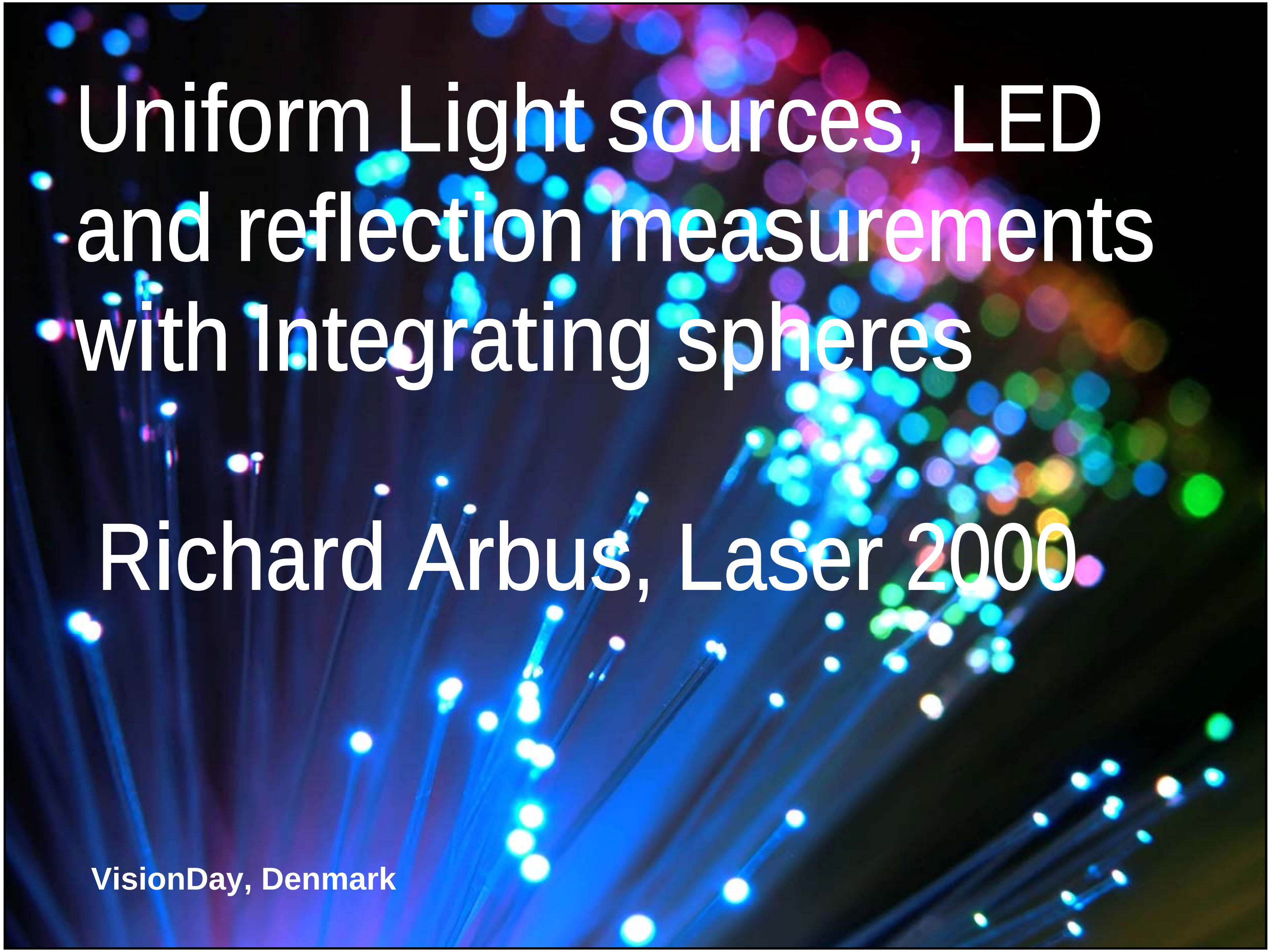
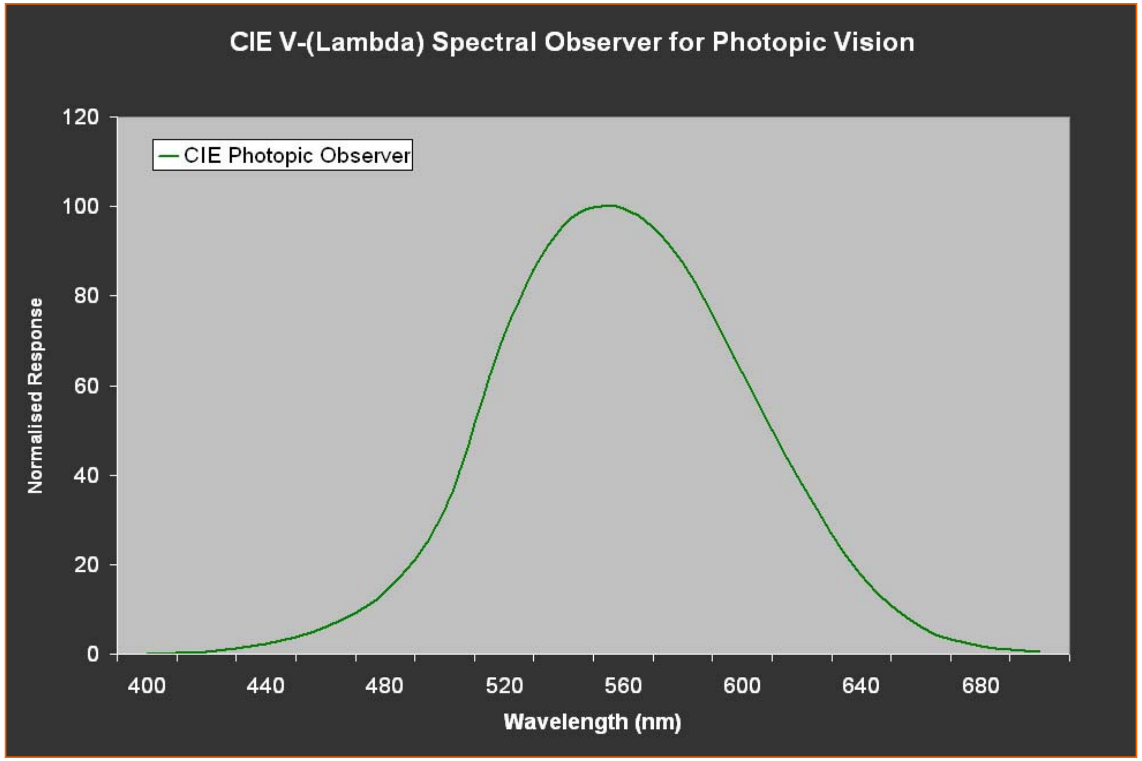

Uniform Light sources, LED and reflection measurements with Integrating spheres
Richard Arbus, Laser 2000
VisionDay, Denmark

# Radiometry vs. Photometry

- Radiometry is the measurement of the absolute amount of light
  - Measured using a "radiometer"
- Photometry is the absolute amount of light scaled to the human visual response
  - Measured using a "photometer"

# Photopic Response



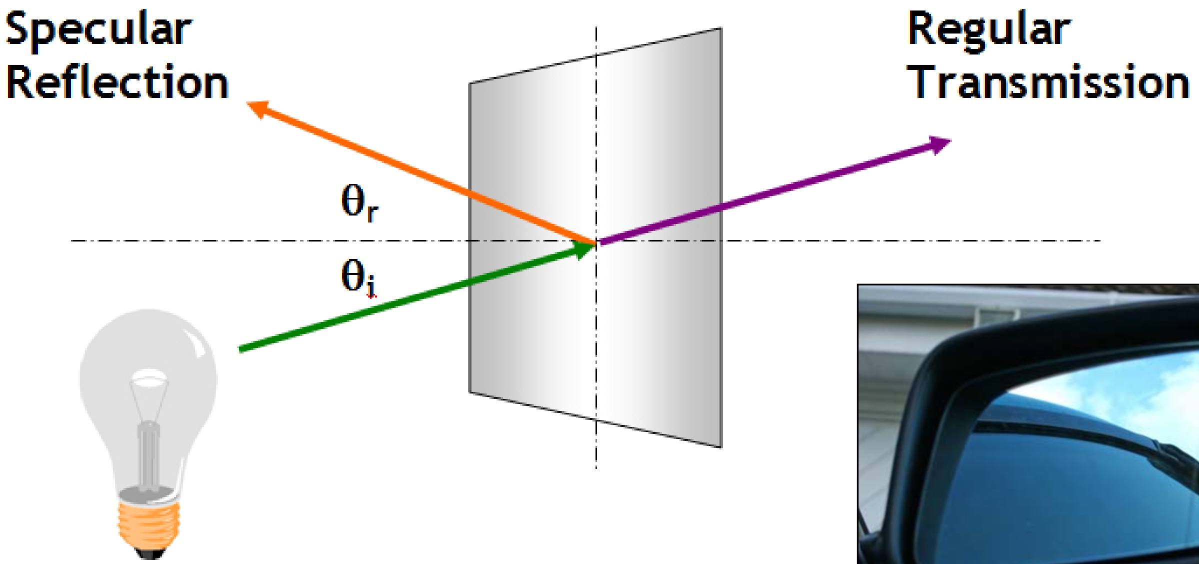
# The Light Measurement Matrix

SPECTRAL

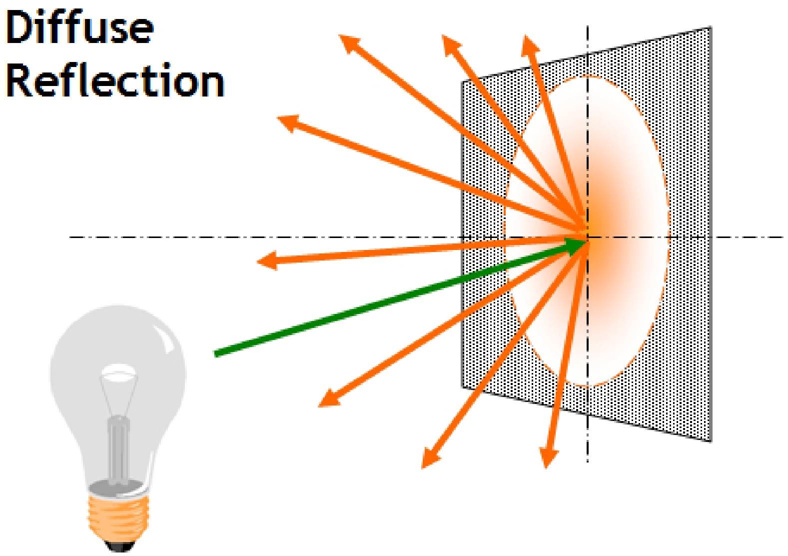
GEOMETRIC

| | Radiometric | | | Photometric | | |
|---|---|---|---|---|---|---|
| **(Total) Flux** | Radiant Flux ($\Phi_e$) | Watt | W | Luminous Flux ($\Phi_v$) | lumen | lm |
| **Flux Received per Unit Area** | Irradiance ($E_e$) | Watt per sq. meter | W $m^{-2}$ | Illuminance ($E_v$) | lux<br>(= lumen per sq. meter)<br>*foot candle*<br>*(= lumen per sq. foot)* | lx<br><br>*fc* |
| **Flux Emitted per Unit Solid Angle** | Radiant Intensity ($I_e$) | Watt per steradian | W $sr^{-1}$ | Luminous Intensity ($I_v$) | candela<br>(= lumen per steradian) | cd |
| **Flux Emitted per Unit Solid Angle per Unit Projected Area** | Radiance ($L_e$) | Watt per steradian per sq. meter | W $sr^{-1}$ $m^{-2}$ | Luminance ($L_v$) | candela per sq. meter<br>(= lumen per steradian per sq. meter)<br>*foot Lambert*<br>*(= $1/\pi$ candela per sq. foot)* | cd $m^{-2}$<br><br>*fl* |

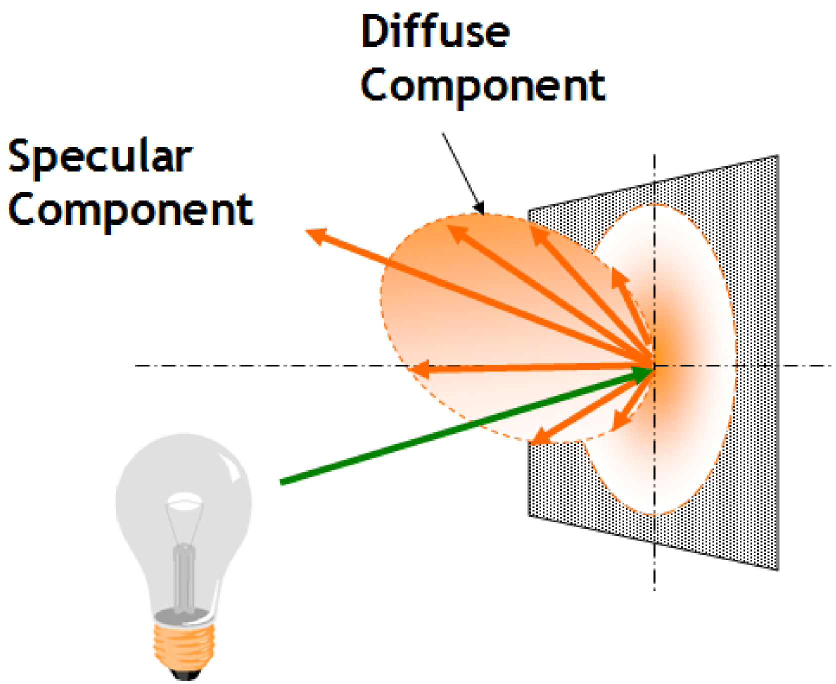
# Specular Reflectance




# Diffuse Reflectance




# Real-Life Reflectance

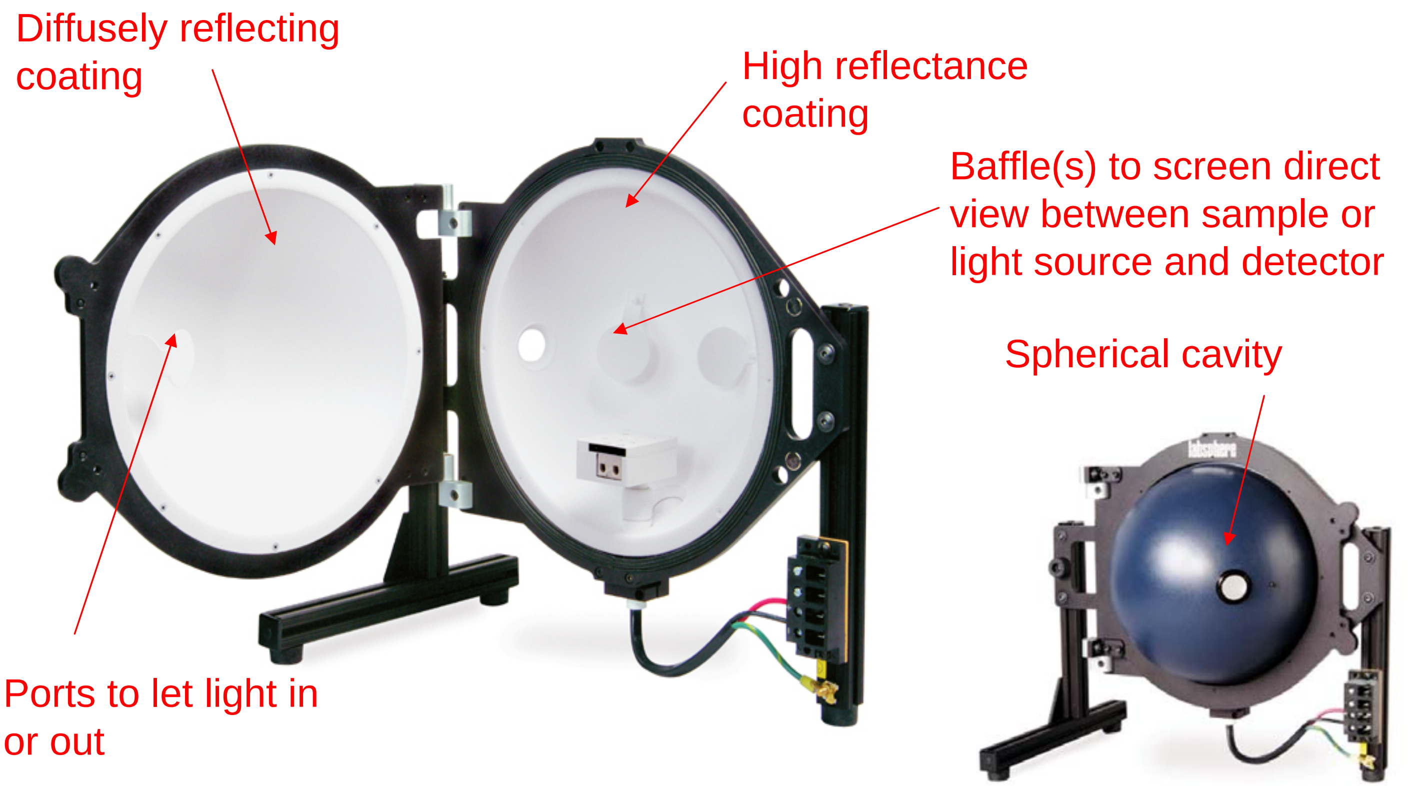


# Integrating Spheres

# What is an Integrating Sphere?

- A hollow, spherical chamber painted internally with a diffuse, high reflectance coating
- Provides directionally insensitive collection of light combined with a photodetector
- Provides a source of uniform luminance or radiance when internally illuminated

# Key Integrating Sphere Features



# When to Use a Sphere?

- If you are testing the total light output of "difficult to measure" sources
- If you need to uniformly illuminate a detector array or imaging system
- If you need to measure the total (spectral) reflectance or transmittance (colour) of a scattering material

# The Perfect Sphere…

- Is perfectly impossible!
- A perfect sphere has no holes and is coated with a 100% reflecting, perfectly Lambertian coating
- Real spheres have holes (ports) to let light in or out, and coatings with good diffuse reflectance at the 92-99% level
- Hence, specify your sphere carefully to ensure it is optimal for your specific application

# Rules of Thumb for Specifying Your Sphere

- Size - how big?
  - Bigger is better (in most cases…)
- Ports – how many and where?
  - Keep port fraction $< 5\%$ and position carefully
- Coating – what reflectance?
  - As high as possible – and it must be diffuse
- Baffles – how many and where?
  - A necessary evil – use with care

# Sphere Size

- The bigger the better for integration uniformity:
  - Caveat 1 – signal level reduces with square of sphere diameter
  - Caveat 2 – larger spheres cost more €€€/£££/$$$
- What affects the maximum & minimum powers a sphere can handle?
  - Sphere size, port fractions, coating reflectance, detector area, detector field-of-view

# Sphere Ports

- Ports (holes) & baffles reduce integration homogeneity
- The challenge is to design an integrating sphere optimised for the type of measurement required
- Design goal: keep total port area under 5% of the total sphere area (5% port fractional area)

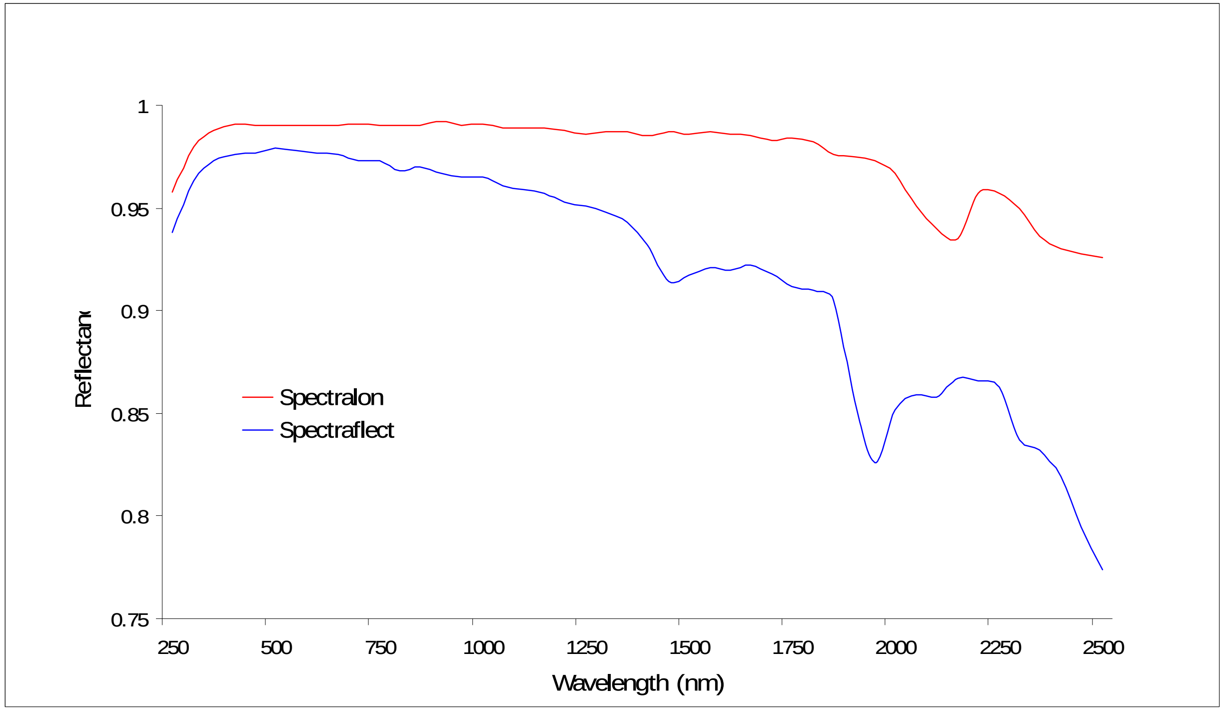
# Sphere Coatings

- Desirable attributes
  - High reflectance
  - Lambertian (diffuse) reflectance
  - Non wavelength selective
  - Stable

# Spectralon®

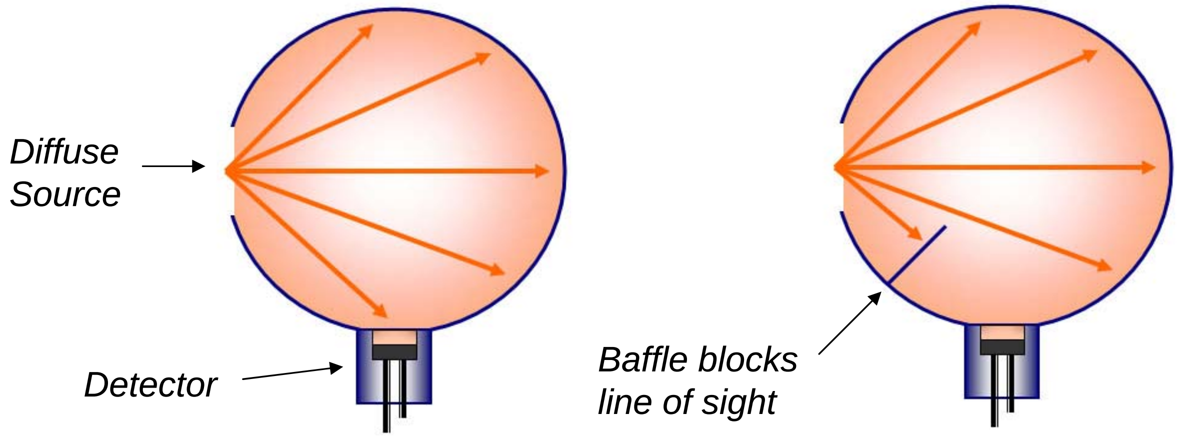
- Solid thermoplastic with highest diffuse reflectance
- Useful range 250-2500nm
- A form of scintered PTFE
- Reflectors machined from solid
- Reflectance ≤ 99.5%
- Reflectance varies with thickness (7mm optimum)
- Thermally, chemically stable & resists UV

# UV-VIS-NIR Reflectance Difference



# Sphere Baffles

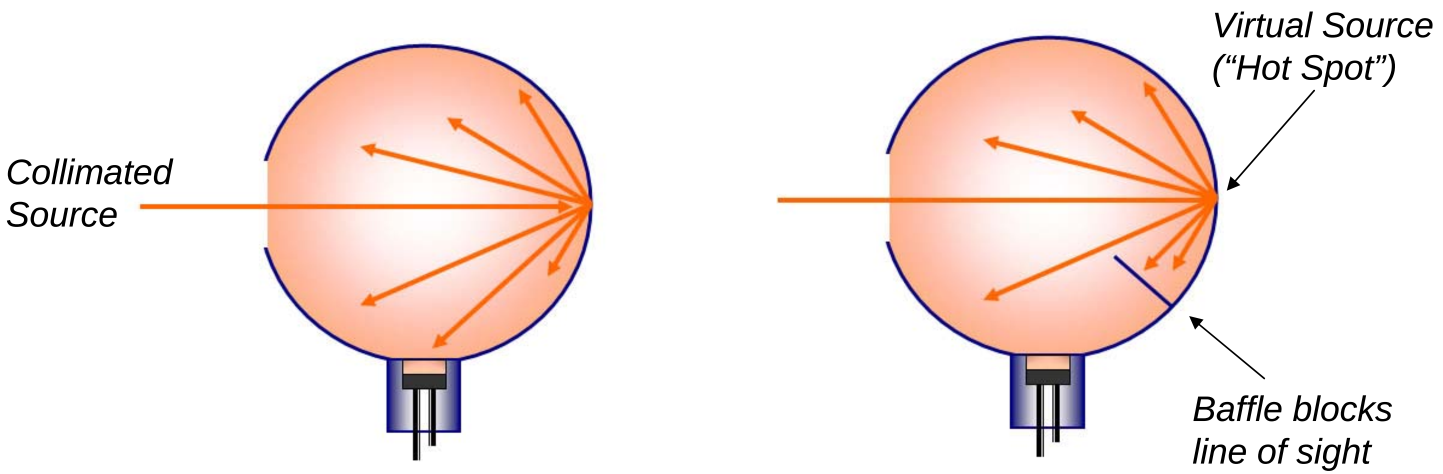
- Baffles block the line of sight between a light source and detector; otherwise you would get an artificially high radiance




Light Measurement & Integrating Spheres
March 2008

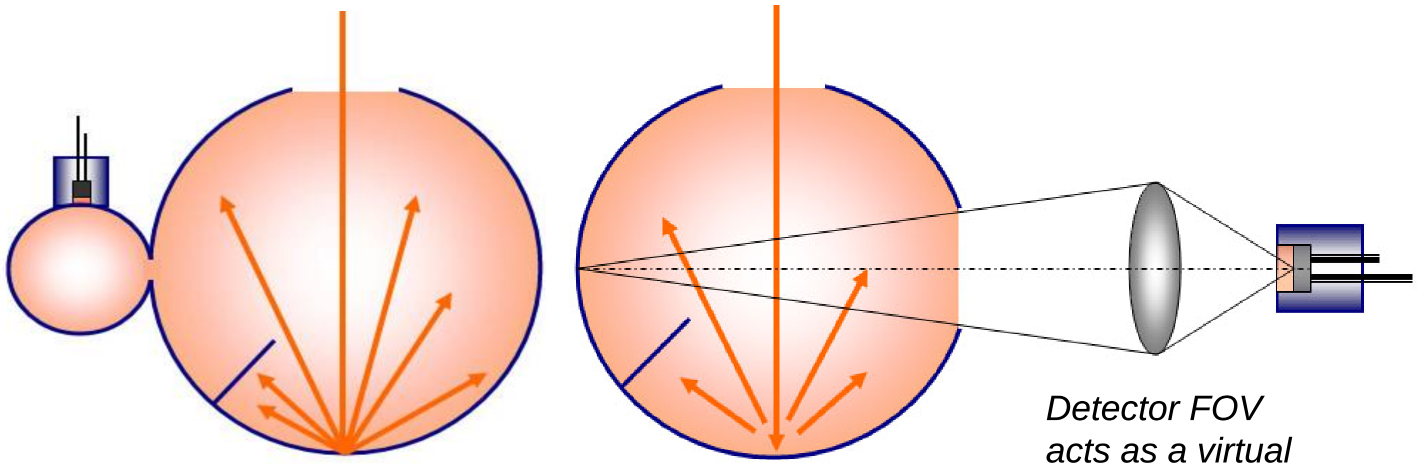
# "Hot Spots"

- For a collimated light source the sphere wall directly illuminated becomes a virtual source, or "hot spot"



# Baffles & Detector FOV

- Baffle placement and size depends on source type and detector field of view (FOV)



Detector with added diffuser

Detector FOV acts as a virtual diffuser

# Example Calculations

- Integrating sphere: 10cm diameter, 98% coating, 2cm input port, 2cm exit port:
  - Throughput = 24.7% (same lost from input!)
- As above but 5mm detector behind 1cm mask:
  - Throughput = 1.9%
- As above but 600 micron fibre, NA = 0.22:
  - Throughput = 0.0014%

# Integrating Sphere Applications

# Integrating Sphere Applications

- Light source outputs
  - Testing Lamp & LED Flux
  - Beam Flux Measurements
- Reflectance & transmittance
- Testing & calibrating imaging systems

# Testing Lamp & LED Flux

# Why Use a Sphere?

- Measures total luminous flux or spectral radiant flux (from which luminous flux and chromaticity are computed)
- Provides for measurement of flux regardless of source size, direction, divergence or size

# Specifying Sphere Size

- Larger is better for spatial integration
- 10 x lamp size if possible or 2 x for fluorescent tubes
- Picture shows the 5m sphere at NPL
- Small sphere for small sources, e.g. LEDs
- A 25cm sphere measures LED flux up to 100 Watts and > 10,000 lumens

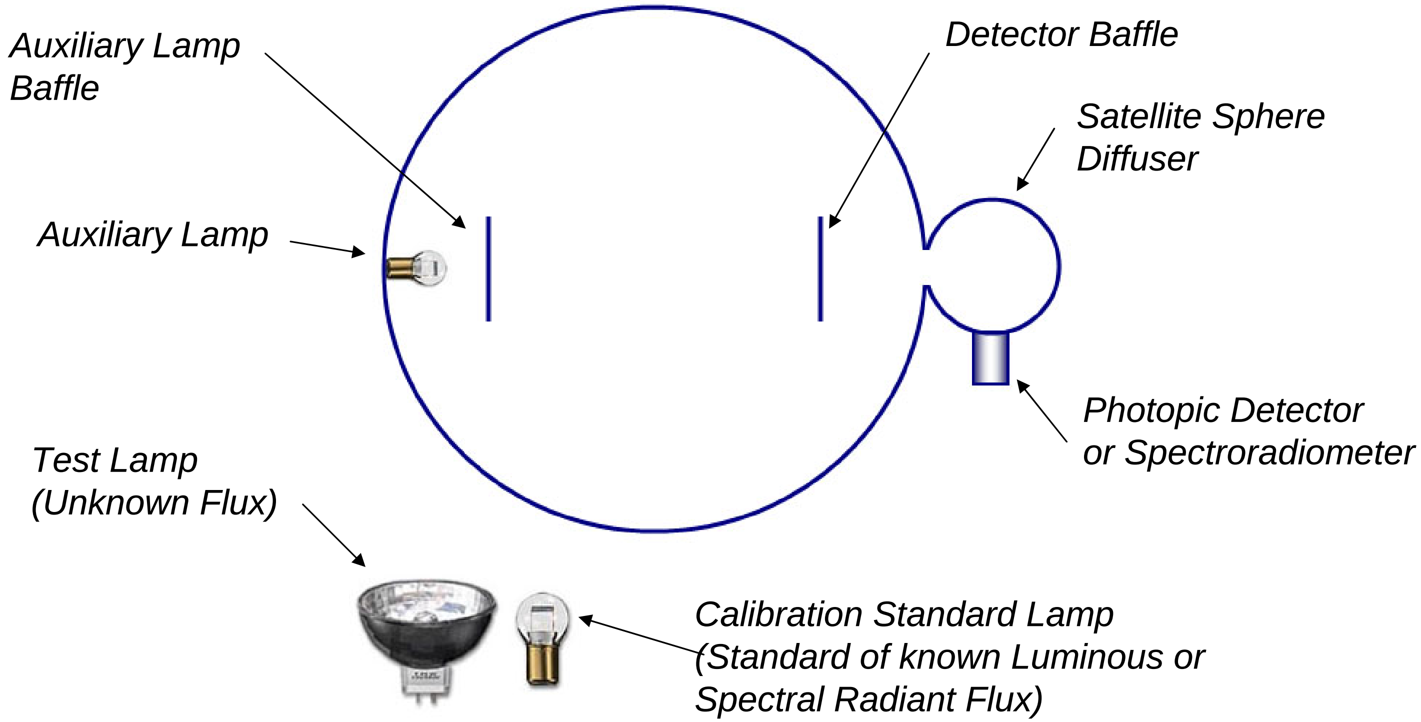
# Self Absorption

- Integrating spheres suffer from an error if the test source differs from the reference source:
  - Reference source is normally a stable tungsten halogen lamp
  - Test is e.g. LED, CFL, LED array…
- Self absorption of lamps leads to substitution error
- Flux of test source greatly underestimated (>15%)

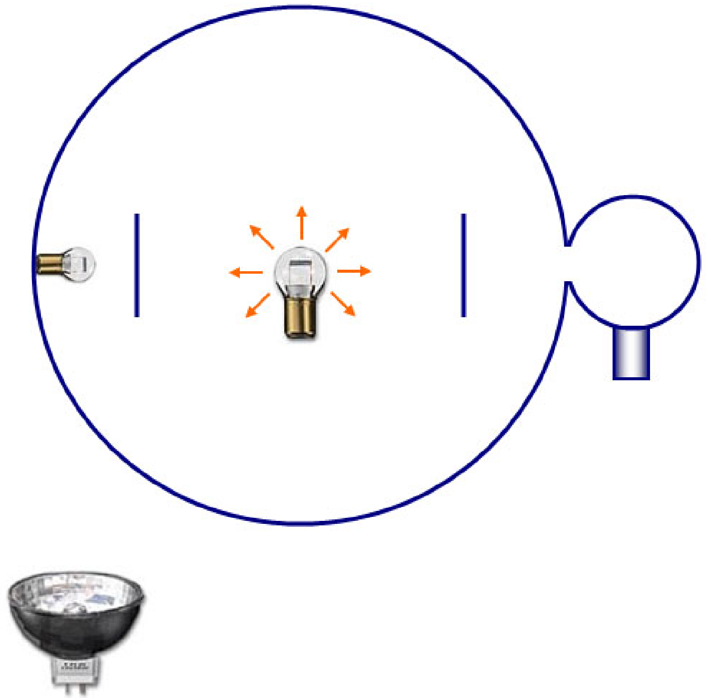
# Important Errors in Testing LEDs

- The absorption of an LED source is one of two key errors commonly encountered when measuring total flux:
  - Sample absorption error when testing physically different sources placed within a sphere
- Other main source of error is the photopic (or colorimetric) response matching when testing spectrally dissimilar sources

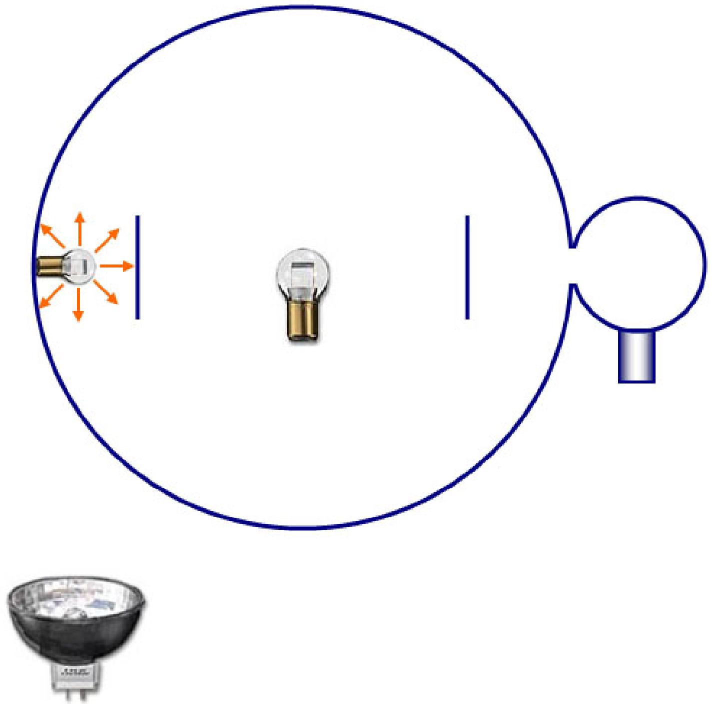
# Auxiliary Correction



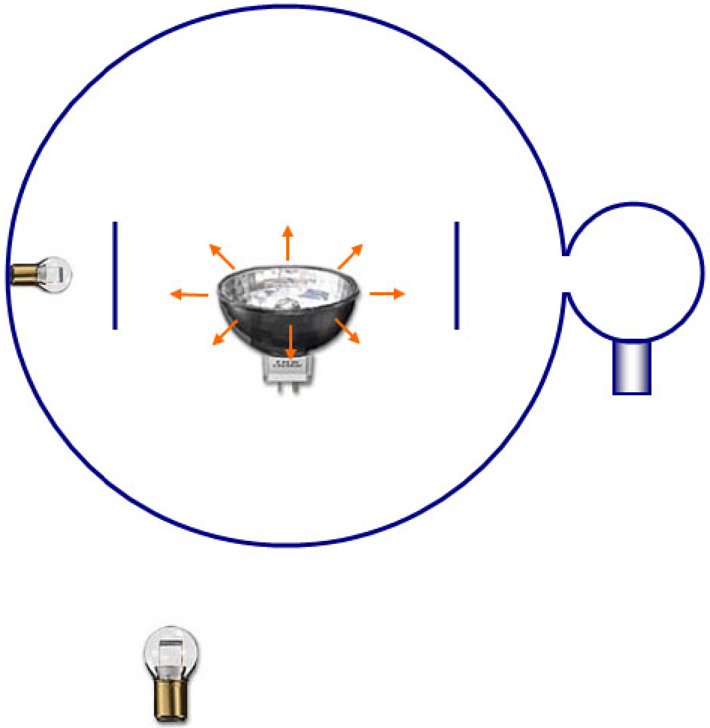
# Standard Lamp On



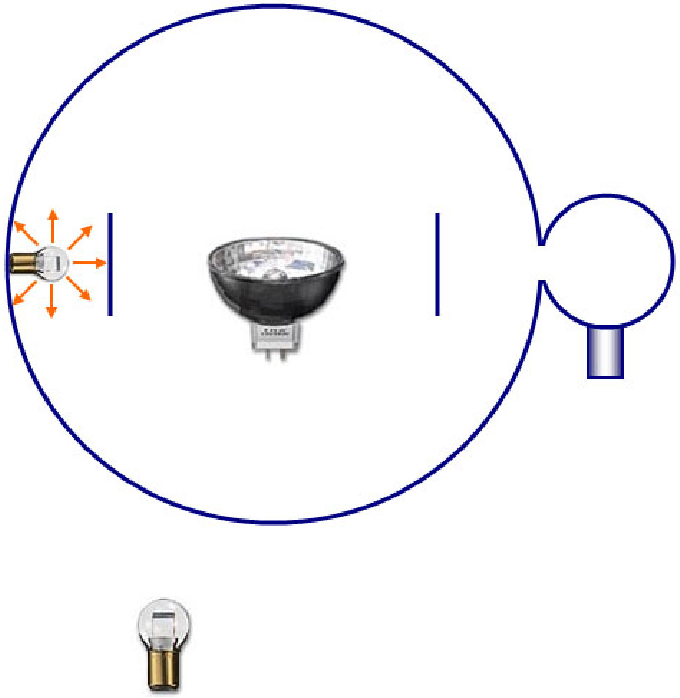
# Auxiliary Lamp On (Standard)



# Test Lamp On



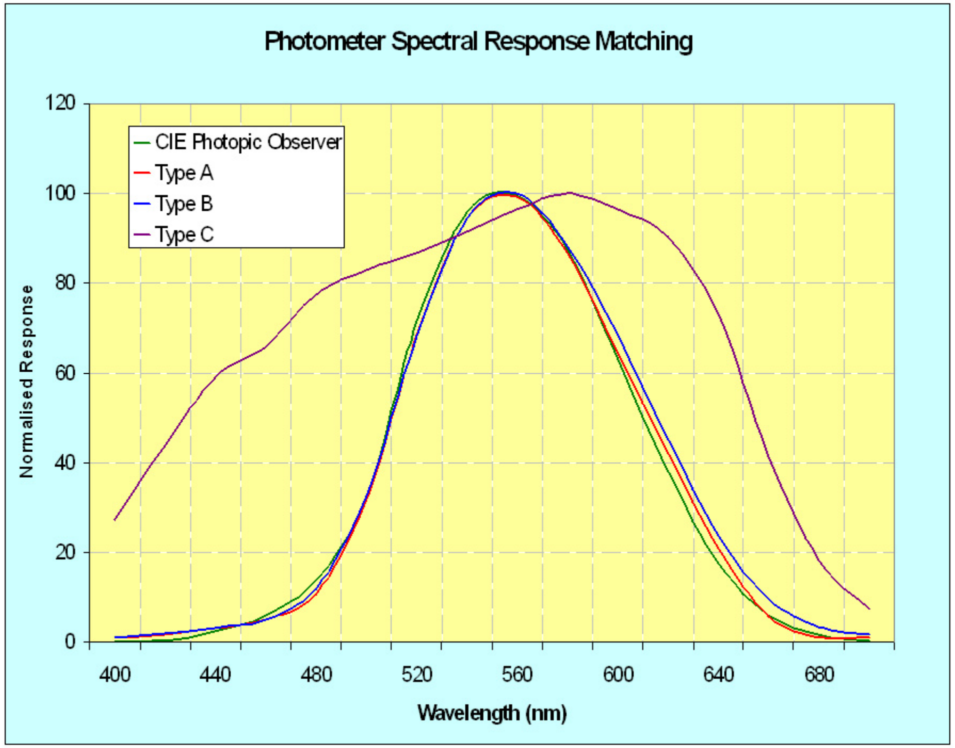
# Auxiliary Lamp On (Test)



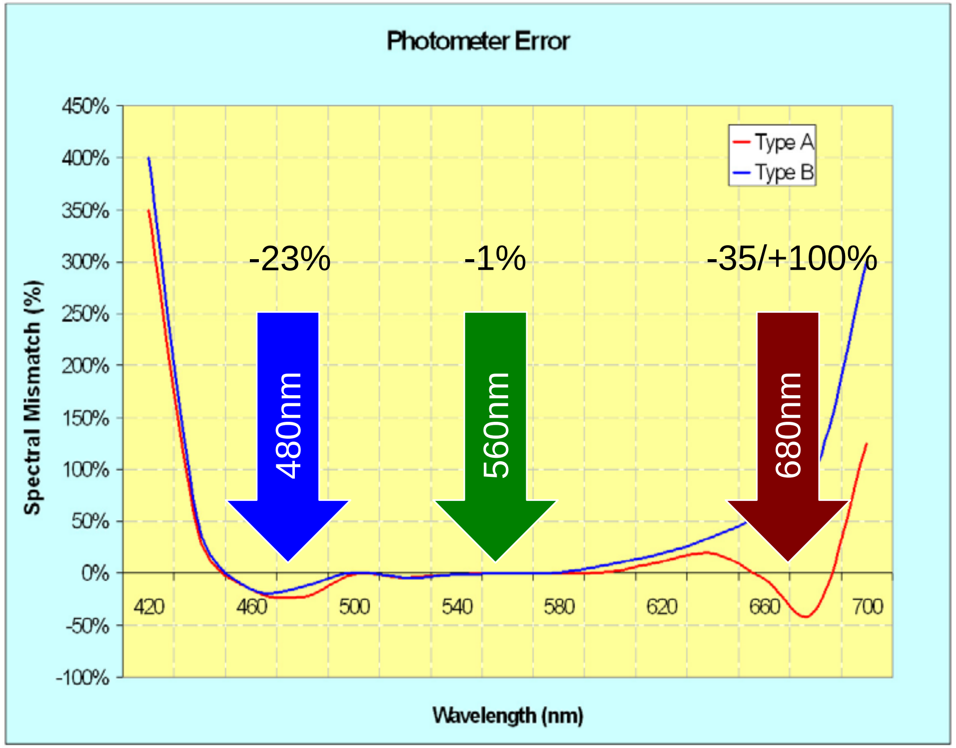
# Photopic Matching Errors

- A photometer is light meter which converts light to an electric current
- Uses a photocell (silicon or selenium)
- Filters scale spectral response of photocell to match the CIE observer
- Any filter based photometer is only accurate when measuring a source similar to that with which it was calibrated
- Reference source is usually a CIE Illuminant A incandescent lamp

# Photometer Response



# Photometer Errors



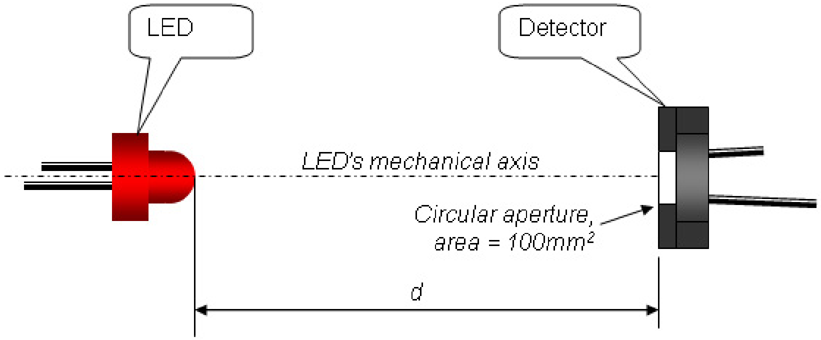
# Solutions

- Filter-based instruments suited to testing broadband sources (or green LEDs)
- For LEDs, calibrate the instrument using a reference LED with similar (identical) SPD
- OK if just need to compare output of LEDs with the same SPD
- OK if spectral mismatch known (calculate correction factor)
- Otherwise use a spectroradiometer

# CIE Average Intensity

- To provide common frame of reference for LED intensity measurements, CIE have developed the concept of average intensity (CIE 127)
  - No longer agrees with true intensity
- Defines two standard conditions for measuring near-field ‘intensity’
  - Condition A: 316 mm (0.001 sr)
  - Condition B: 100 mm (0.01 sr)
- Use condition A for narrow view angle LEDs

# CIE Average Intensity Realised




***Distance d =***

- ***316mm for CIE condition A (0.001 sr)***
- ***100mm for CIE condition B (0.01 sr)***

- Directional
- Near field intensity
- Beam tube with baffles, known solid angle

# CIE Condition A & B Realised

# Intensity versus Angle

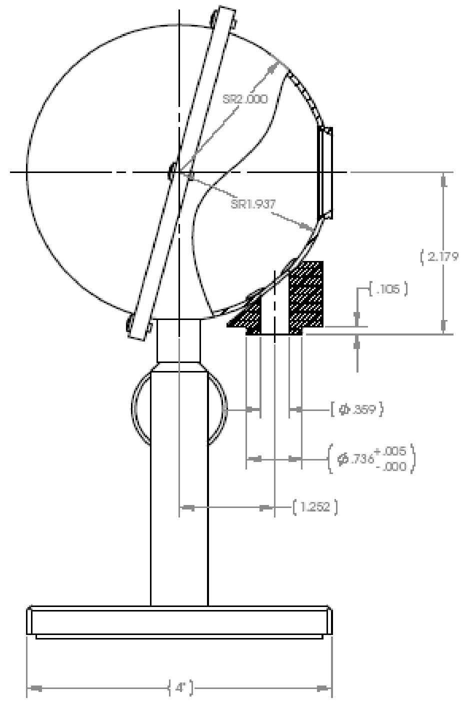
# Light Source Outside the Sphere

- Traditional radiometers use detectors that are ill-suited to many light sources:
  - Thermopile radiometers ideal for high powers (> 10-100mW) but can only measure beams of < 50mm diameter.
  - Bare photodiodes are fast and sensitive but have small acceptance areas, saturate at low flux and cannot record the flux of beams > 5-10mm diameter.

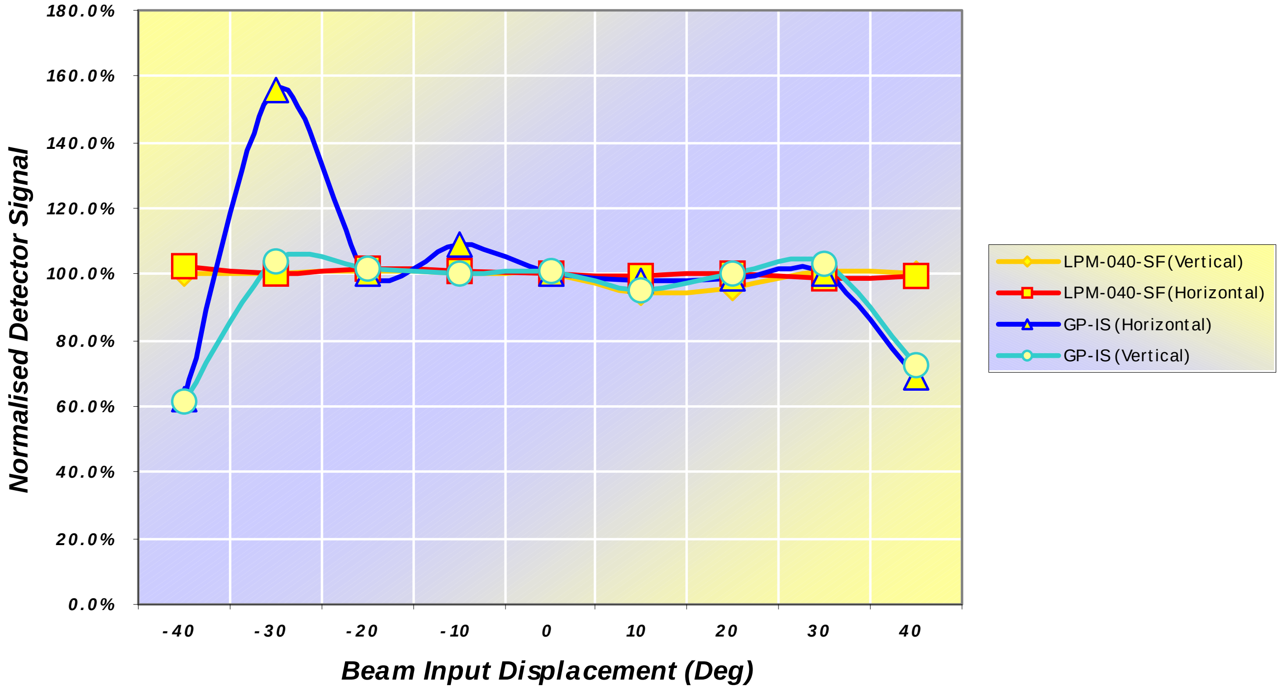
# Why a Use a Sphere?

- Measuring power (luminous or radiant flux) regardless of the size, divergence or position of the source at the sphere input.
- In other words, the power reading will depend only on the magnitude of the beam and not on the source's divergence (etc).
- An integrating sphere will attenuate high power lasers for measurement with fast-response photodetectors.

# How LPM Avoids Hot Spots



# Sphere Alignment Sensitivity



# Reflectance & Transmittance

- Collect total hemispherical reflectance or transmittance together with:
  - UV-VIS-NIR spectrophotometers
  - FTIR spectrometers
  - Colorimeters
  - Reflectometers
  - Haze Meters

# Measure

- Spectral reflectance
- Spectral transmittance
- Diffuse versus specular reflectance (gloss)
- Reflectance versus angle of incidence
- Transreflectance
- Forward scatter
- Total integrated scatter
- Haze
- Reflected & transmitted colour
- Absorption of gases
- SPF

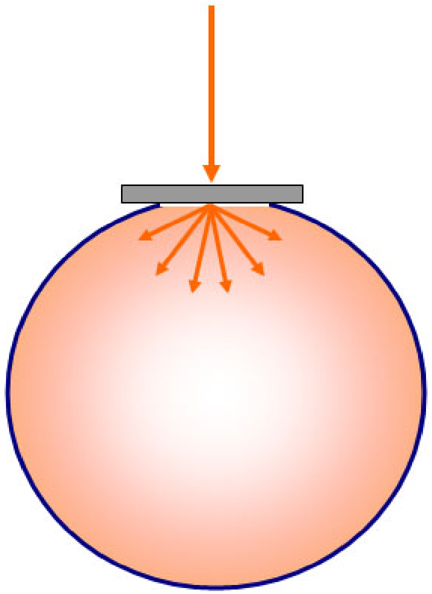
# Spectral Analysis

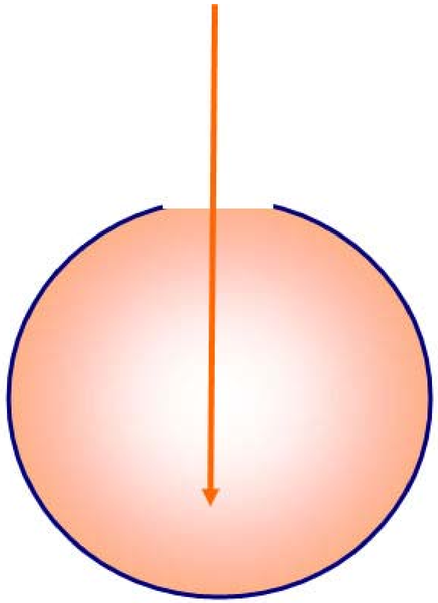
- Integrating spheres used in reflectance or transmittance are usually combined with a spectrometer or colorimeter
- Measurements are of spectral or tristimulus reflectance or transmittance
- CIE chromaticity is calculated from measured spectral reflectance/transmittance

# Reflectance/Transmittance Integrating Spheres

# Transmittance

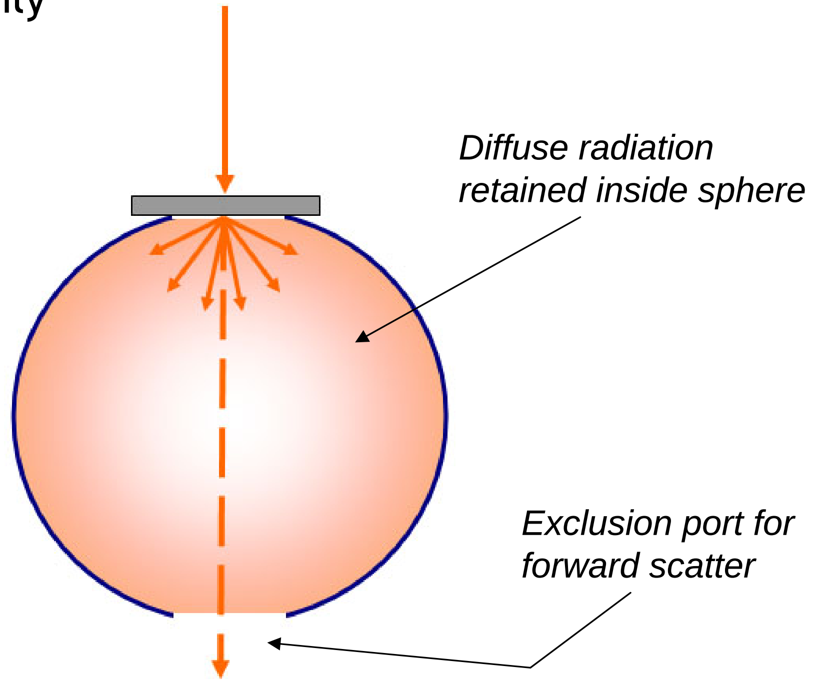
- Total transmittance of scattering materials collected in a sphere
- Calibration is against an open input port (100% transmittance) – by substitution





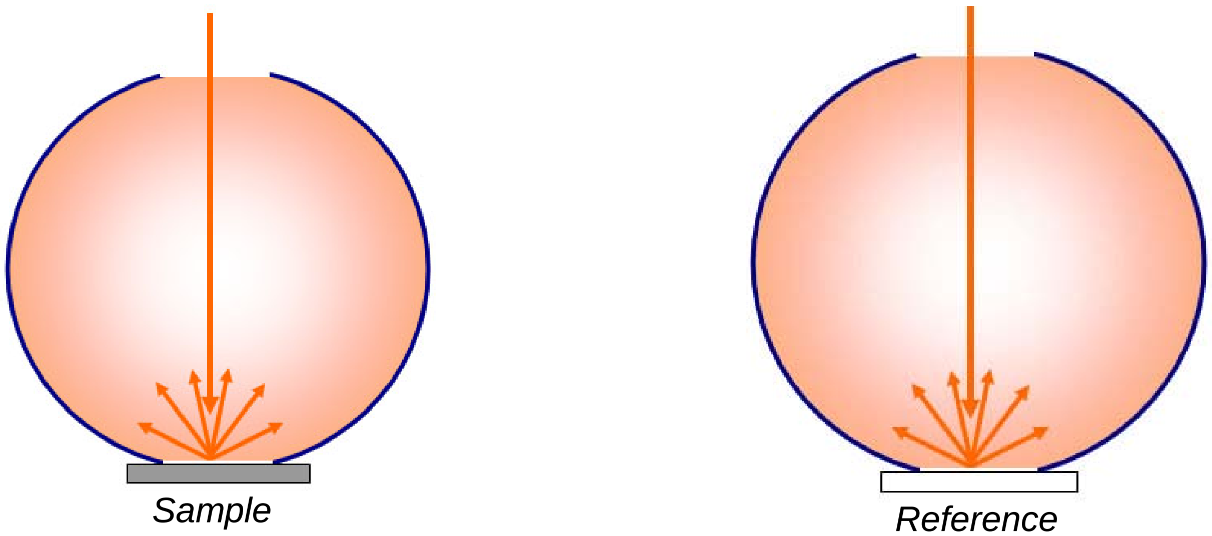
# Haze

- Haze is the diffuse-only transmittance



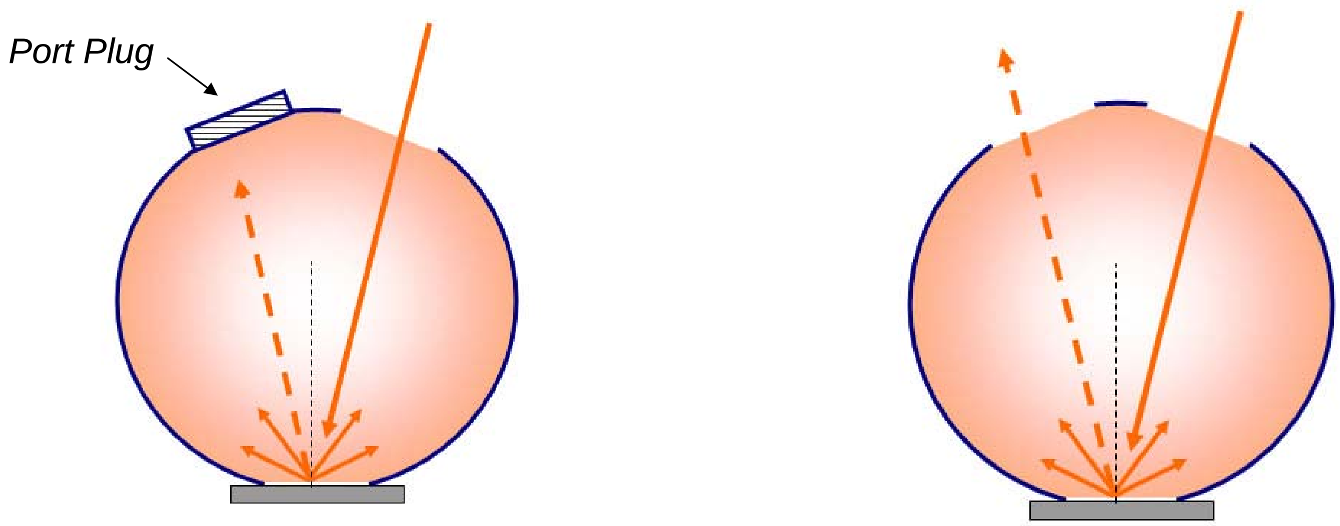
# Reflectance

- Total transmittance of scattering materials collected in a sphere
- Calibration is against a reference tile – by substitution



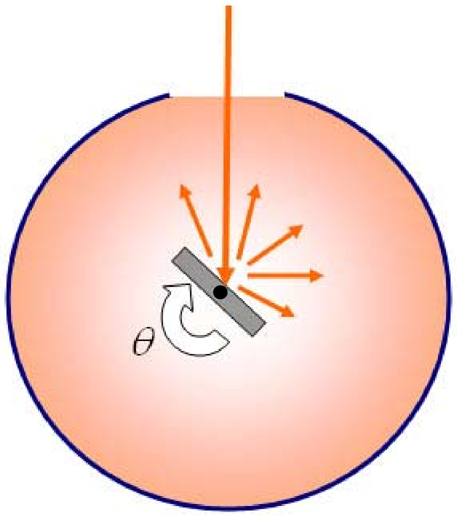
# Diffuse vs. Specular Reflectance

- Illuminate at 8°; specular component included
- Remove port plug (or replace with light trap); specular component excluded



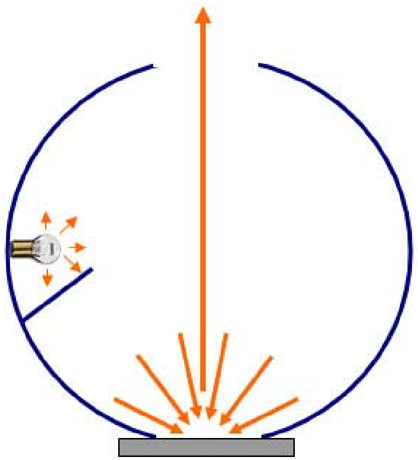
# Reflectance vs. Angle

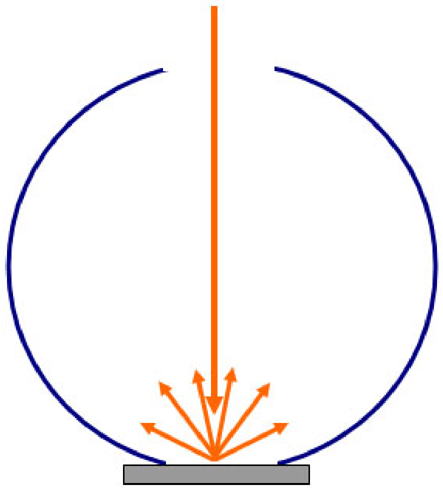
- The total reflectance versus angle of incidence can be measured by placing a sample in the centre of a sphere on a rotating stage



# Reciprocal Geometries

- Diffuse illumination with directional collection (D/0, D/8)
- Directional illumination with diffuse collection (0/D, 8/D)





*Diffuse illumination with directional collection is completely reciprocal (equivalent) to directional illumination with diffuse collection per Helmholtz law of optical reciprocity*

# Sample Substitution Error

- Integrating sphere measurements of reflectance & transmittance suffer from a unique error when measured in substitution
- The "substitution error" arises due to sample re-illumination
- Systematic, predictable and non-random error; typically 3-4%

# Solving Sample Substitution

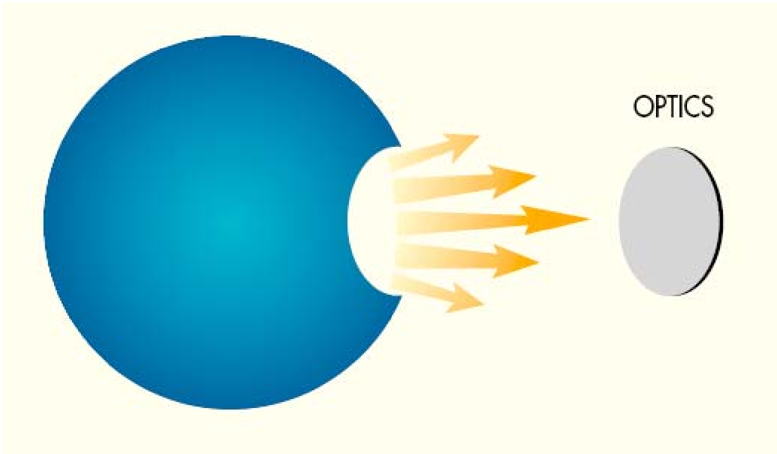
- Ignore!
- Place sample and reference on sphere at same time
  - Dummy port on single beam instruments – measure sequentially
- Match reflectance of sample & standard
- Double beam instruments do not suffer from this error

# Uniform Light Sources

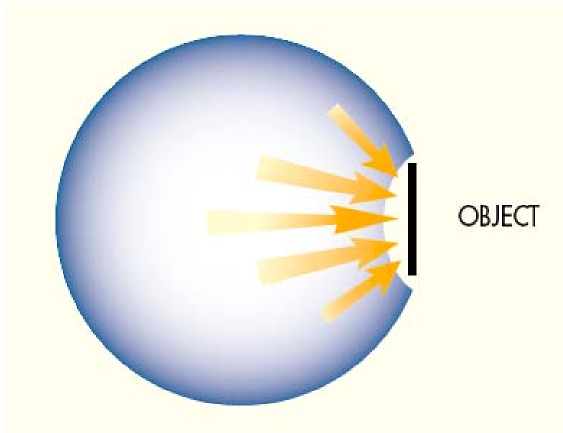
- Provide known radiance/irradiance with 99% uniformity to test and calibrate:
  - CCD arrays & cameras
  - CMOS sensors
  - Detectors & detector arrays
  - Electronic imaging devices
  - Focal plane arrays
  - Photometers
  - Radiometers
  - Remote sensing systems
  - Film sensitometry

# Uniform Source Integrating Sphere

# Uniform Light Sources

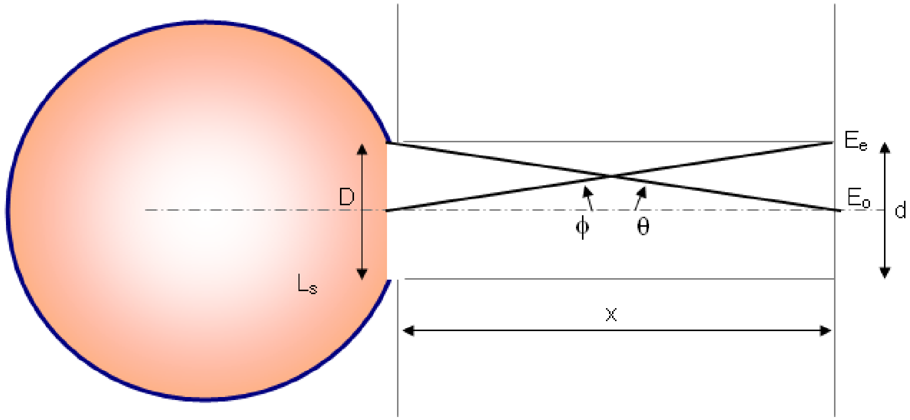



*A uniform light source serves as a source of uniform radiance (luminance) when viewed through imaging optics*




*A uniform light source uniformly irradiates (illuminates) objects placed in the plane of its exit port; illumination is diffuse*

# Uniform Irradiance

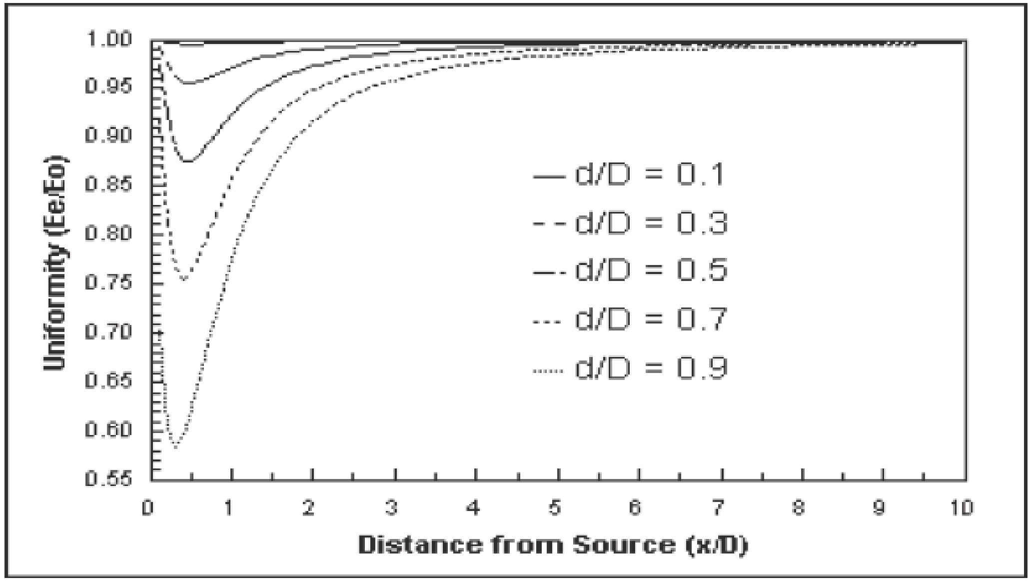



$$E_e = E_0 \cos^4 \phi$$

$$E_0 = \pi L_s \sin^2 \theta$$

*The irradiance uniformity (edge to centre, $E_e/E_0$) will vary with off-axis angle $\phi$. Irradiance uniformity is 100% in plane of exit port, then decreases as the object moves away, before increasing again at longer distances. For ($\phi$, $\theta$) < 10°, the cos$^4$ law applies.*

# Irradiance Uniformity vs. Distance



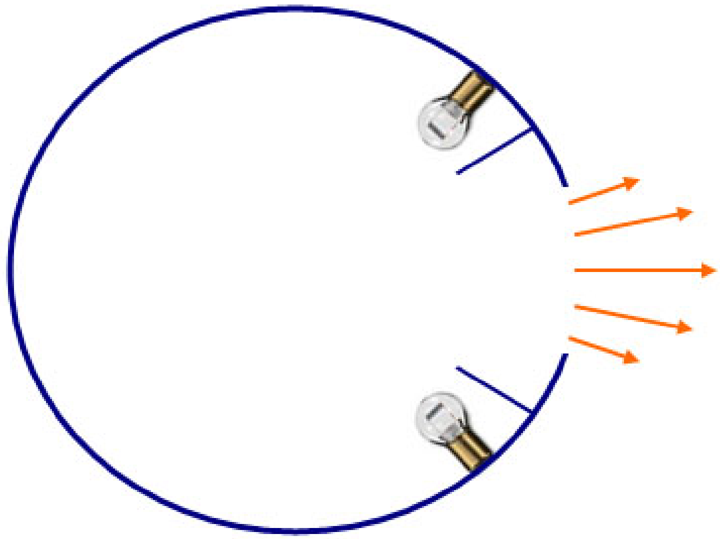
# Selection Rules of Thumb

- Size of exit port defined by front objective on camera, the measurement FOV or size of detector array
- Size of exit port relative to sphere diameter drives uniformity:
  - 1/3 for > 98% uniformity
  - 1/4 for > 99% uniformity

# How to Specify a Uniform Source

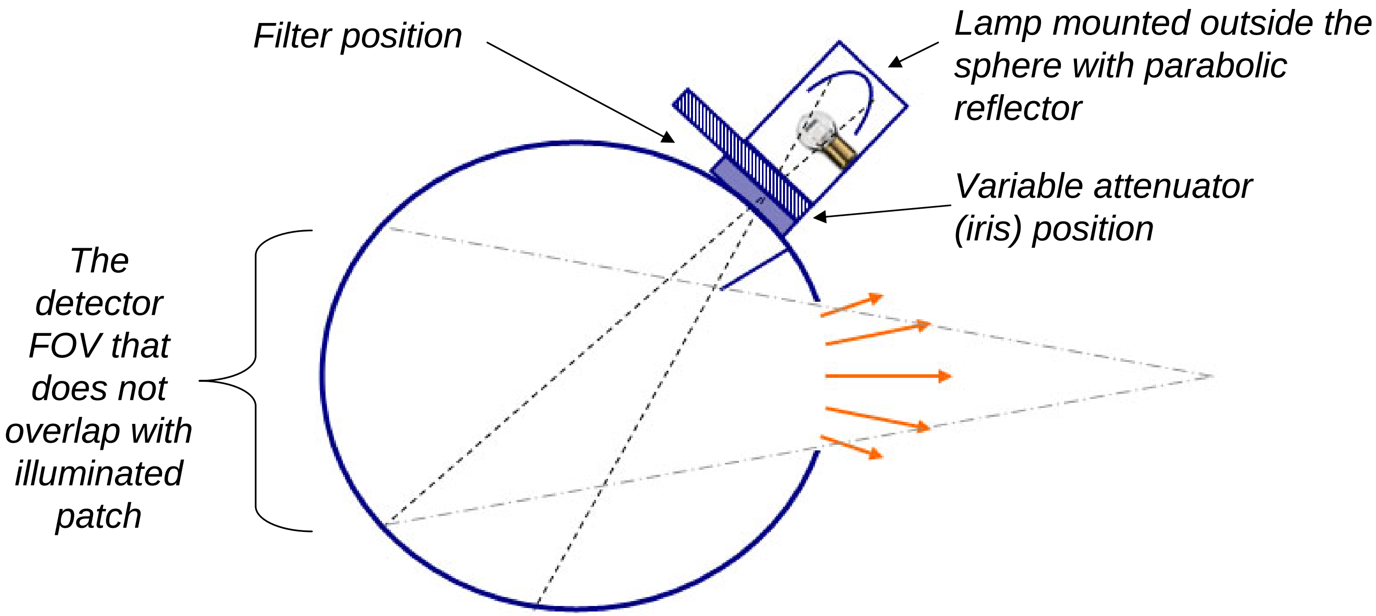
- Sphere size
  - Larger is better for uniformity
- Sphere coating
  - Spectral range; throughput (Spectralon)
- Number of lamps & type of lamps
  - Radiance level; colour temperature
- Placement of lamps
  - Imaging vs. non-imaging; external if continuous radiance adjustment required
- Output monitoring
  - Do you need to track luminance over time?
  - Spectral or broadband analysis?

# Internal Lamps



*Plus: highest efficiency*
*Minus: luminance not continuously adjustable (lamp must be operated at constant current); no spectral filtering*

# External Lamps



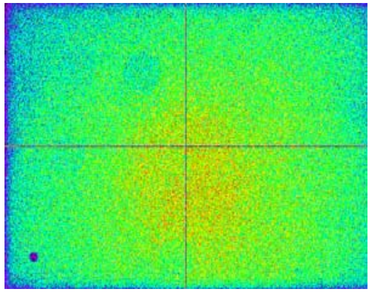

*Minus: lower efficiency*
*Plus: can be attenuated for variable luminance; can be filtered to achieve desired spectral power distribution (colour temperature)*

# Illumination Efficiency

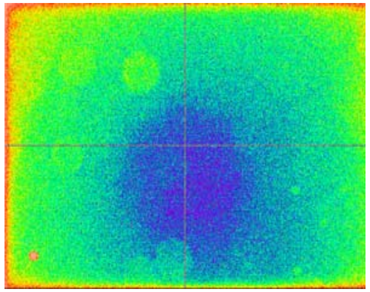
- Internal lamp provides 100% efficiency
- External lamp gives 40% of this luminance
- Fitting a variable attenuator reduces this luminance to 72%
- External lamp with attenuator gives 29% of the luminance of an internal lamp of same power

# Correcting CCD Errors

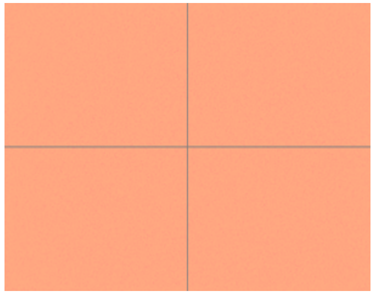
- Create correction matrix from acquired image
- Multiply data images by correction matrix



Uncalibrated image of Uniform Light Source



Calibration image of Uniform Light Source



Corrected image

# Further Information

- Visit www.labsphere.com to download…
- Technical Guides to:
  - Integrating Sphere Theory & Applications
  - Integrating Sphere Radiometry & Photometry
  - Uniform Light Source Applications
  - Diffuse Reflectance Materials & Coatings
  - LED Radiometry
  - Tracking Uniform Source Radiance
  - SPF of Sunscreens & Fabrics
  - Reflectance Spectroscopy (various)


Still Awake?