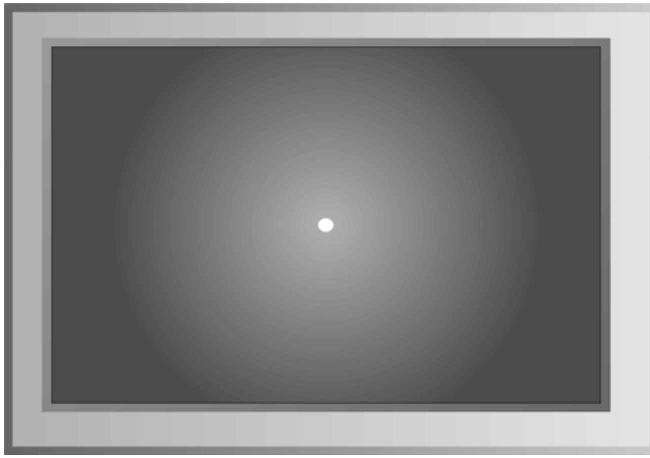
Simple BRDF (In Plane)

- **Extremes:**
  - **Lambertian (flat)**
  - **Specular (spike)**
  - **Haze is in between.**
- **Haze characteristics:**
  - **Proportional to illuminance**
  - **Directed in specular direction**

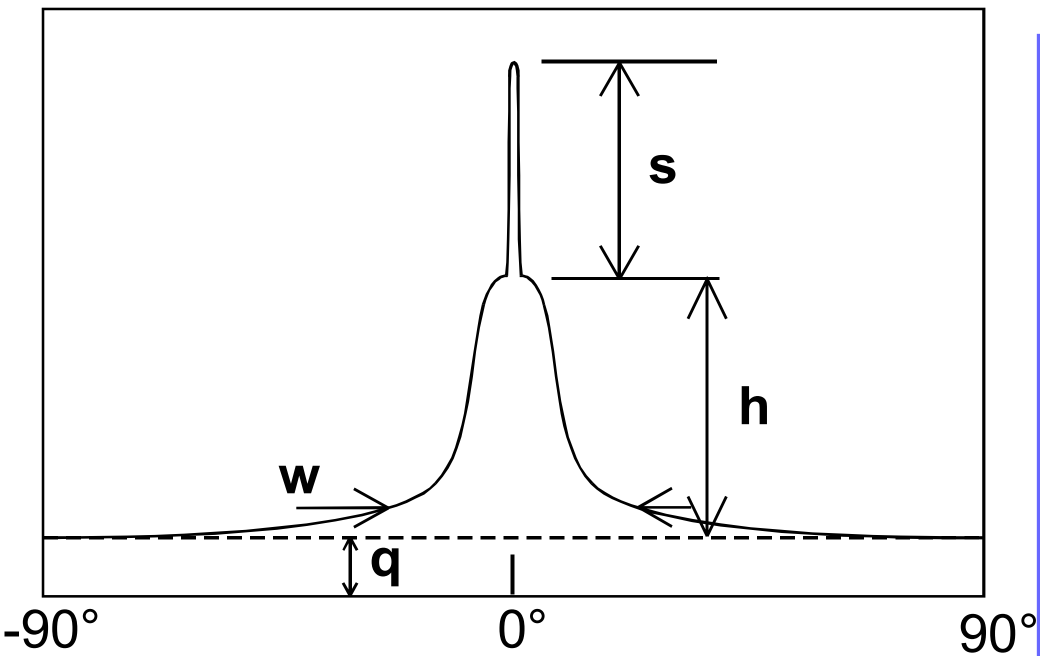
NOTE: 3 to 5 orders of magnitude possible (or more!—your eye has no trouble seeing this range!)



Three Component Model, Cont.

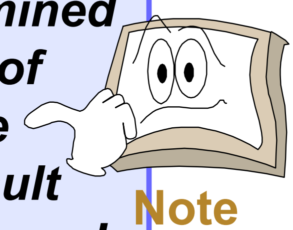


In the most general case, when there is a Lambertian, specular, and haze component, there are at least four parameters that are needed to specify the reflection characteristics since haze has a peak and a width (at the very least).



KEY POINT

If we make only one or two simple measurements, the problem is underdetermined and an infinite number of displays can exhibit the same measurement result yet look different to the eye! This underscores the need to make several different measurements to adequately characterize reflection from displays.



Display Industry Desires Simple Measurement Methods

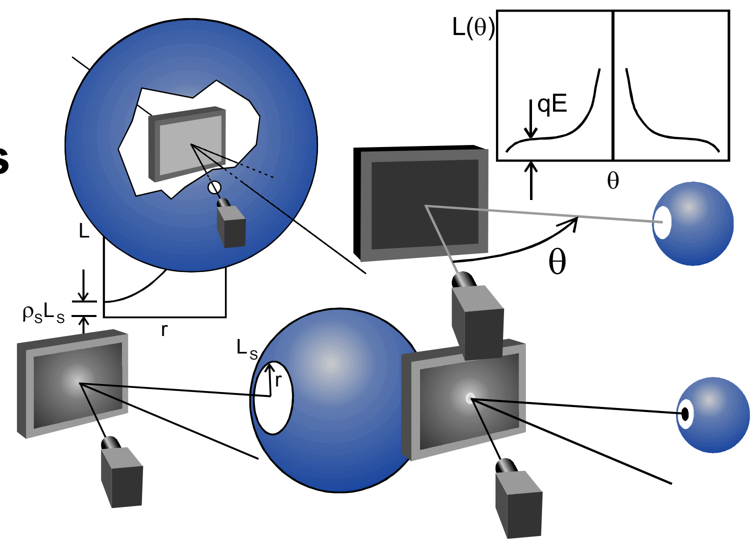
BRDF measurements are hard; simpler and faster methods are desired (required).

Acceptable Methods Must Be...

Robust: Results not subject to small apparatus imperfections or irregularities or choice of equipment

Reproducible: Same results obtained with same displays around the world

Unambiguous: Apparatus configuration and requirements clearly presented and all important concerns made obvious

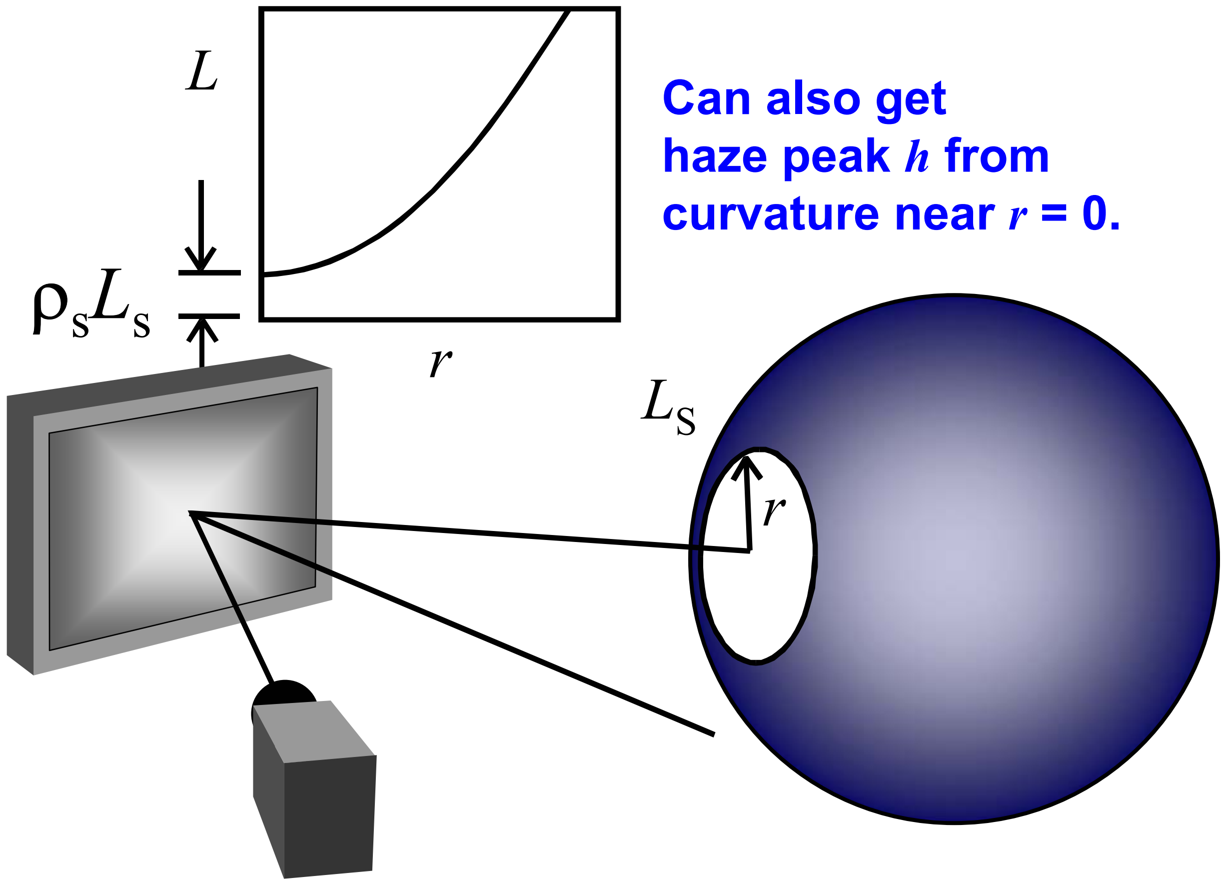


OBJECTIVE: To find the minimum set of measurements to adequately quantify reflection performance for a variety of applications.

Variable Radius Source Method (VRSM) Isolation of Specular (ρ_s) and Haze Peak (h)

Method Under Research

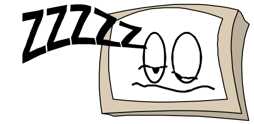
Apparatus geometry may be important for extracting any haze-peak information. Focusing on source rather than display may be required for specular component measurement. More work needed. Non-smooth surfaces (e.g., orange-peel like or heat-laminated) or specular-only displays that exhibit spikes may create problems for the method.



Can also get haze peak h from curvature near $r = 0$.

Reflection Measurements, Cont.

VRSM, Cont.



Boring Alert

$$L = qE + \rho_s L_s + \int_0^{2\pi} \int_0^{\pi/2} H(\theta_i, \phi_i, \theta_r, \phi_r) L_i(\theta_i, \phi_i) \cos(\theta_i) d\Omega.$$

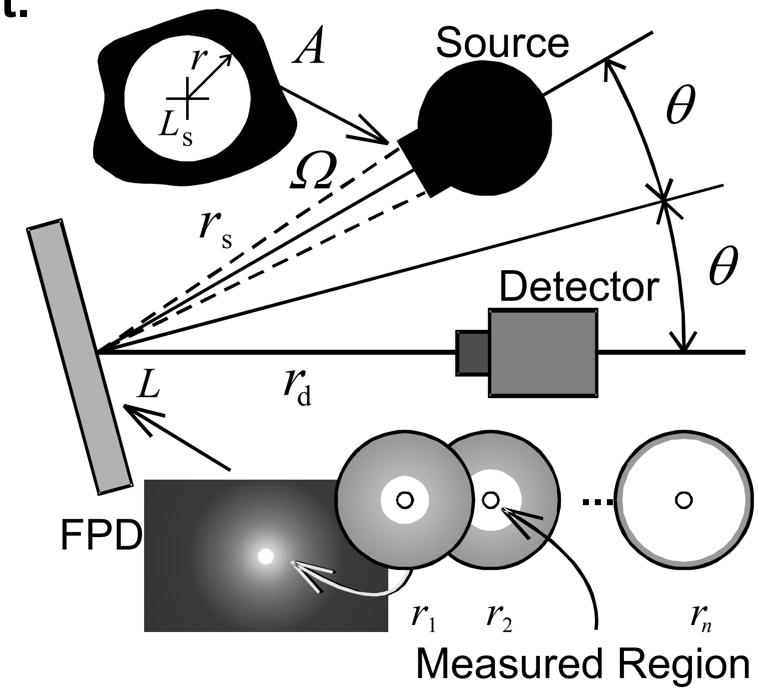
Very small source subtense, $H = h$, a constant.

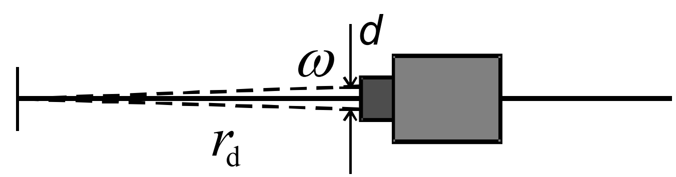
$$L = qE + \rho_s L_s + hE = \rho_s L_s + (q+h)E$$

$$E = L_s \Omega \cos\theta = \frac{L_s A \cos\theta}{r_s^2} = \frac{\pi L_s \cos\theta}{r_s^2} r^2$$

$$L = \rho_s L_s + \left[(q+h) \frac{\pi L_s \cos\theta}{r_s^2} \right] r^2$$

$$L(r) = c + ar^2 \qquad \begin{cases} \rho_s = c / L_s \\ (q+h) = a r_s^2 / (\pi L_s \cos\theta) \end{cases}$$





Note for black: $h >> q$. Typically: h ~ 10, whereas q ~ 0.05 or less.

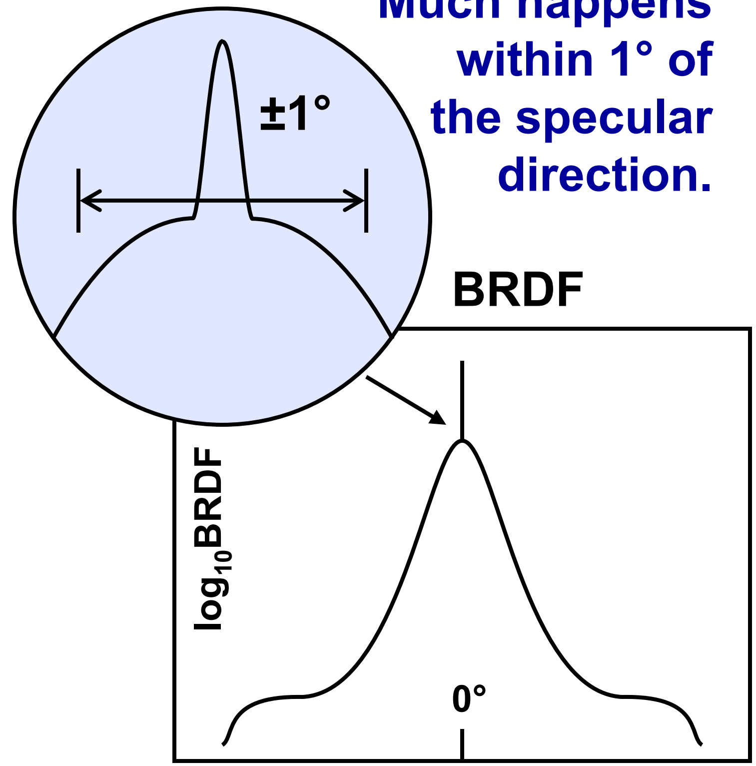
Complications: source too large, detector too large...

- Try fitting to 6th order polynomial & use quadratic result (don't need odd terms).

$$L(r) = c + ar^2 + fr^4 + gr^6$$

- Veiling glare in detector may or may not require corrections based upon measurement of black glass—more work needed here.
- Measuring a few hundredths of a degree spot can require telescopic adaptor in order to use general-purpose luminance meter.

Much happens within 1° of the specular direction.



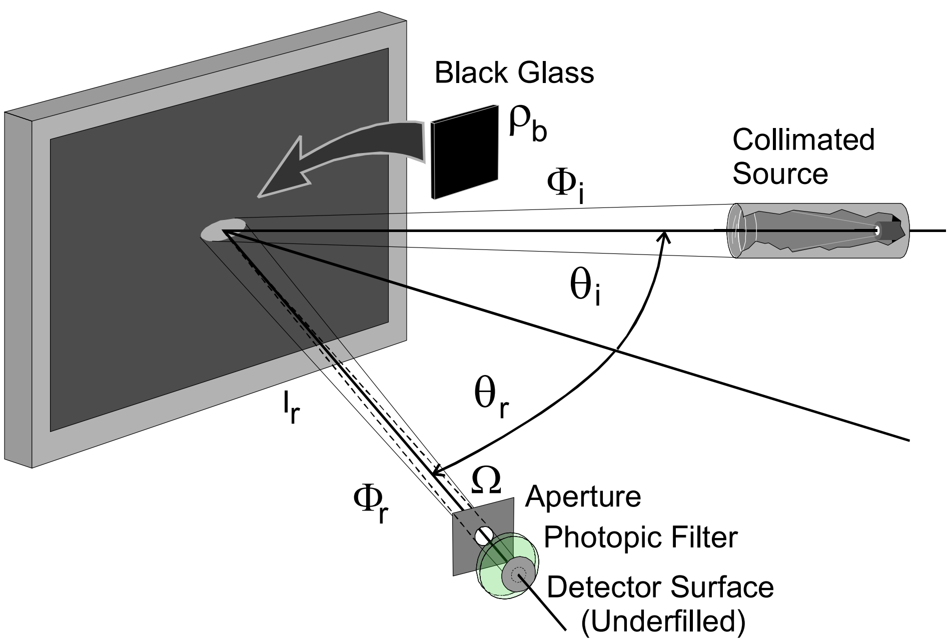
- Measurement of source made via black glass (needs calibration for specular angle employed) provides relative measurement not requiring absolute calibration of telescopic adaptor. May also reveal that the detector will need a small veiling-glare correction for each radius.
- May not work for certain types of displays (non smooth like laminated paper [orange peel] or specular-only displays with spikes).

EXTRACTION OF SOME BRDF PARAMETERS

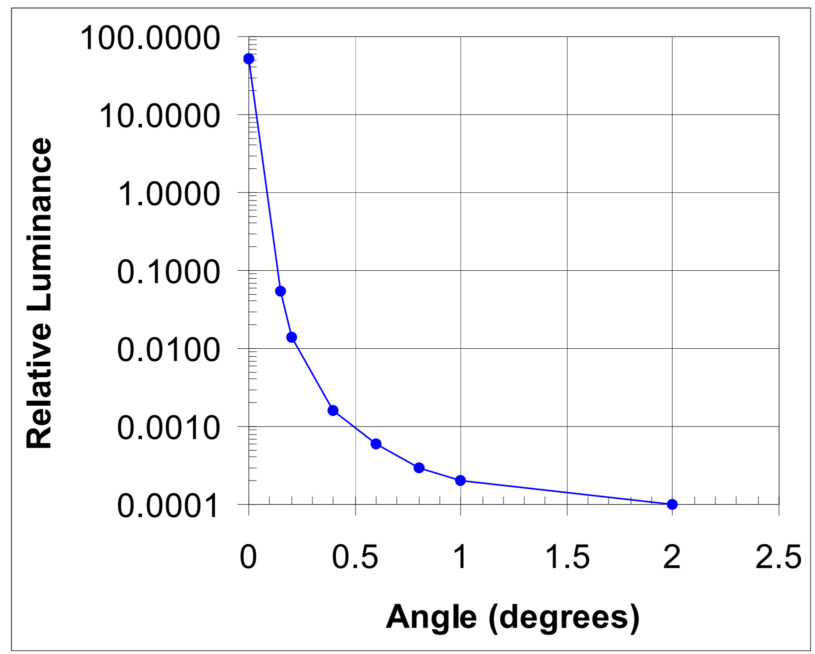
ULTIMATELY, ALL OUR RESULTS MUST BE BASED UPON HRBRDF MEASUREMENTS

High-Resolution BRDF Measurement for Comparison (Resolution < 0.2°)

The BRDF of black glass is indicative of the quality of the measurement apparatus.



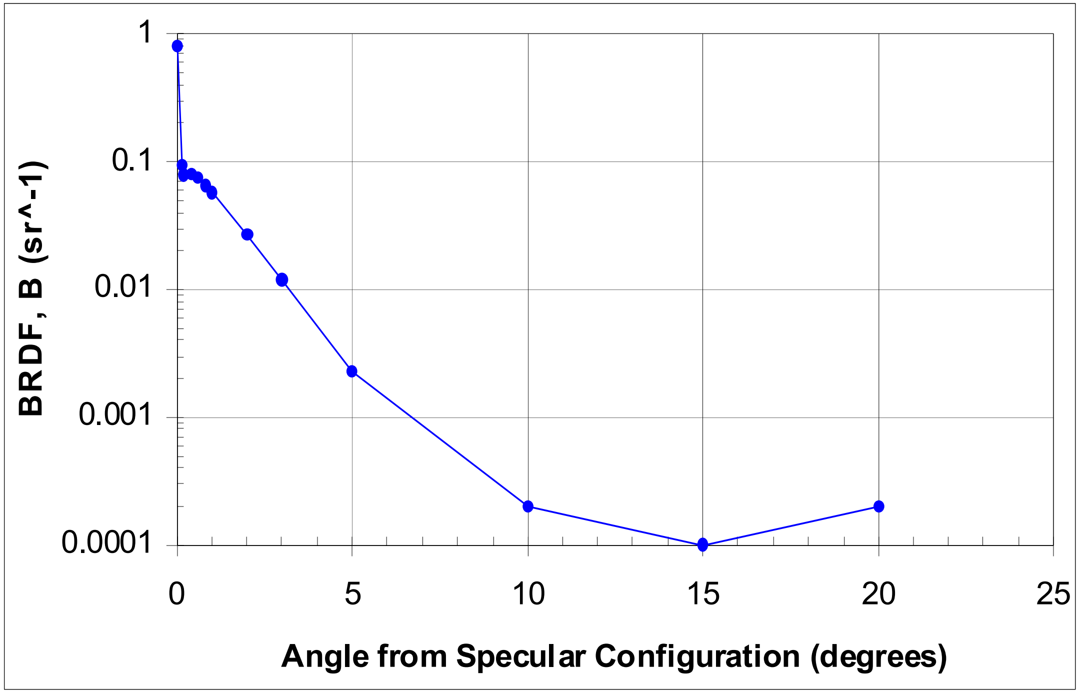
BLACK GLASS (4%)



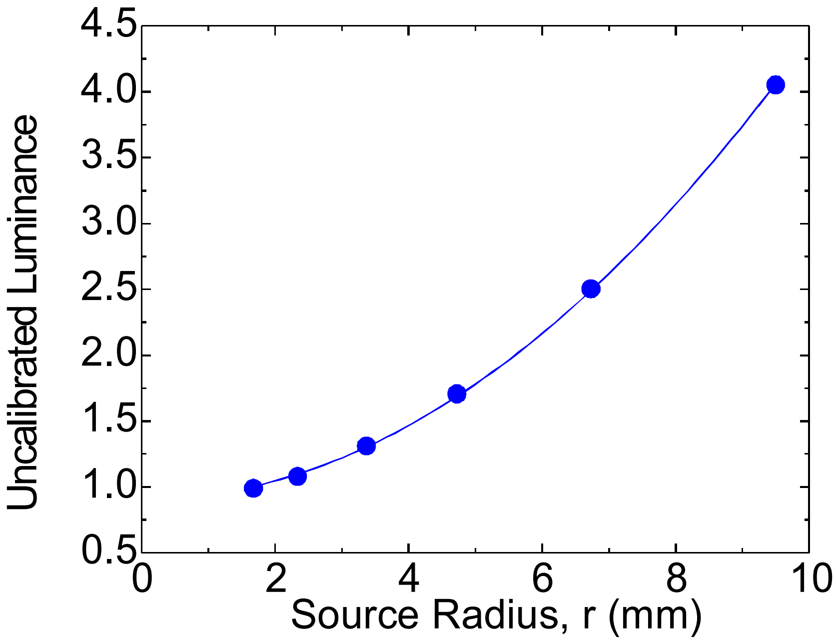
Initial Results vs. Detector Subtense (Sample D01)

	VRS-1	VRS-2	VRS-3	VRS-4	HRBRDF
Spec.Ref., ρ_s	0.000787	0.000689	0.000657	0.00066	0.000619
Haze Pk., h	9.7	9.89	9.94	9.5	10.03
Subtense (°)	1.48	0.33	0.16	2.18	0.166

Relative expanded uncertainty (k=2) estimated to be 10 %.



BRDF results for sample D01.



Data for smallest subtense fitted to quadratic. Source subtense max = 1°

THANKS FOR LISTENING!

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Projector Test
NISTSU01 Targets for Setting Up Displays
NIST