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advancing the technology of light

# Workshop Agenda (All times in MDT)

- 0730-0840 Sphere Theory and Applications (Durell)
- 0840-0910 Uniform Source Tutorial (Durell)
- 0910-0920 Sphere Calibrations (Durell)
- 0920-0930 (Virtual) Coffee Break
- 0930-1010 Considerations for Uniform Source Specifications (Scharpf)
- 1010-1020 Commercial considerations (Scharpf)
- 1020-1040 NASA GLAMR Case Study (Brendan McAndrew, NASA GSFC)
- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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# Integrating Sphere Theory

CALCON Workshop 2020

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# Sphere Technology

- DIFFUSE REFLECTANCE COATINGS AND MATERIALS
  - Geometry & Spectrum
  - Applications
- INTEGRATING SPHERES
  - Theory
  - Design
  - Applications

# Diffuse Reflecting Materials & Coatings

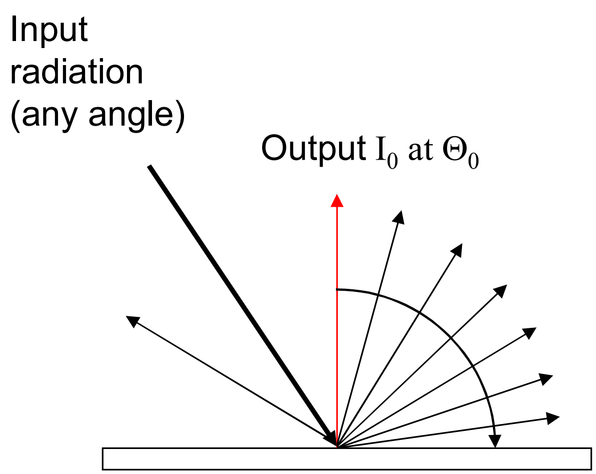
## GEOMETRY

**Ideal is perfectly Lambertian (diffuse)**

## SPECTRUM

**Ideal is perfectly reflecting (100%)**

# Geometry - Lambertian Reflector

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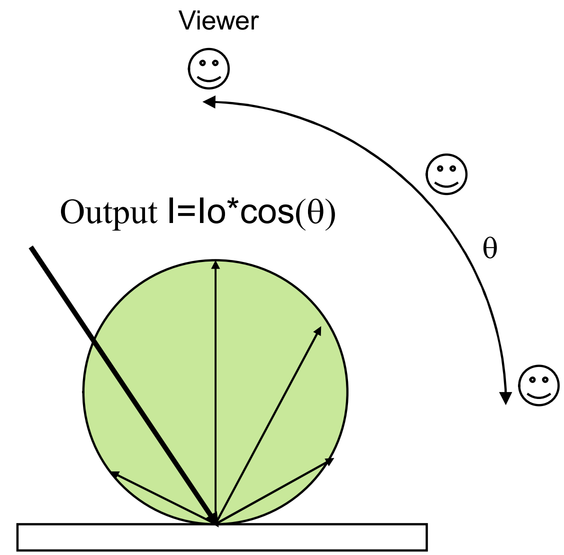


Equal Energy scattered at all angles over $\pi$ steradians with 100% Reflectance

To an observer, $I_0$ seems to vary as to cosine of the angle $\theta$. Intensity is a function of the area of the target presented to the angle of the viewer.

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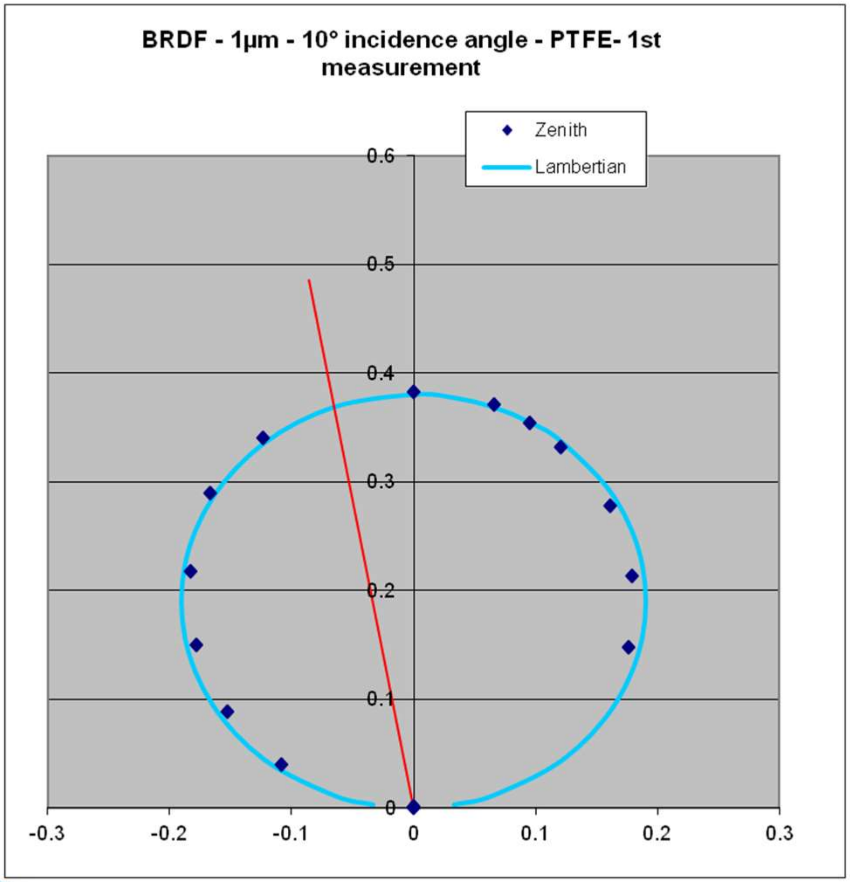
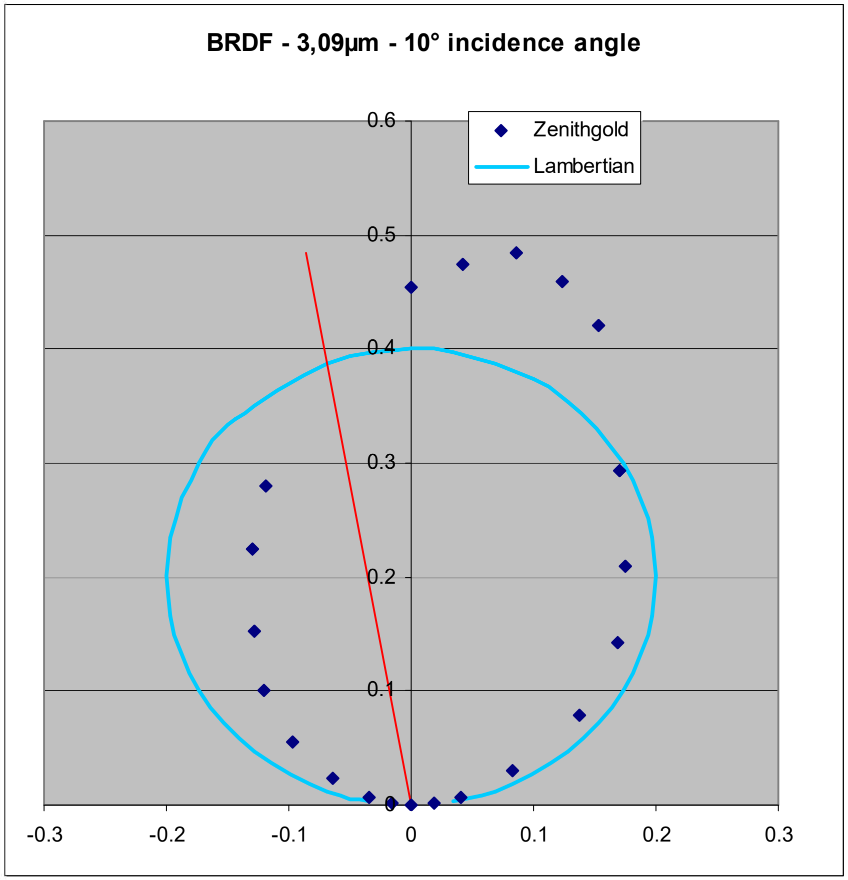
# Real "Lambertian" Materials – Spectralon & Infragold

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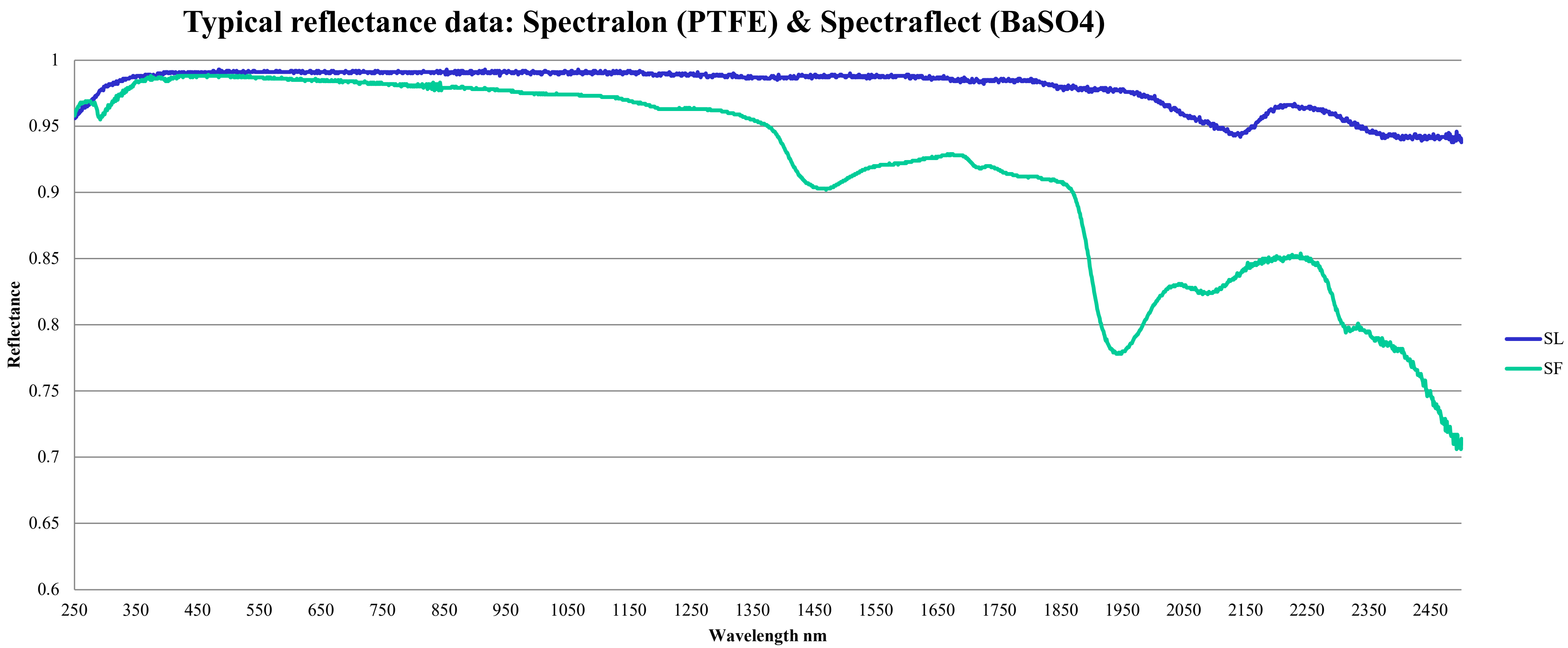
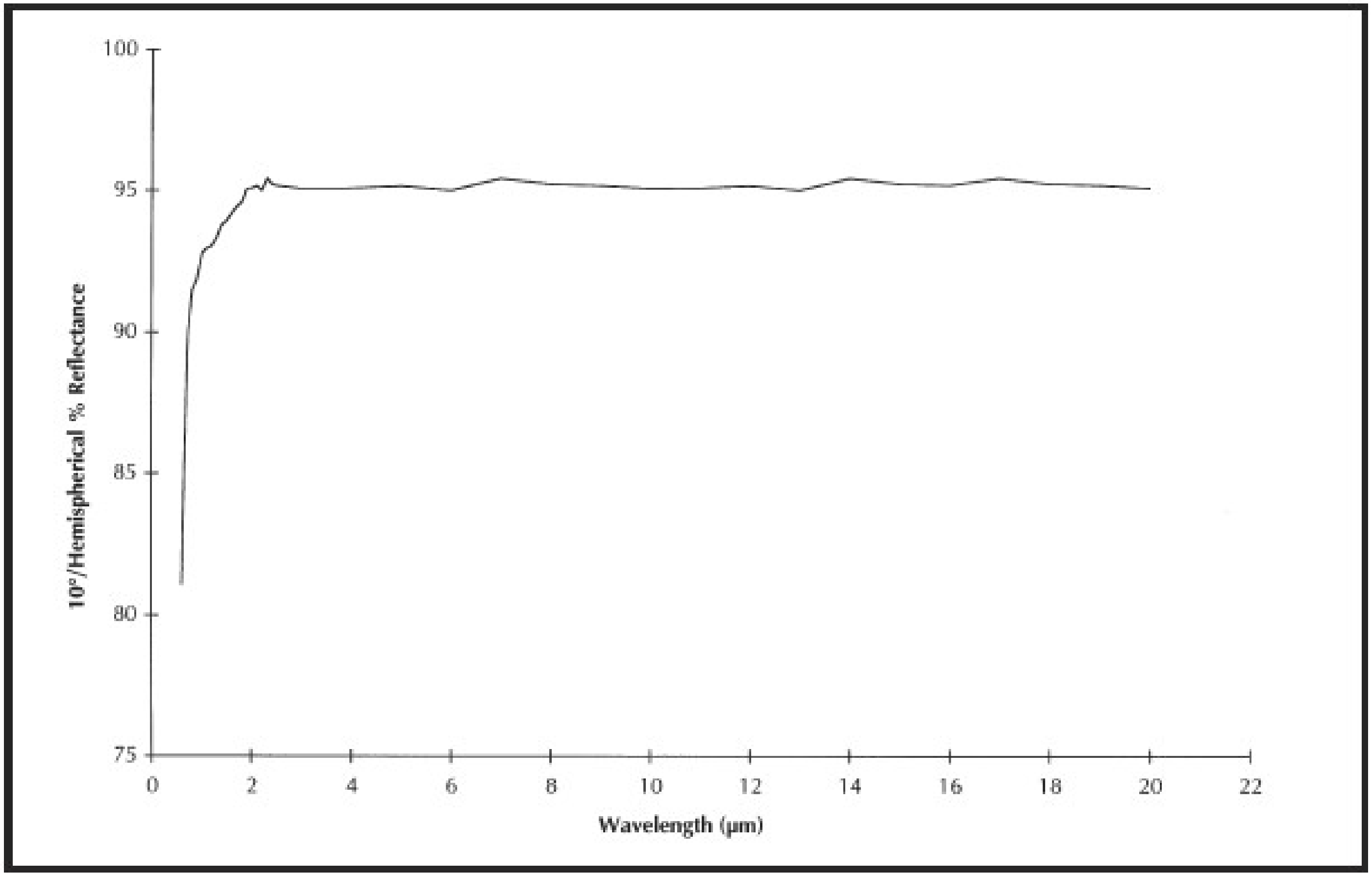
# Real "White" Reflectance Materials

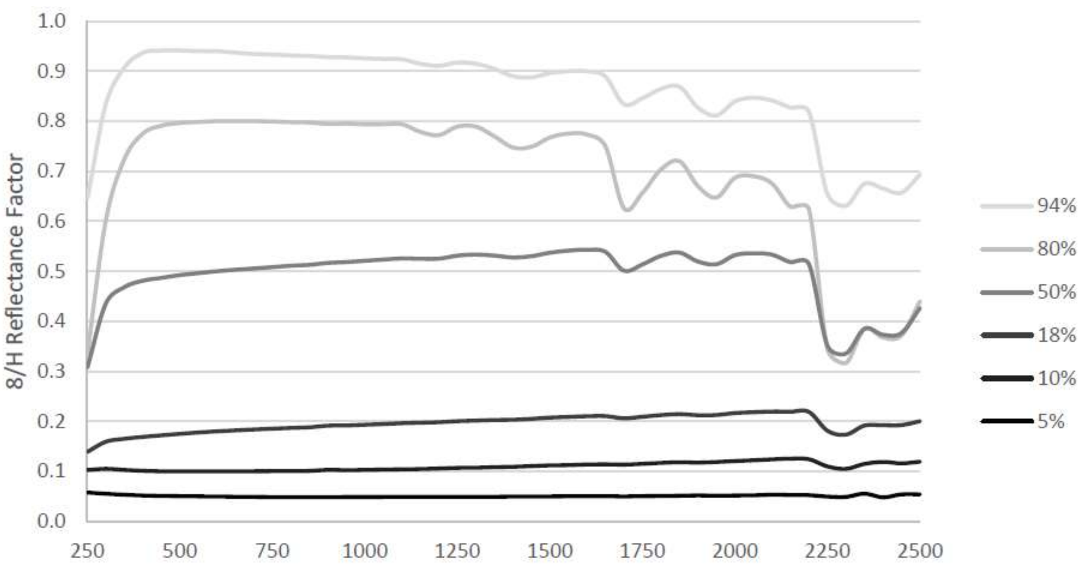


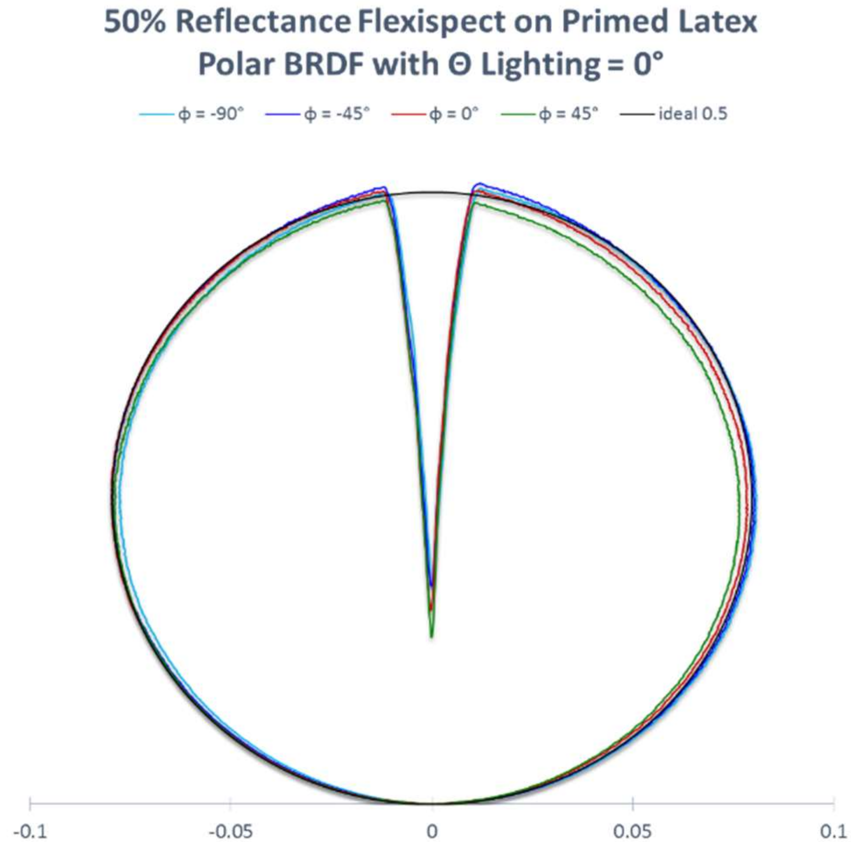
# InfraGold for >650nm (IR Applications)



# Permaflect - Lightweight Targets

- Washable & Weather Proof
- Reflectance from 5%-95%
- Various Substrates & Mountings
- Available Travel Cases
- Mosaics/Patterns



# Reflectance Material & Coating Applications

- Integrating Spheres
- Reflectance Standards
- Lambertian Targets
- Backlighting
- Laser Chambers

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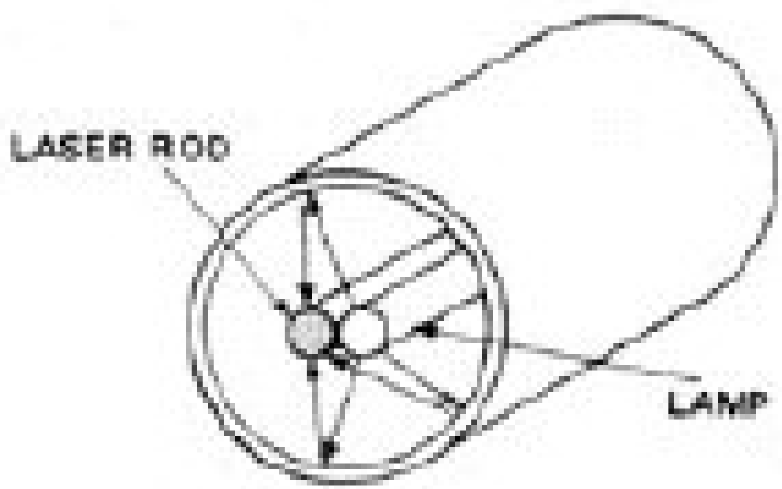
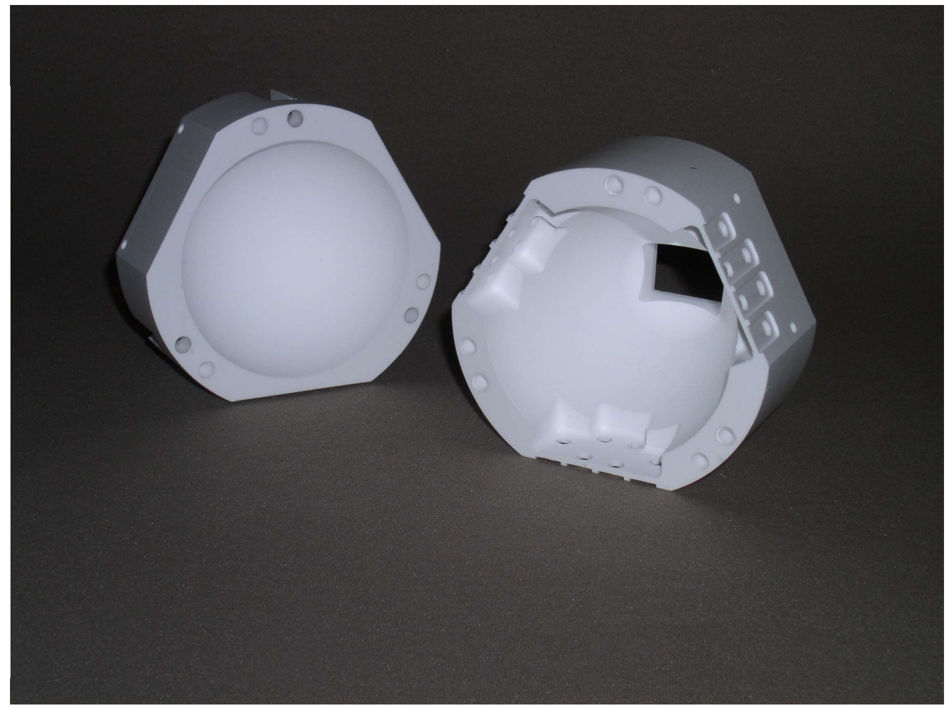
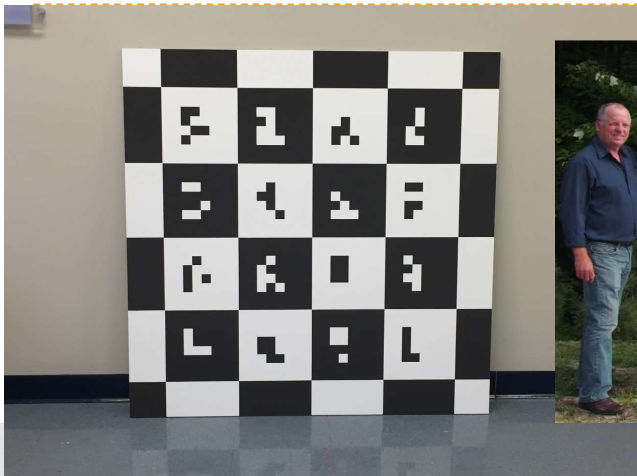
# Laser Pump & LED Chambers



# Lambertian Targets – Spectralon and Permaflect



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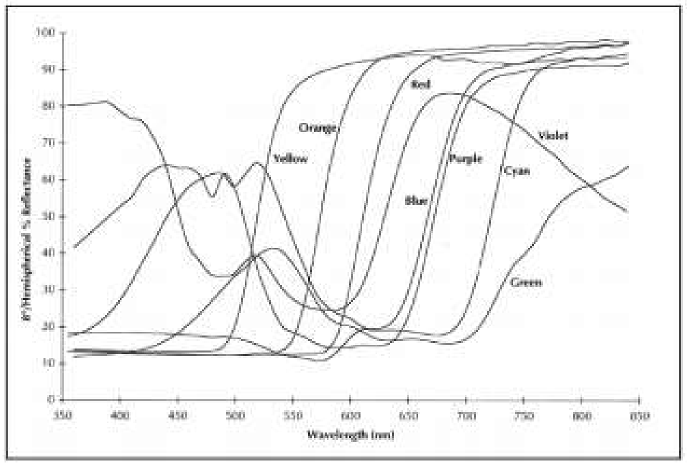
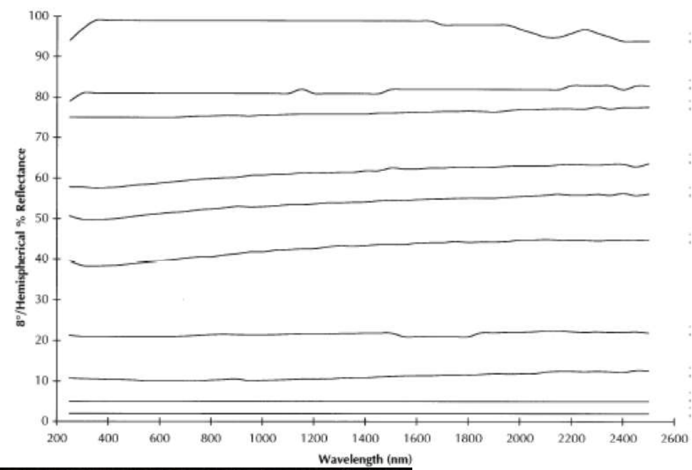
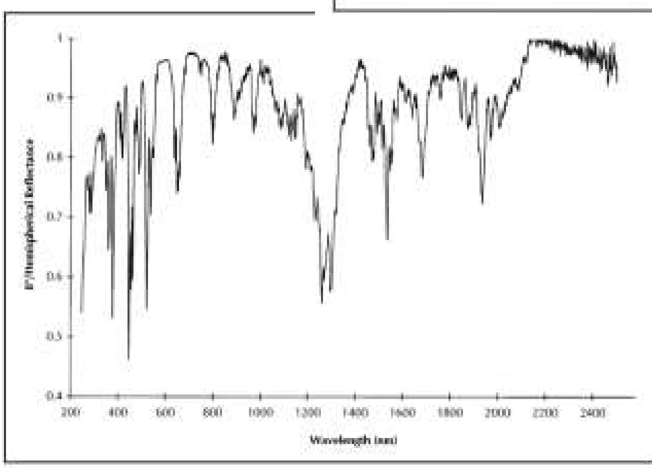
# Spectralon Standards – Color, Grey & Wavelength

Hemispherical Spectral Reflectance Factors




ɪispherical Spectral Reflectance Factors for Spectralon Standards

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# Practical Integrating Sphere Theory

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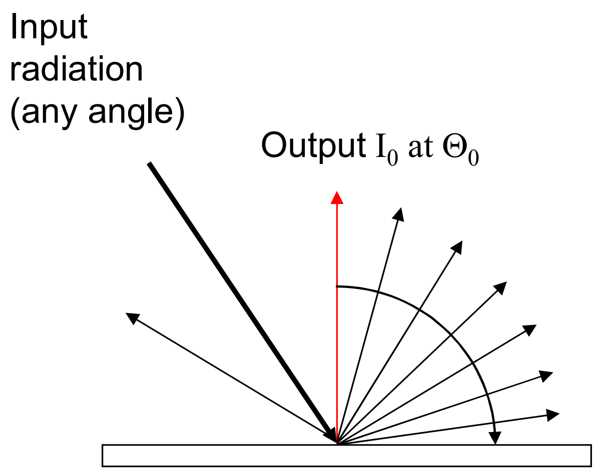
# Lambertian Reflector & Spherical Shape

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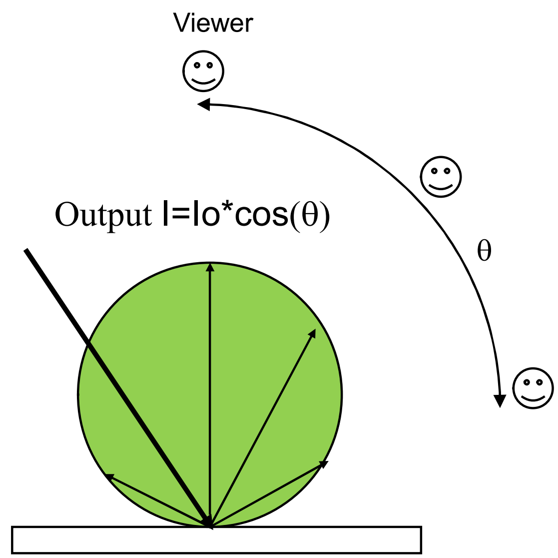


Equal Energy scattered at all angles over $\pi$ steradians with 100% Reflectance

To an observer, $I_0$ seems to vary as to cosine of the angle $\theta$. Intensity is a function of the area of the target presented to the angle of the viewer.

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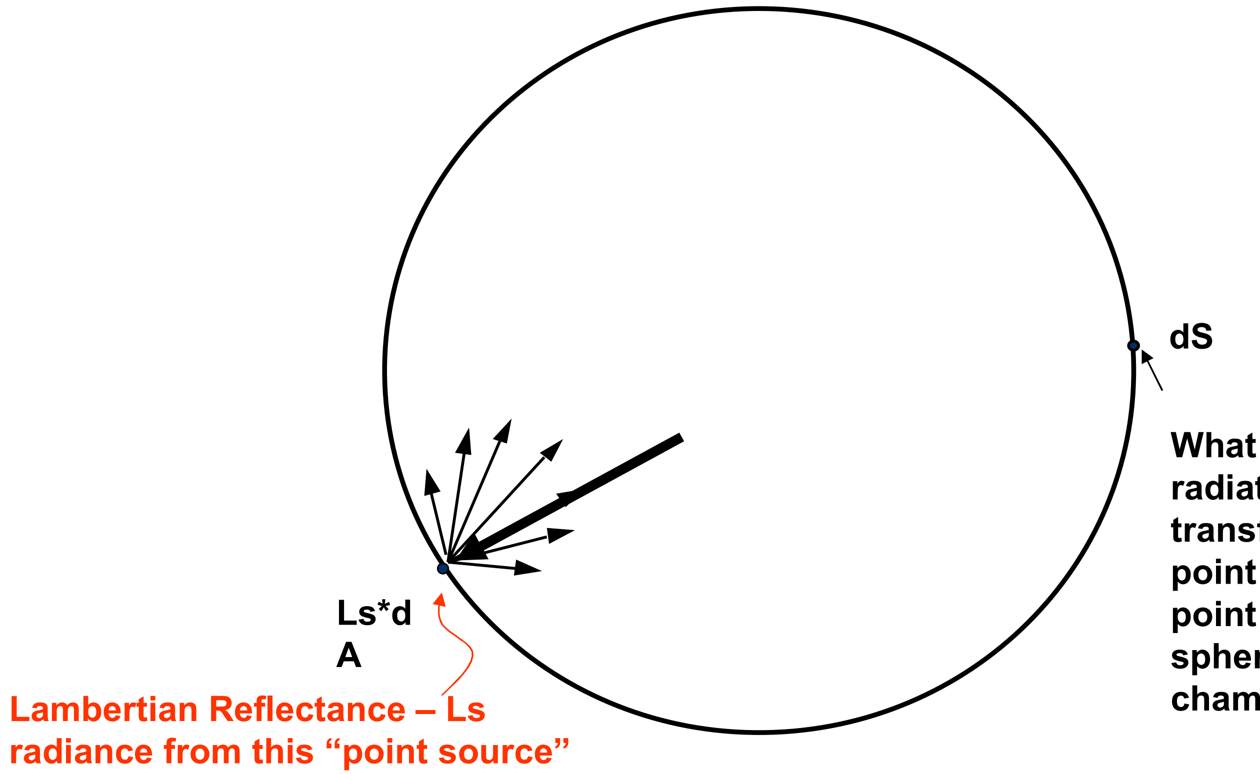
# Put a Lambertian Reflector in a Spherical Shape...




**What is the radiation transfer from point dA to point dS in a spherical chamber?**

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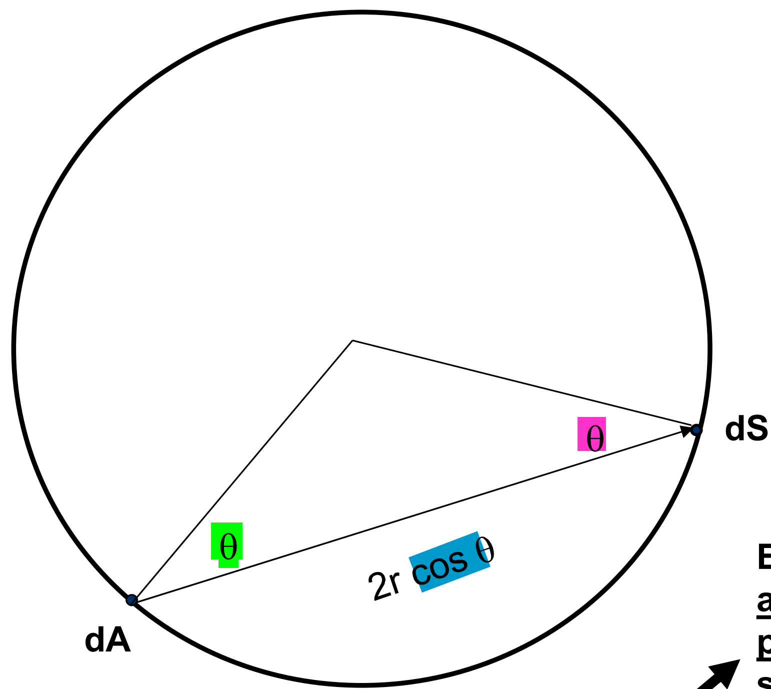
# Sphere + Lambertian




Lambertian coating

$$\Phi_s = \frac{(L \cdot dA \cdot \cos\theta)(dS \cdot \cos\theta)}{(2r \cdot \cos\theta)^2} = \frac{L \cdot dA \cdot dS}{4r^2}$$

Spherical shape

**Energy is equal at all spatial points in the sphere with no angular dependence!**

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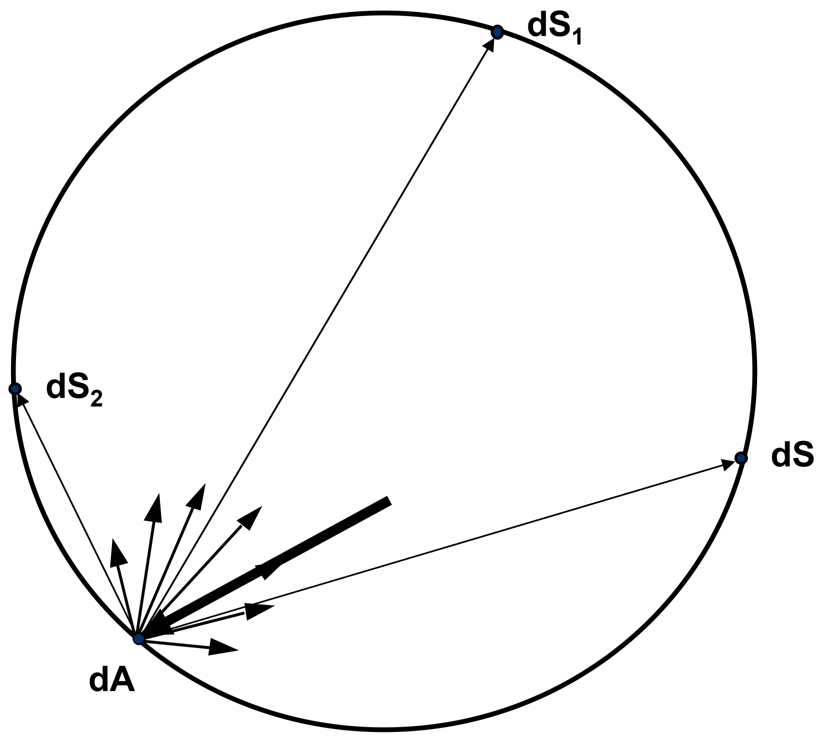
# Sphere – Equal Energy at ALL points.




**Energy is <u>equal at all spatial points</u> in the sphere with <u>no angular dependence</u>!**

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# The Sphere Multiplier

- There are <u>multiple bounces</u> in the sphere and there are ports in the sphere
  - The summation of multiple bounces reduces to a Taylor Series
- The Sphere Multiplier (M) is the resulting summation of the multiple reflections and losses for ports.

$$M = \frac{\rho_0}{1 - \rho_0 (1 - f)}$$

  - "$\rho_0$" is the first reflection in the sphere or the actual reflectivity of the sphere wall.
  - "f" is the fractional area of the sphere of all ports and non-reflective surfaces (lost photons)

- The M factor is usually around 10-25 for most normal spheres and is driven most directly $\rho_0$ and the number of ports (port fraction=f). It also implies the average # of reflections in the sphere.
- M is also a "Sensitivity Factor" to sphere degradation.

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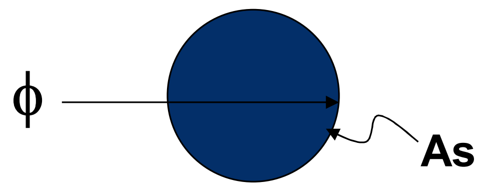
# Energy Density at the Sphere Wall

- Energy at any point on the sphere wall after the first reflection is given by:




$$\frac{\phi_i}{A_s} \quad (W/m2)$$

- But now, we have *multiple bounces* which leads to some "average" increase so we apply the "Sphere Multiplier":

$$\frac{\phi_i}{A_s} * M = \frac{\phi_i}{A_s} * \frac{\rho_0}{1-\rho_0(1-f)} \quad (W/m2)$$

- This is Average Energy Density at the Sphere Wall.

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# Radiance of the Sphere Wall

- Since we know the energy density (W/m2) at the sphere wall, the radiance of any point of the sphere wall can also be determined by dividing by $\pi$ steradians:

- The Sphere Radiance Equation is therefore: $\dfrac{\phi_i}{\pi A_s}$ *(W/m2-sr)*

$$\textbf{Sphere Radiance (L)} = \frac{\phi_i}{\pi A_s} * \frac{\rho_0}{1-\rho_0(1-f)}$$

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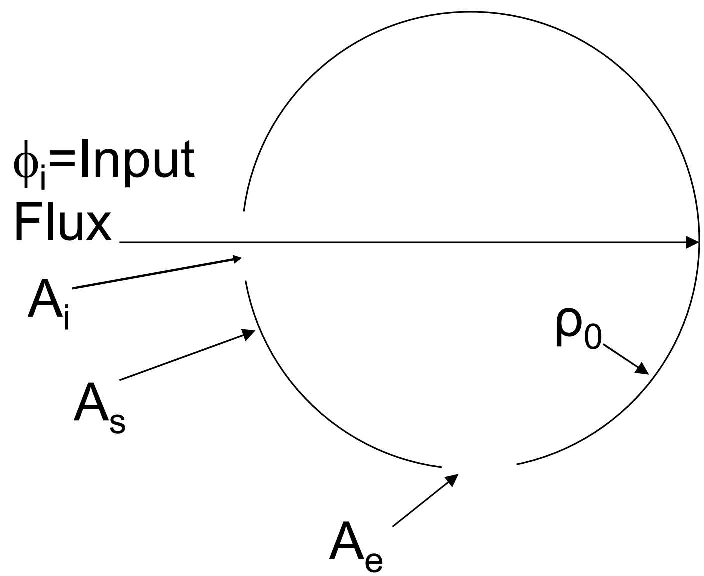
# Throughput – Energy at a Port

- Energy at a port means we assume pi-steradian solid angle (drops pi from Sphere Radiance).
- Efficiency Calculation: 10cm sphere (98%) w/(2) 2cm ports
  - f is the fractional area of all ports in the sphere
- ~Equals 24.7% at the exit port.




$$Flux = \phi_i * \left( \frac{A_e}{A_s} \right) * \frac{\rho_0}{1 - \rho_0 (1 - f)}$$

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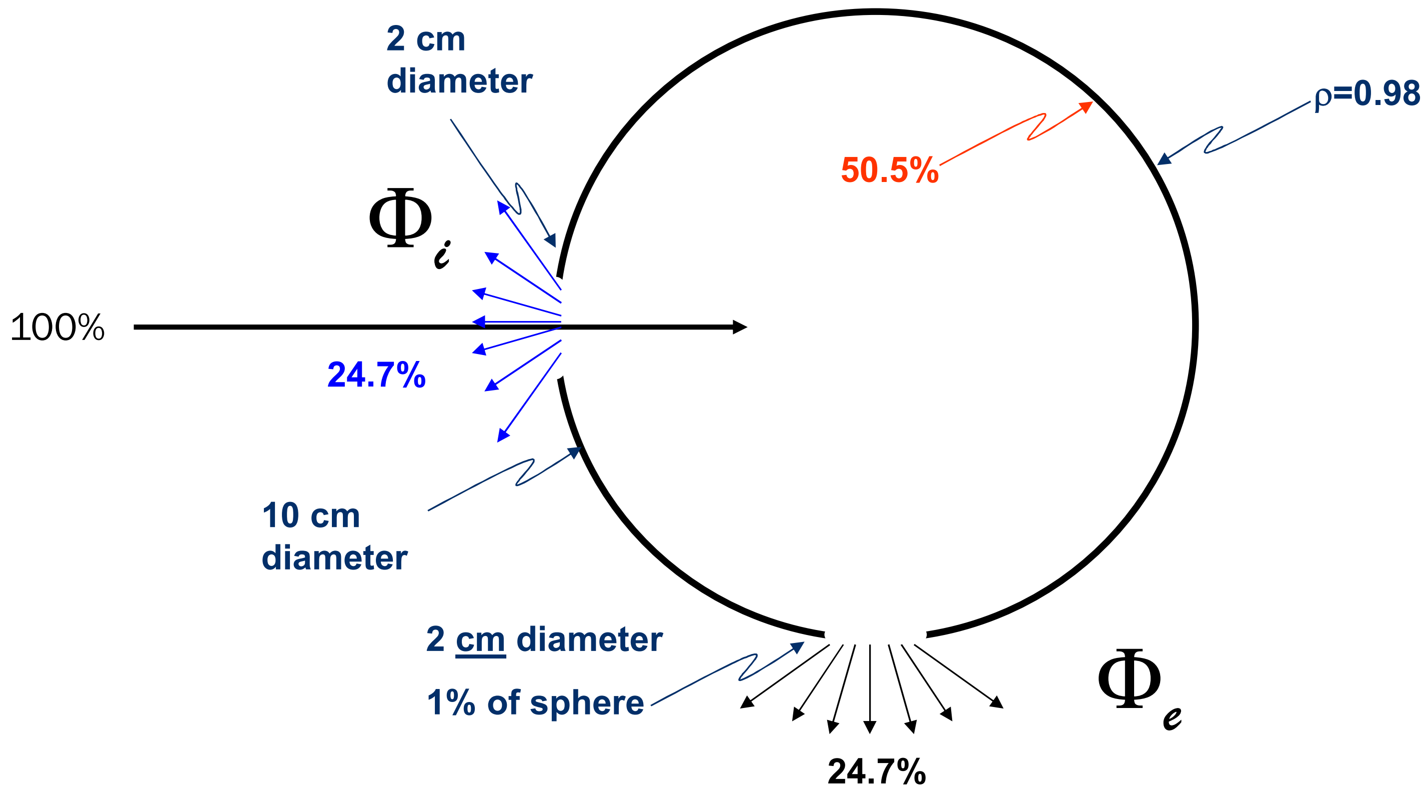
# So…where does the energy go?




M=24.7

T=24.7%

# Throughput for a Detector

- Sphere Wall Radiance, $L = \frac{\phi_i}{\pi A_s} * \frac{\rho_0}{1 - \rho_0 (1 - f)}$

- Throughput for Detector: $$T_{Detector} = \phi_i * \frac{1}{\pi A_s} * \frac{\rho_0}{1 - \overline{\rho}} * A_d * \Omega$$

- L * Detector Area ($A_d$) * Solid Angle (Ω)

- Example: 0.5cm detector – 10cm Sphere
  - -15-20dB (NA 1.0)

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# Throughput for a Fiber Optic

- Sphere Wall Radiance, $L = \frac{\phi_i}{\pi A_s} * \frac{\rho_0}{1-\rho_0(1-f)}$
- Throughput for Fiber:

$$T_{Detector} = \phi_i * \frac{1}{\pi A_s} * \frac{\rho_0}{1-\bar{\rho}} * A_f * \Omega * (1-r)$$

- L * Fiber Core Area ($A_d$) * Numerical Aperture (Field of View, (Ω)) * (1-Reflectance of Fiber Face (r))
- Example: Telecom Fiber (10cm Sphere, 98%):
  - 9um Fiber/NA 0.2 = (>-95dB!)

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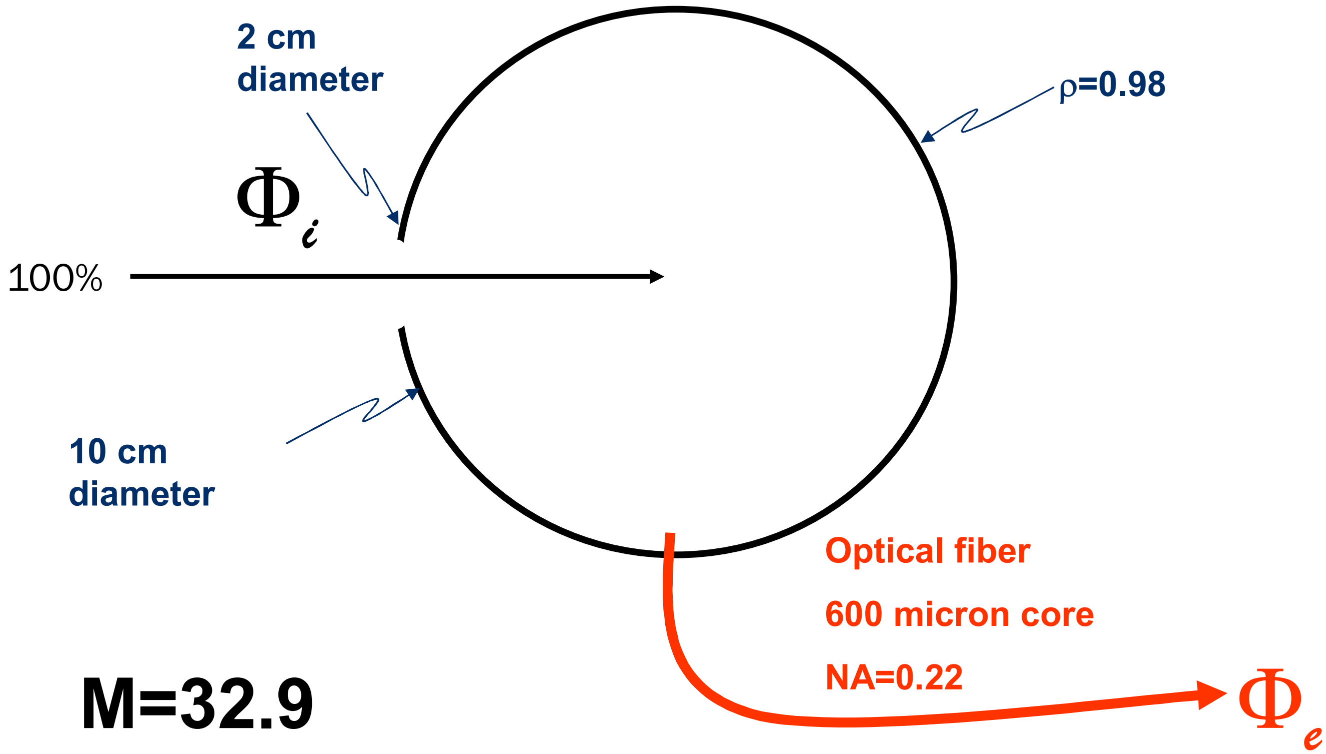
# Throughput to a typical fiber-fed spectrometer




**M=32.9**

**$T=1.4X10^{-5}$ =0.0014%= -48.5dB**

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# Throughputs for a 10cm, 98% Reflectance Sphere.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **dB to Detector** | | | | | | | | |
| | | NA | 0.018 | 0.126 | 0.178 | 0.399 | 0.691 | 1.000 | |
| | | Solid Ang. | 0.001 | 0.05 | 0.1 | 0.5 | 1.5 | 3.142 | |
| mm | Det. Active Area | | sr | sr | sr | sr | sr | sr | |
| 1 | 0.01 | cm2 | -67.73 | -50.74 | -47.73 | -40.74 | -35.97 | -32.76 | dB |
| 2 | 0.04 | cm2 | -61.71 | -44.72 | -41.71 | -34.72 | -29.95 | -26.74 | dB |
| 5 | 0.25 | cm2 | -53.75 | -36.76 | -33.75 | -26.76 | -21.99 | -18.78 | dB |
| 7.5 | 0.5625 | cm2 | -50.23 | -33.24 | -30.23 | -23.24 | -18.47 | -15.26 | dB |
| 10 | 1 | cm2 | -47.73 | -30.74 | -27.73 | -20.74 | -15.97 | -12.76 | dB |
| 25.4 | 2.25 | cm2 | -44.21 | -27.22 | -24.21 | -17.22 | -12.45 | -9.24 | dB |
| | | | | | | | | | |
| | **dB to Fiber** | | | | | | | | |
| | | NA | 0.12 | 0.2 | 0.3 | 0.4 | 0.6 | 1 | |
| Refl Fiber | 0.8 | Sr | 0.045 | 0.126 | 0.283 | 0.503 | 1.131 | 3.142 | |
| um - diam | Fiber Area | | sr | sr | sr | sr | sr | sr | |
| 9 | 6.36E-07 | cm2 | -100.13 | -95.69 | -92.17 | -89.67 | -86.15 | -81.71 | dB |
| 12 | 1.13E-06 | cm2 | -97.63 | -93.19 | -89.67 | -87.17 | -83.65 | -79.22 | dB |
| 25 | 4.91E-06 | cm2 | -91.26 | -86.82 | -83.30 | -80.80 | -77.28 | -72.84 | dB |
| 100 | 7.85E-05 | cm2 | -79.22 | -74.78 | -71.26 | -68.76 | -65.24 | -60.80 | dB |
| 250 | 4.91E-04 | cm2 | -71.26 | -66.82 | -63.30 | -60.80 | -57.28 | -52.84 | dB |
| 1000 | 7.85E-03 | cm2 | -59.22 | -54.78 | -51.26 | -48.76 | -45.24 | -40.80 | dB |
| 5000 | 1.96E-01 | cm2 | -45.24 | -40.80 | -37.28 | -34.78 | -31.26 | -26.82 | dB |

## Sphere Time Constants

- Due to the multiple reflections in a sphere and the “random” path length of each photon, not all photons arrive at a designated point at the same time.
- A sphere acts very much like a “photon-capacitor” and has a time constant similar to that capacitor analogy.
- This Time Constant is driven by the D (diameter of the sphere), $\rho_0$ (the reflectance) and, c (the speed of light).

$$e^{-t/\tau} \quad \text{where} \quad \tau = -\frac{2}{3} \cdot \frac{D}{c} \cdot \frac{1}{\ln \rho_0}$$

- Typical time constants are 2-10ns (100-500Mhz)

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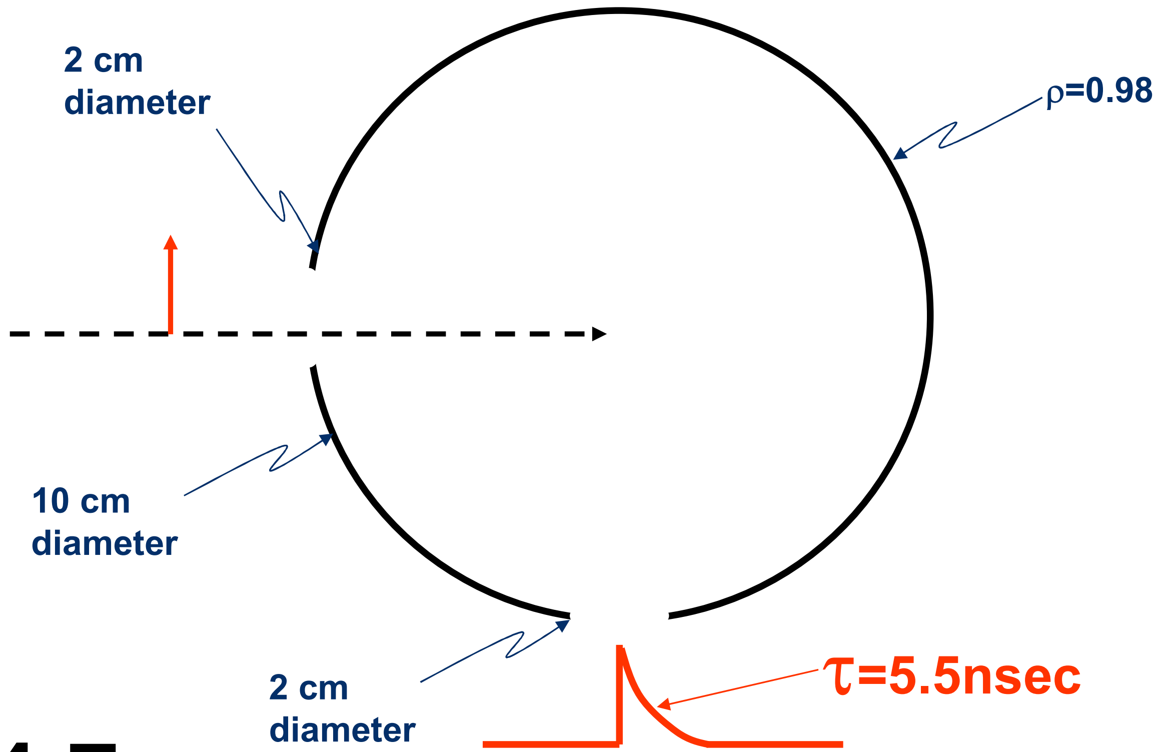
# Sphere Time Constants – Impulse Input




M=24.7

## Sphere Practical Advice

- Ratio of 1:3 largest port to Diameter of Sphere.
- 5% Port Area-to-Surface Area Ratio.
- Spheres do not remove speckle (coherence) – but you can play tricks!
- M factor is also a “sensitivity factor” to dust and changes to the sphere.
- Spheres are depolarizing.
- Baffle placement or use depends on the application.
- Throughput most directly follows $D_1^2/D_2^2$ Ratio (Surface Area).
- Spectrally homogenous field even with multispectral sources.

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# Optical Modeling Uniformity with Spheres

- Computer (Monte Carlo) modeling of sphere performance is possible, but only really useful for special cases.
- REASONS:
  - BRDF of coating not fully known
  - Statistical fluctuations in the result are greater than parameter being investigated
- SPECIAL CASES:
  - Overly “filled” spheres with low performance requirements
    - Example – Irradiance uniformity on multiple samples positioned inside a sphere
  - Poor BRDF
    - Example – Rough surface at 100 and 200 microns

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# Sphere Coating Advice (1 of 2)

**BaSO4 (350 - 1300nm)**

- Cheapest coating
- "Likes" hydrocarbons & dust
- Hydroscopic & Water Soluble
- Damage threshold ~1.0W/cm2
- Vacuum compatible
- Thickness ~1.5mm
- Does Not like vibration or shock
- Heat limited to 80C
- Do not use with UV

**PTFE (< 250 - 2500nm)**

- Best throughput and function
- "Likes" hydrocarbons & dust
- Hydrophobic
- Damage Threshold ~8.0W/cm2
- Vacuum Compatible
- Requires thick walls (~7mm) – translucent
- OK Vibration & Shock
- OK to 300C
- OK for UV
- Thermal Expansion/Contraction – avoid thermal cycling

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# Sphere Coating Advice (2 of 2)

**ZenithGold (0.8um to >26um)**

- Best IR coating >2500nm
- Not that reflective (94-95%)
- Not that diffuse
  - Gets worse with longer wavelengths
- OK for pretty much all liquids
- Thermally stable to >500C
- Damage threshold ~20W/cm2
- Vacuum compatible
- Thickness ~0.010mm
- OK vibration & shock & thermal cycles

**Historical Sphere Coatings**

- MgO2
- Packed PTFE

**Other Coatings**

- Deep UV – MgF2/Al
  - <200-1000nm
- UV to IR – MgF2/Ag
  - <0.2 to >3.0um

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# Integrating Sphere Applications

# Uses of Integrating Spheres

Radiometers/Photometers

Reflectance/transmittance measurements

Uniform source

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# Sphere Used with a Radiometer/Photometer

**The integrating sphere is used as a non-imaging optic to achieve the desired collection geometry**

**Advantage: geometry**

**Disadvantage: signal level (sometimes this is an advantage)**

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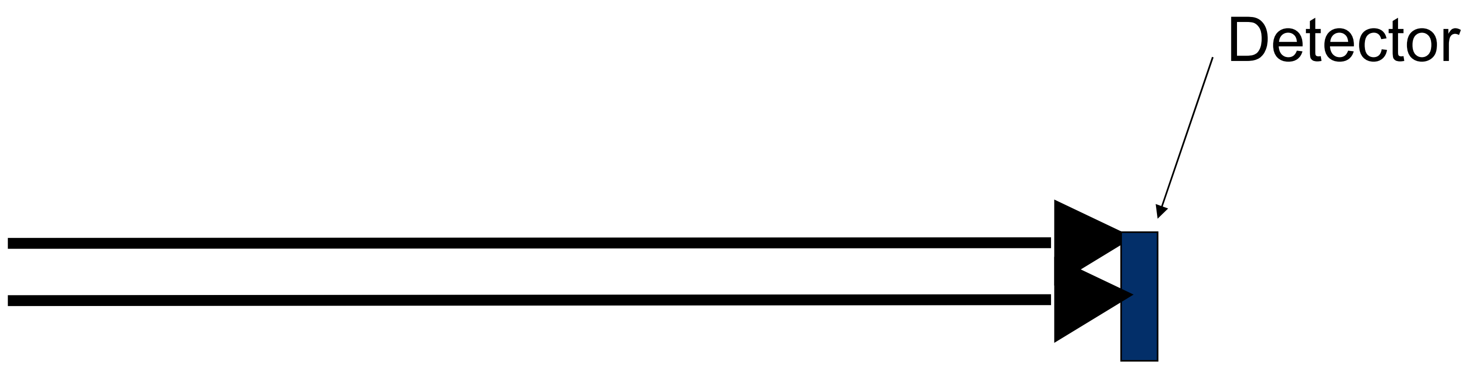
# Classic Laser Power Meter – Detector - Spatial

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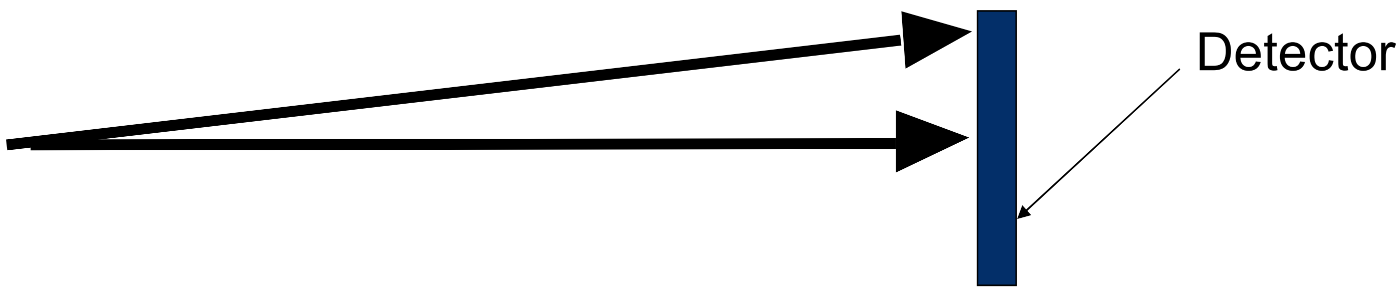
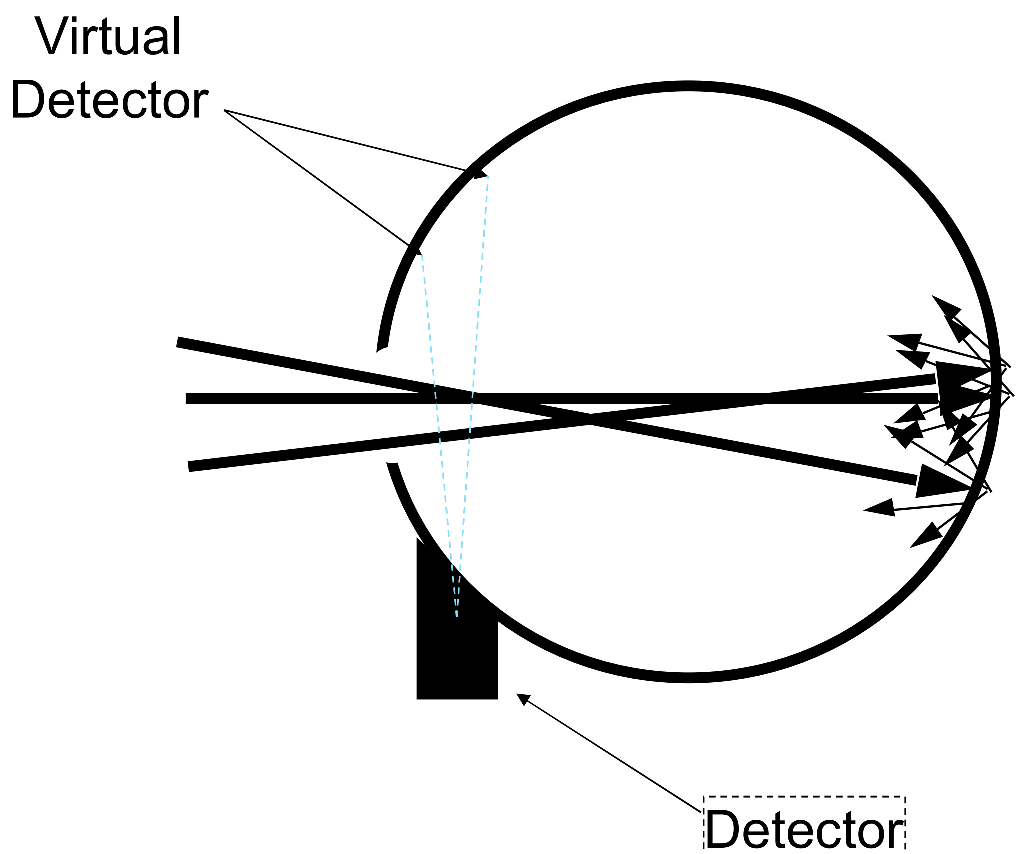
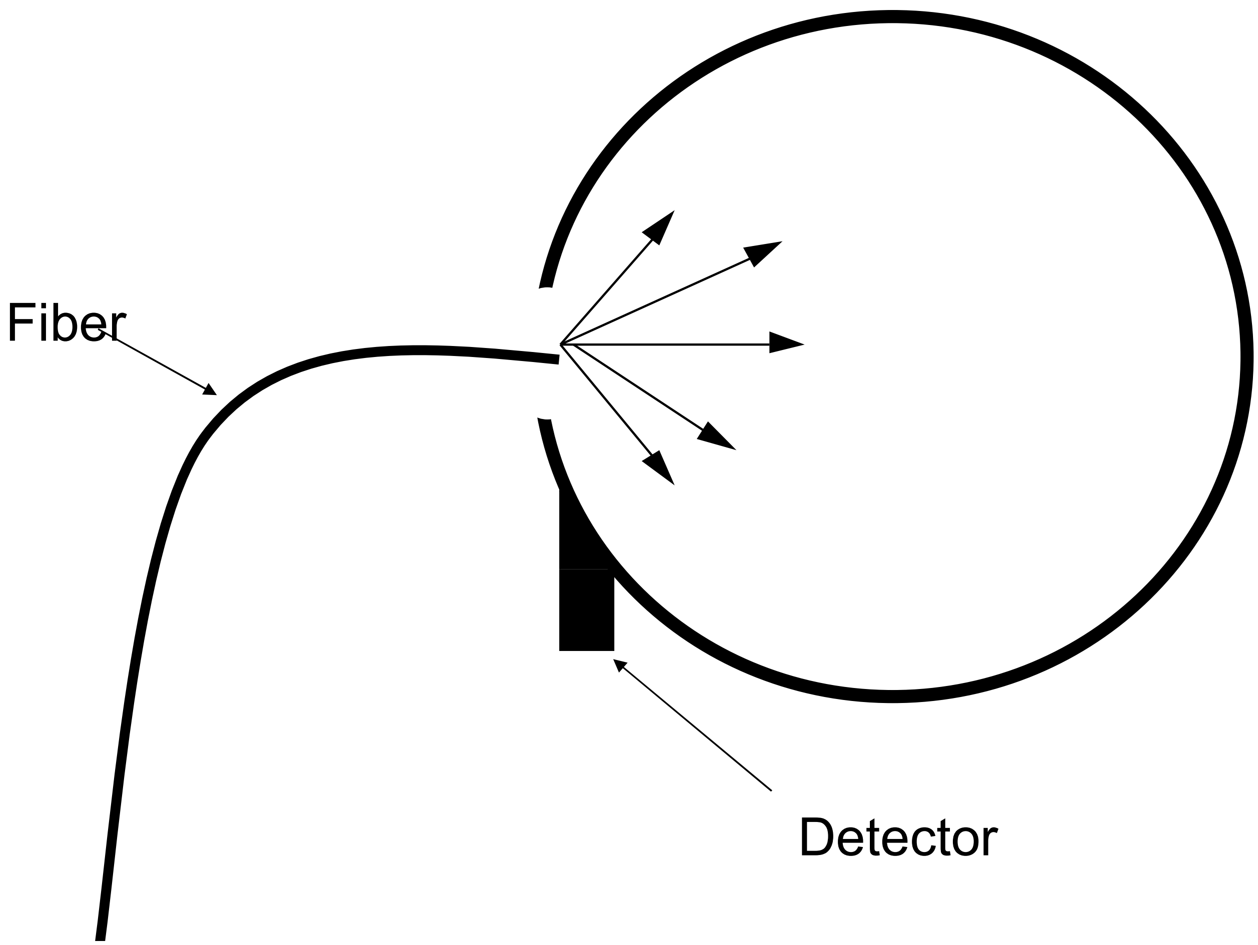
# Classic Laser Power Meter – Detector - Geometric



# Laser Power Meter - Sphere



# Fiber Input Laser

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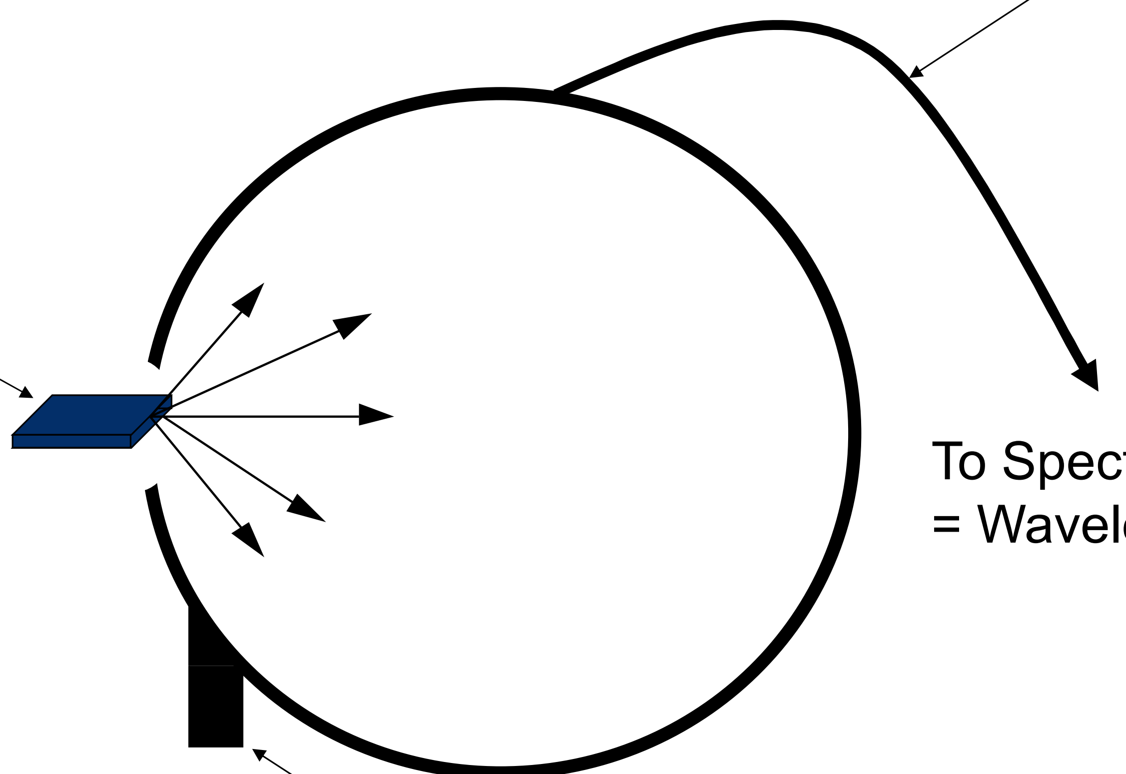
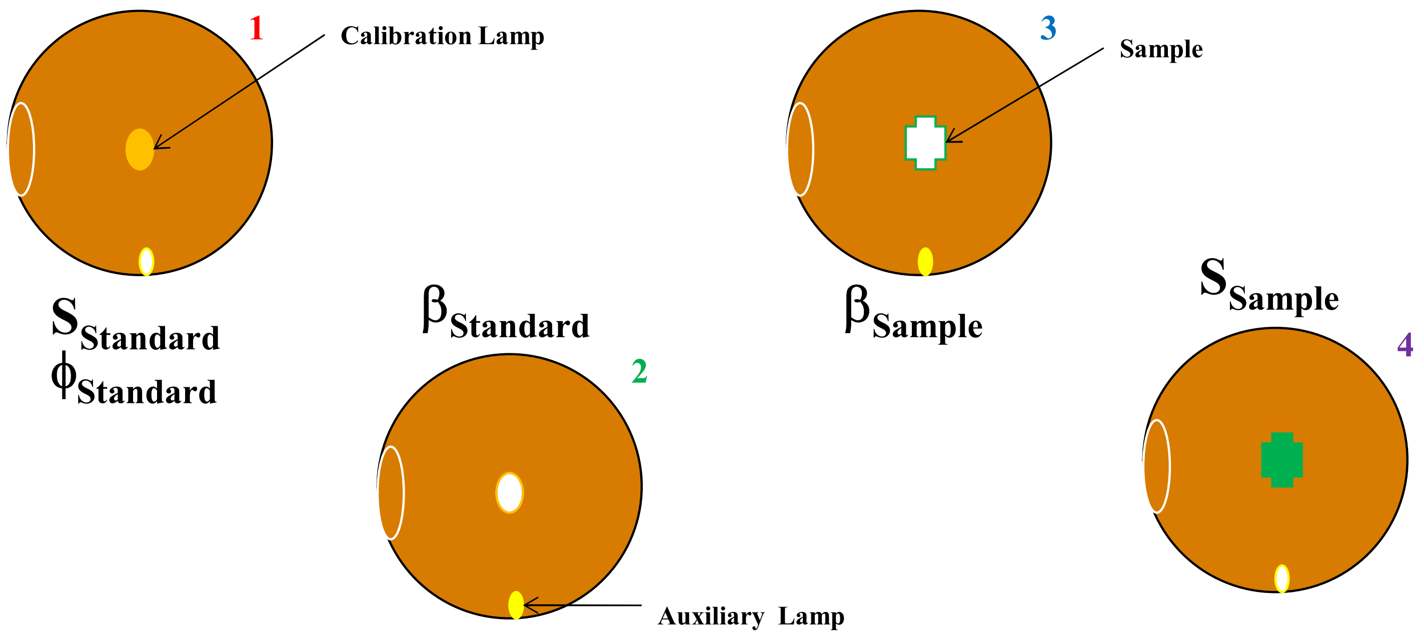
# Diode Laser + Multiple Detectors



# Lamp/Source Measurement - Internal




$$\phi_{Sample}(\lambda) = \frac{S^{4}_{Sample}(\lambda)}{S^{1}_{S\tan dard}(\lambda)} * \frac{\beta^{2}_{S\tan dard}(\lambda)}{\beta^{3}_{Sample}(\lambda)} * \phi^{1}_{S\tan dard}(\lambda)$$

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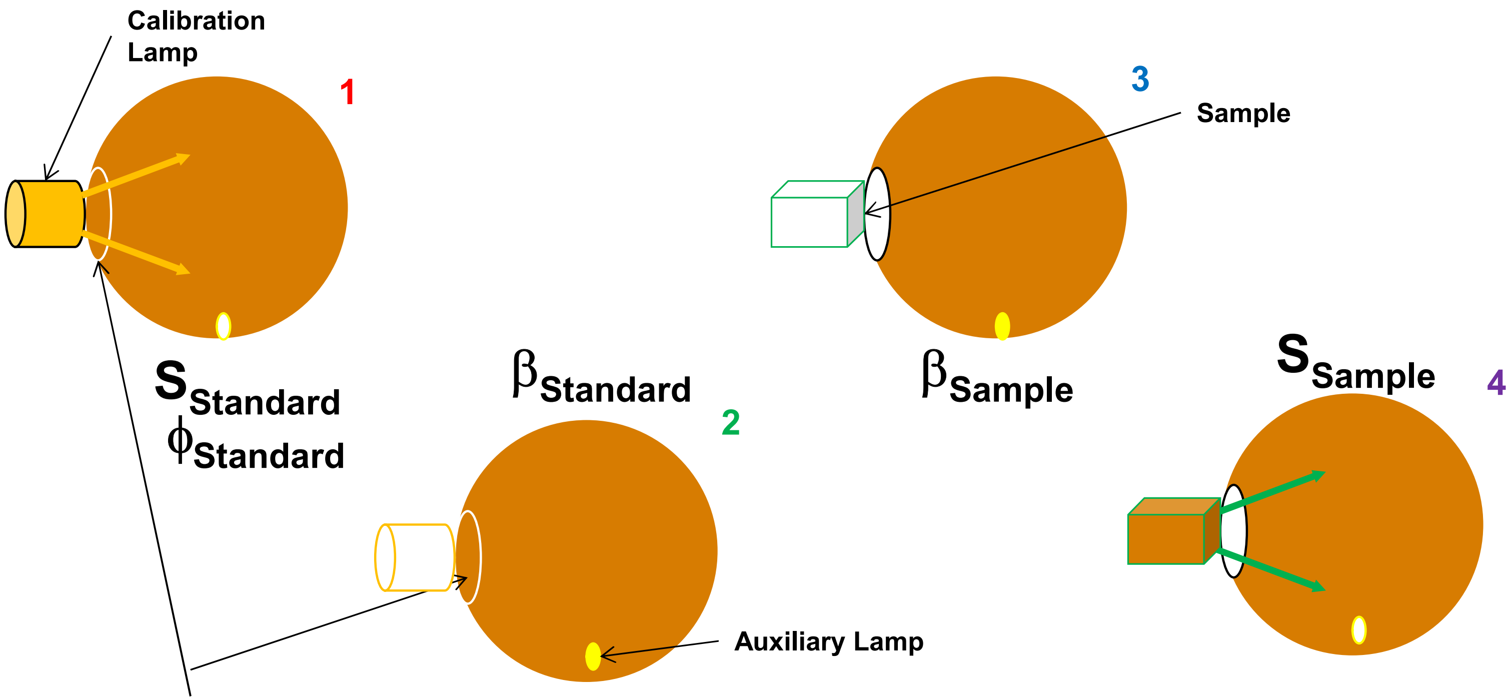
# Lamp/Source Measurement - External




$$\phi_{Sample}(\lambda) = \frac{S^{\,4}_{Sample}(\lambda)}{S^{\,1}_{Standard}(\lambda)} * \frac{\beta^{\,2}_{Standard}(\lambda)}{\beta^{\,3}_{Sample}(\lambda)} * \phi^{\,1}_{Standard}(\lambda)$$

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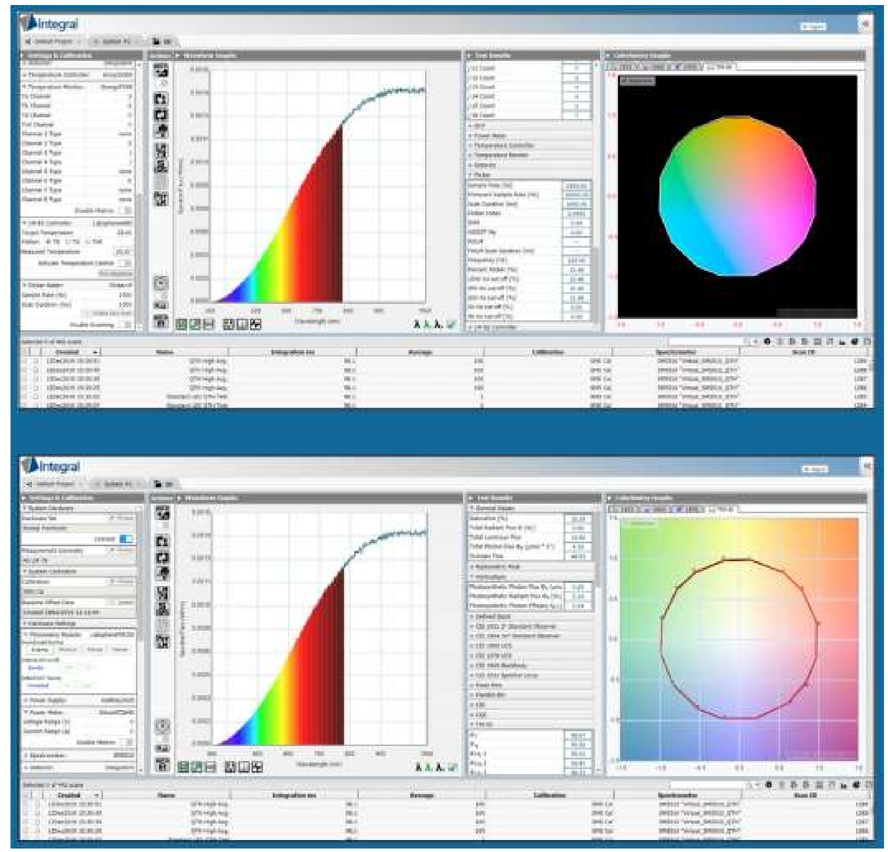
# Spectral vs. Photometric Lamp Measurement

- **Color temperature (correlated color temperature)**
- **Chromaticity**
- **Color rendering index**
- **Color Quality System Metrics (NIST)**
- **Dominant wavelength and purity (for LEDs)**
- **Optical Characterization with Thermal Control**
- **Electrical Performance**

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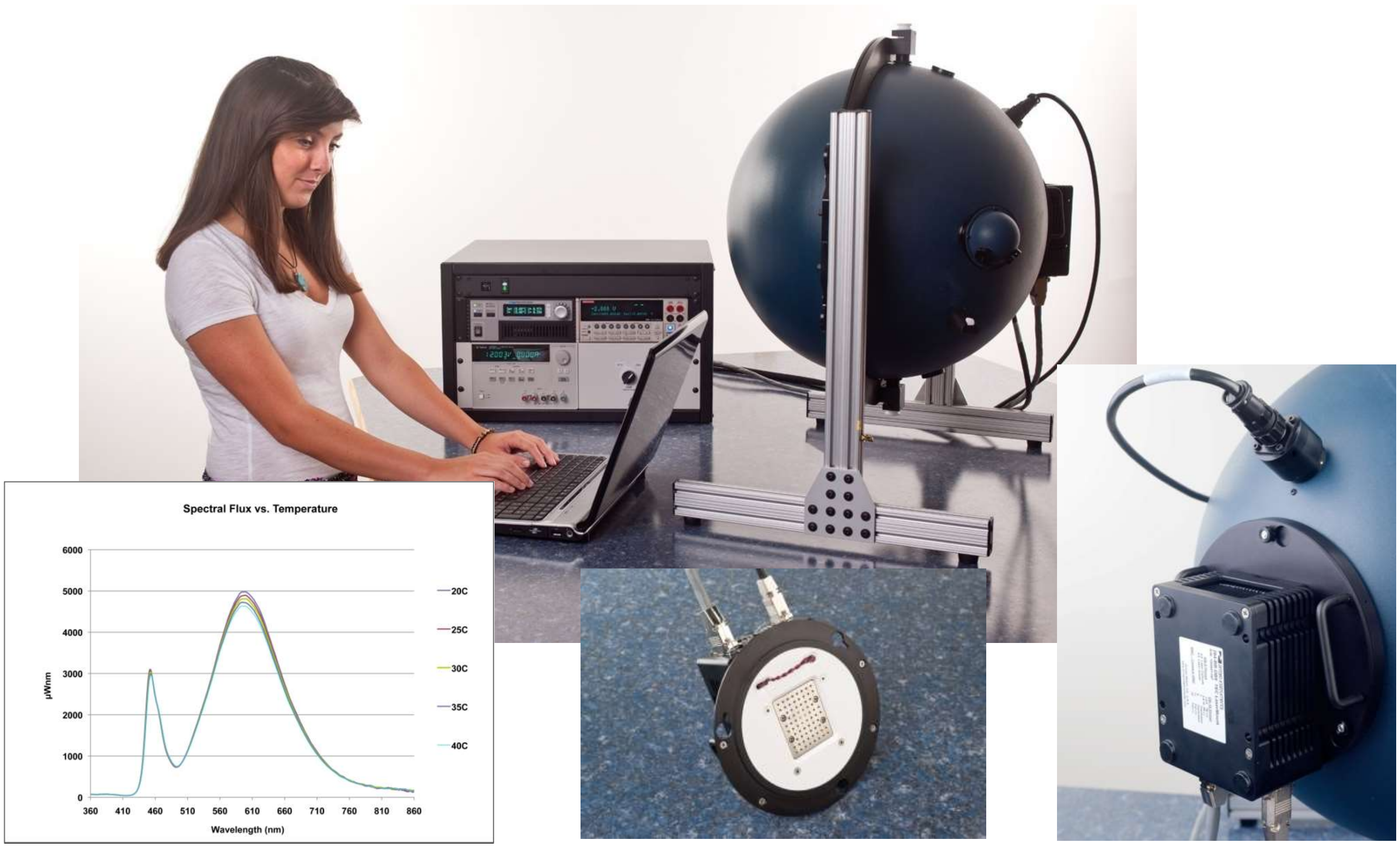
# Lamp/Source – Optical, Electrical and Thermal Characterization

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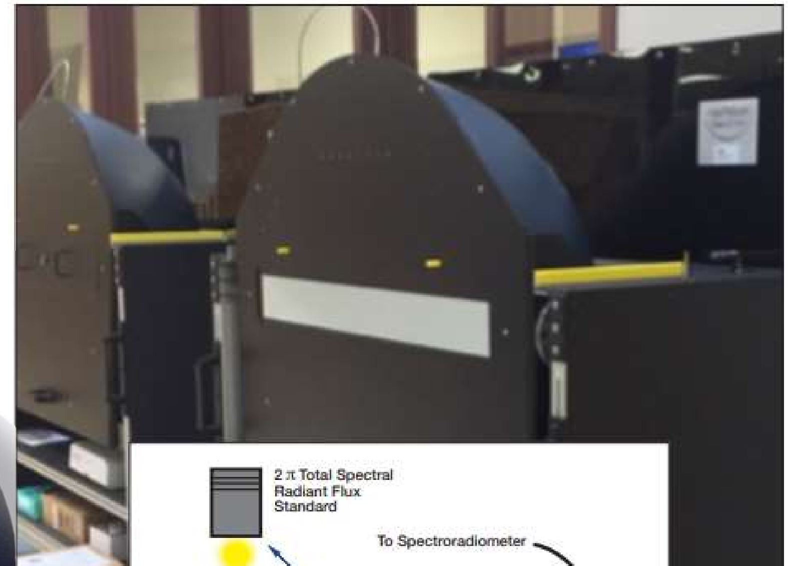
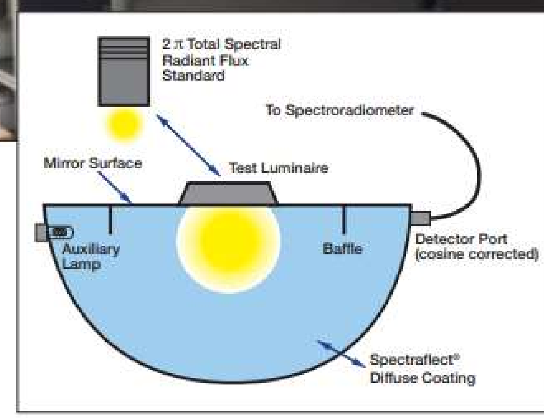
# Complete Luminaire AC/DC & Thermal Characterization


LM-82 Ambient Thermal Sphere Test

AC/DC Variable Impedance System






Production Half-Moon “Sphere”

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## Uses of Integrating Spheres

Radiometers/photometers

**Reflectance/transmittance measurements**

Uniform source

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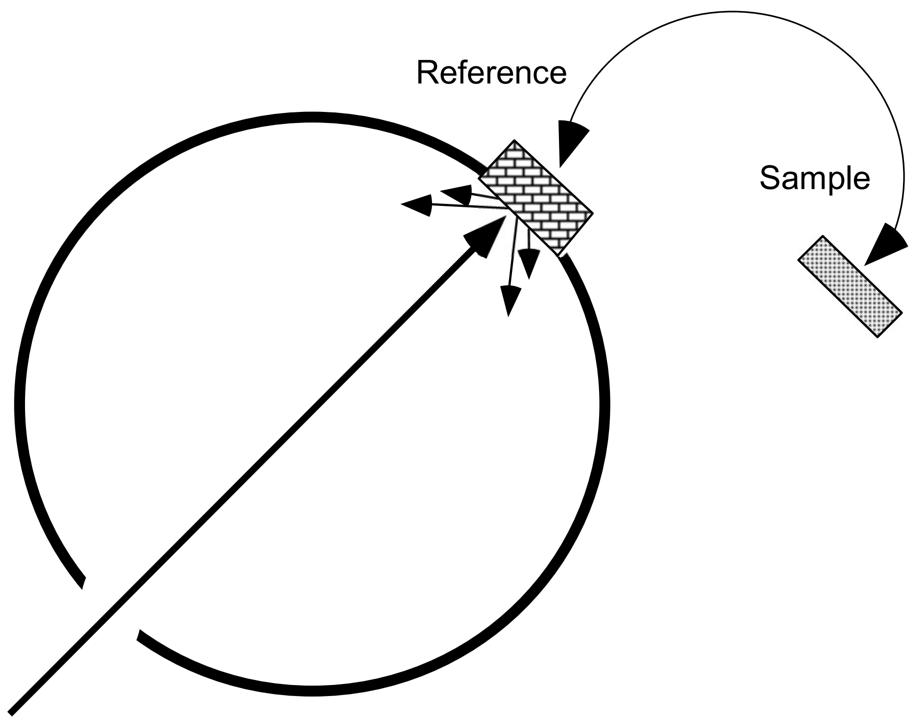
# Substitution Method for Reflectance Measurement

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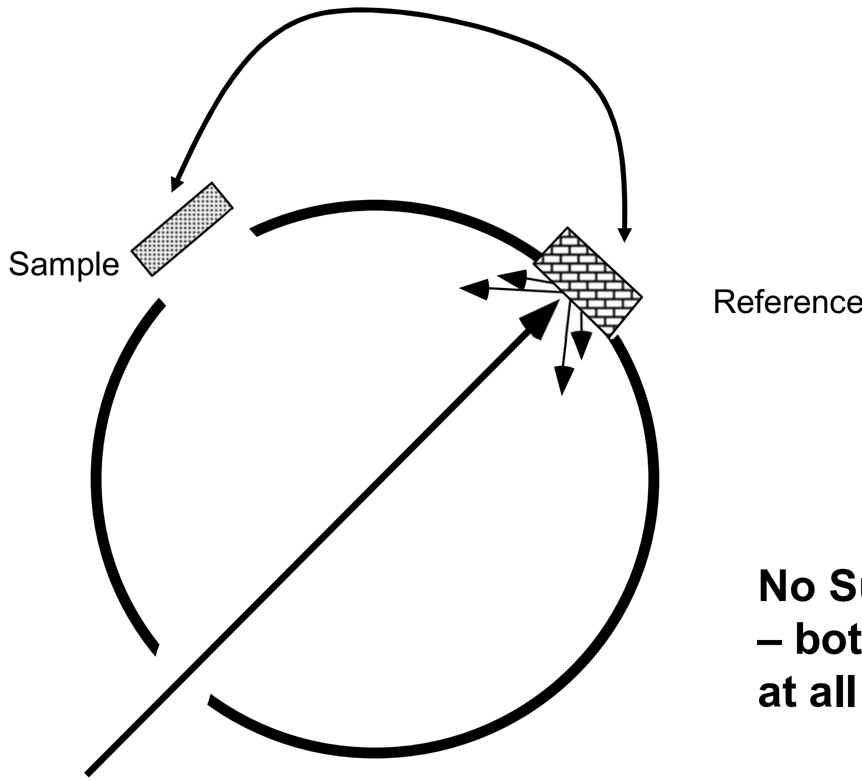
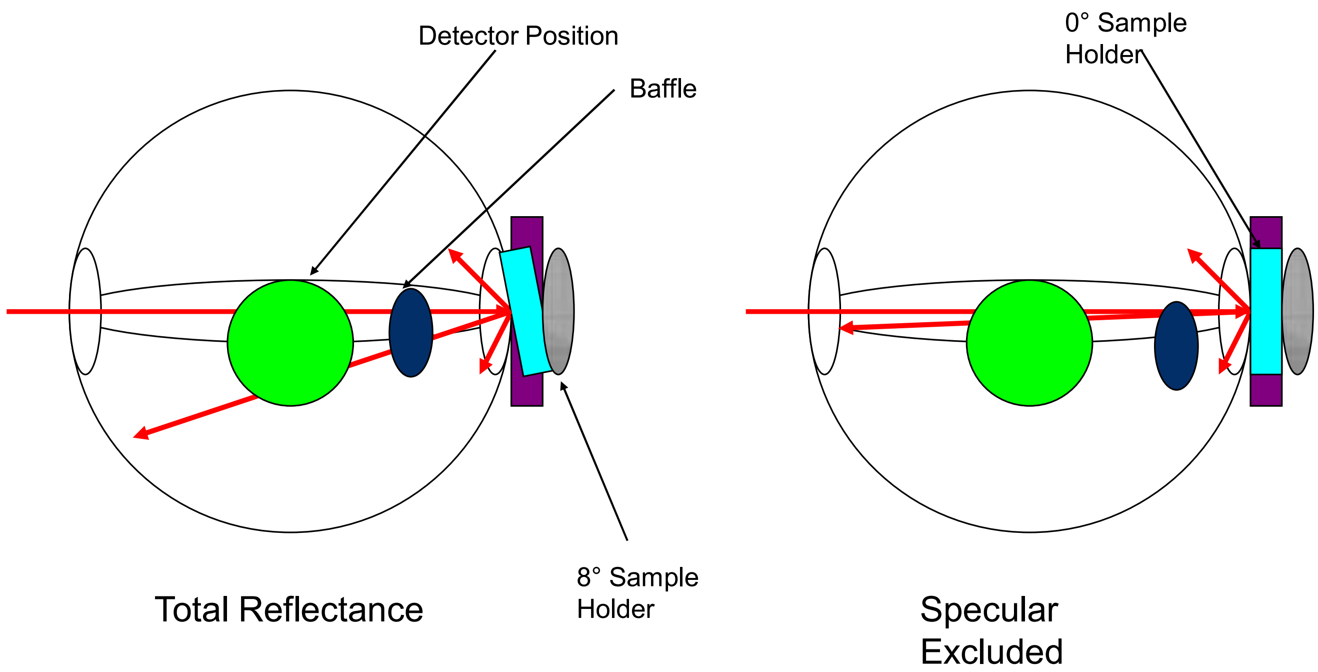
# Comparison Method for Reflectance Measurement




**No Substitution Offset – both items on sphere at all times**

# 8°/D Hemispherical Reflectance Anatomy




Can also be done using “absolute reference” of the sphere wall

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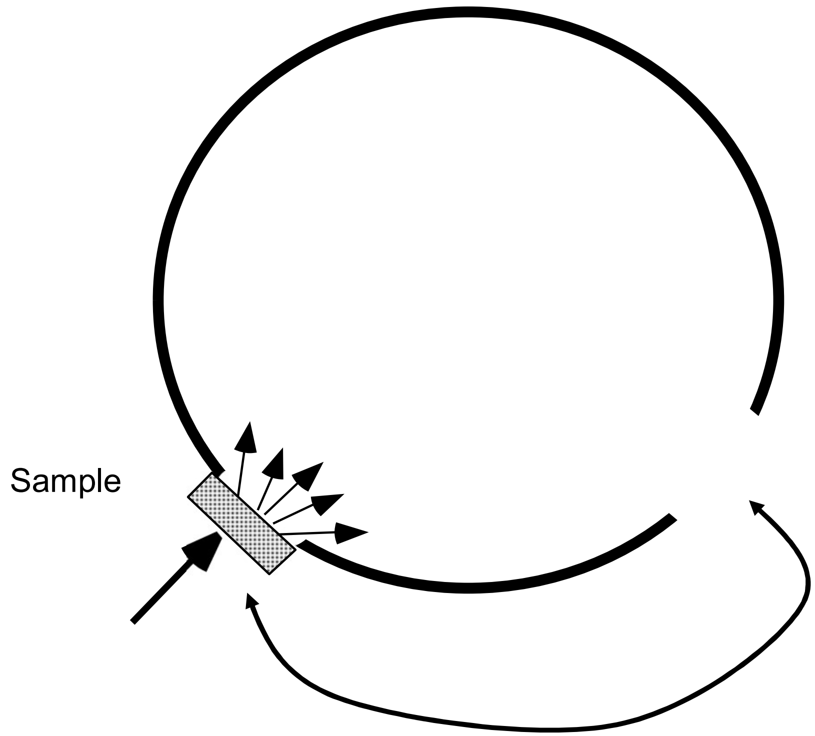
# Transmittance Measurement

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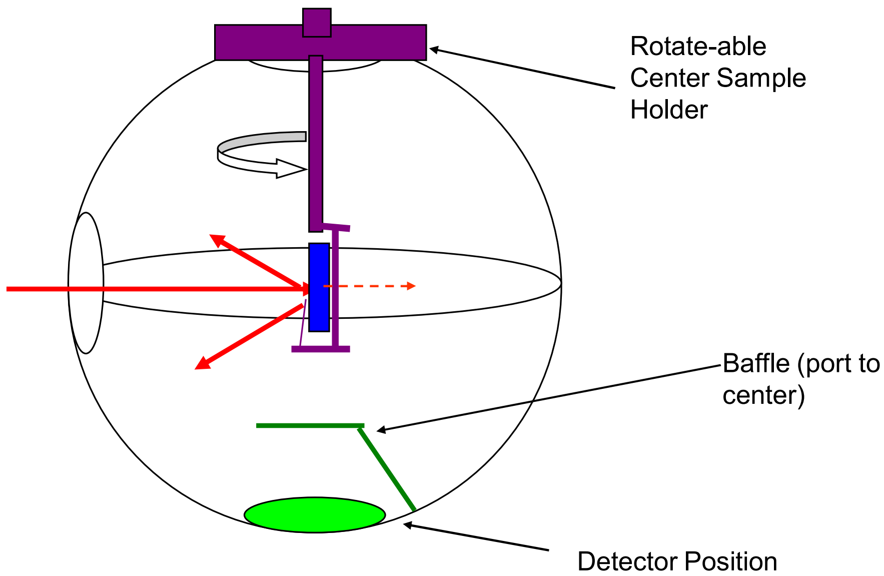
# Center Mounted Anatomy




MULTI-ANGLE & “TRANS-FLECTANCE”:
(1-R-T-A)=0

- Variable Angle
- Quantum Efficiency Measurements for Phosphors/Fluors (IQE/EQE)
- Transflectance – BE CAREFUL
  - Very hard to do absolute.

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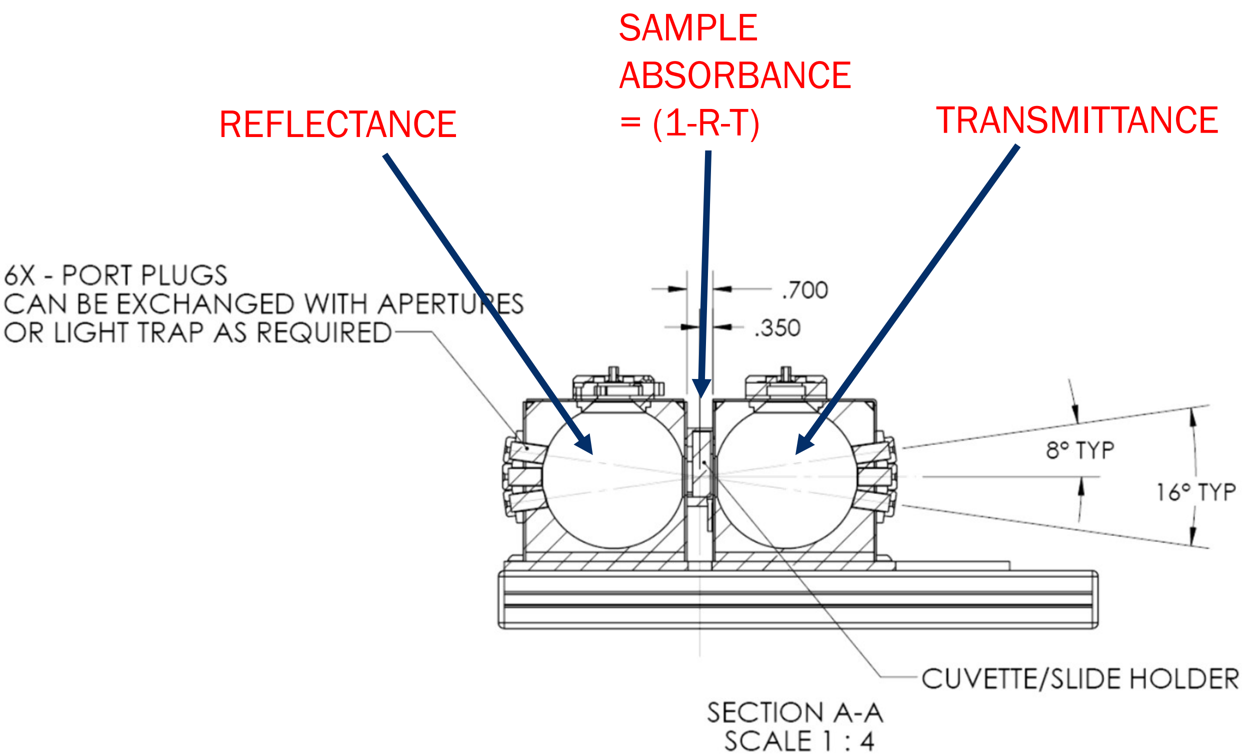
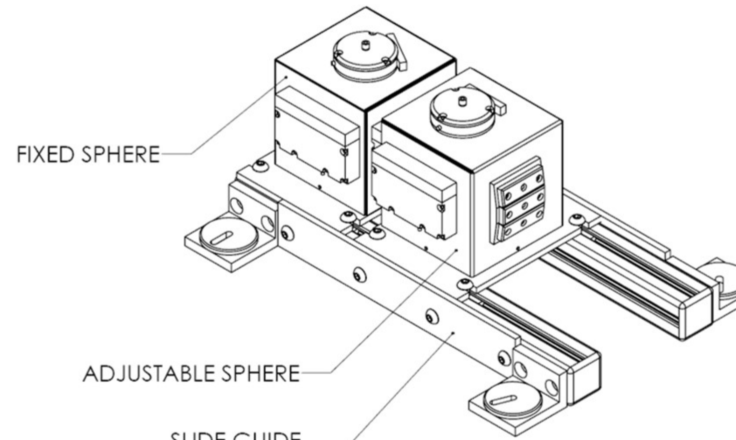
# RTA Double Sphere – Reflectance-Transmittance-Absorbance




- Also can be used for IQE/EQE for phosphors
- Possible to get absolute values (still difficult)

# Uses of Integrating Spheres

Radiometers/photometers

Reflectance/transmittance measurements

**Uniform source**

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# Uniform Source Sphere Overview

# Workshop Agenda (All times in MDT)

- 0730-0840 Sphere Theory and Applications (Durell)
- 0840-0910 Uniform Source Tutorial (Durell)
- 0910-0920 Sphere Calibrations (Durell)
- 0920-0930 (Virtual) Coffee Break
- 0930-1010 Considerations for Uniform Source Specifications (Scharpf)
- 1010-1020 Commercial considerations (Scharpf)
- 1020-1040 NASA GLAMR Case Study (Brendan McAndrew, NASA GSFC)
- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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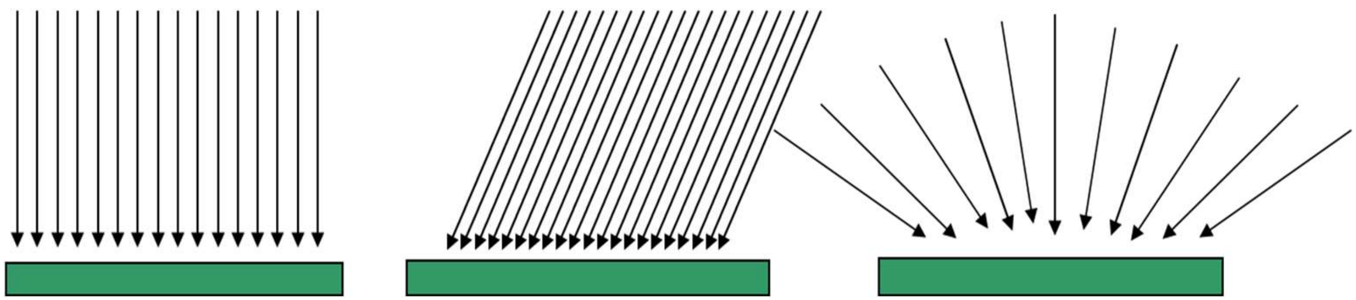
# Radiometry - Irradiance

- Irradiance/Illuminance



UNITS: $W/m^2$ - lux (lumens/$m^2$) - ph/$m^2$/s

Any bare detector or bare FPA (no lens) is sensitive to irradiance

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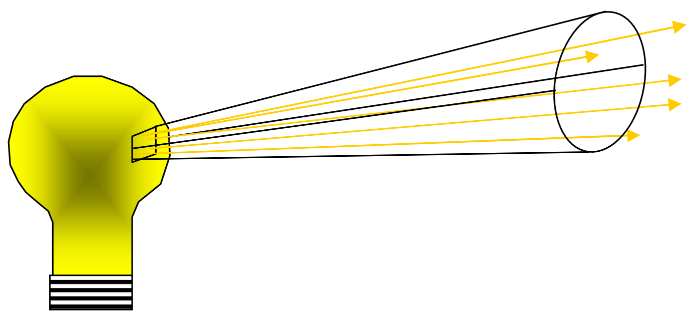
# Radiometry - Radiance

- Radiance/Luminance



UNITS: $W/m^2/sr$ - $cd/m^2$ - $ph/s/m^2/sr$

Any detector with lens is sensitive to radiance

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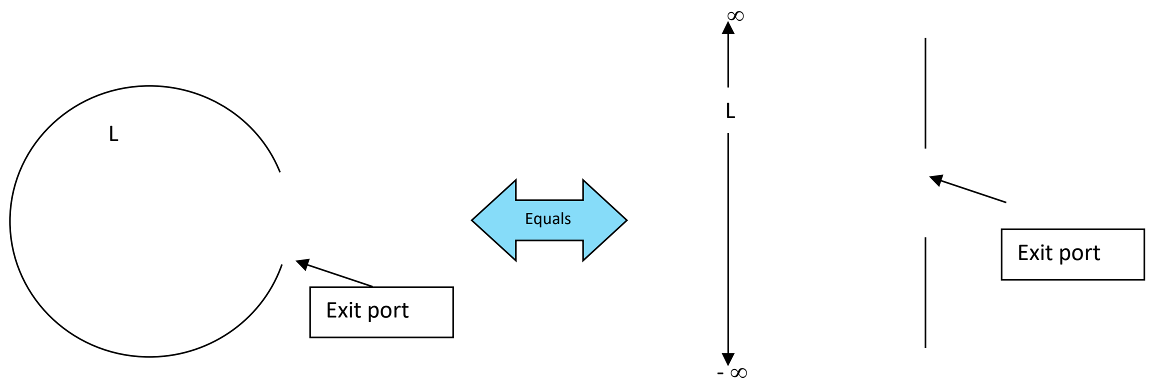
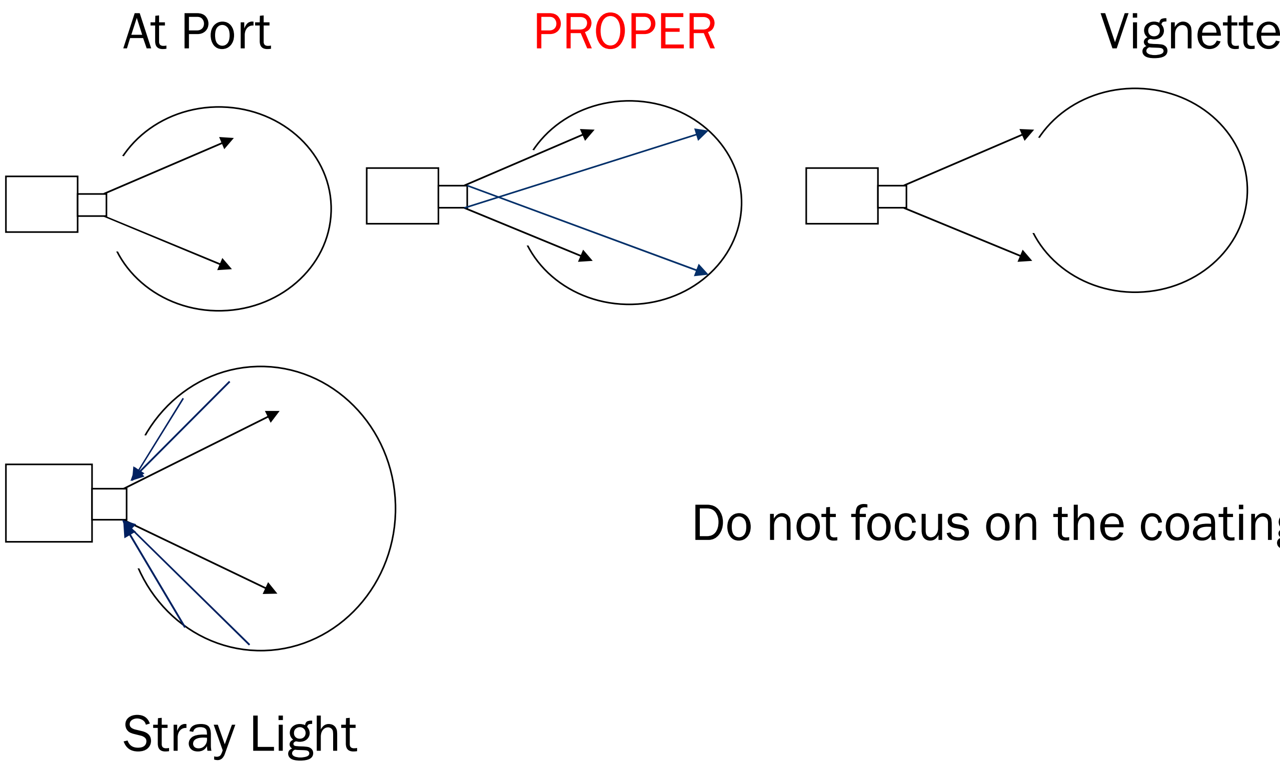
# Sphere as a Lambertian Field

- Radiance is constant whatever the distance to the sphere is.




- A good working model of an integrating sphere is to consider the port to be a hole in a wall, and, at a totally arbitrary distance behind it, another wall of infinite extent

# Proper FOV/Focus with a Sphere




Do not focus on the coating

# Sphere Radiance Measurements

- As far as possible from the sphere to avoid stray light without vignetting
- There is no need to focus at the entrance port of the sphere
- It is better not to focus on the sphere wall (granularity of coating)
- The sphere diameter has to be 3 times the sphere port for good uniformity

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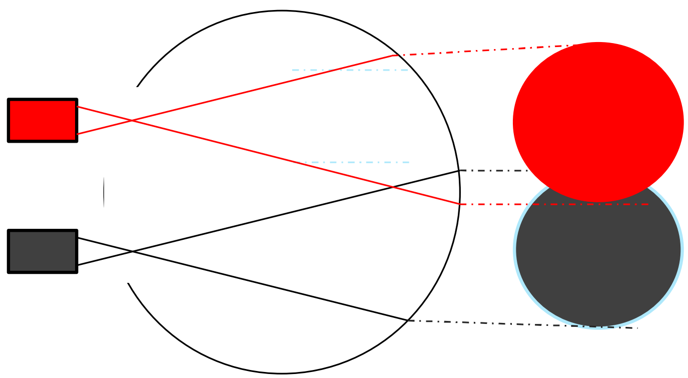
# Definition of Radiance Uniformity

- Labsphere's standard way of measuring uniformity

Luminance meter focussed at the entrance port



- The uniformity is measured as the difference in sphere's radiance between the red spot and the grey spot.
- Typically normalized to center of the port.
- Translate in X-Y or Angular

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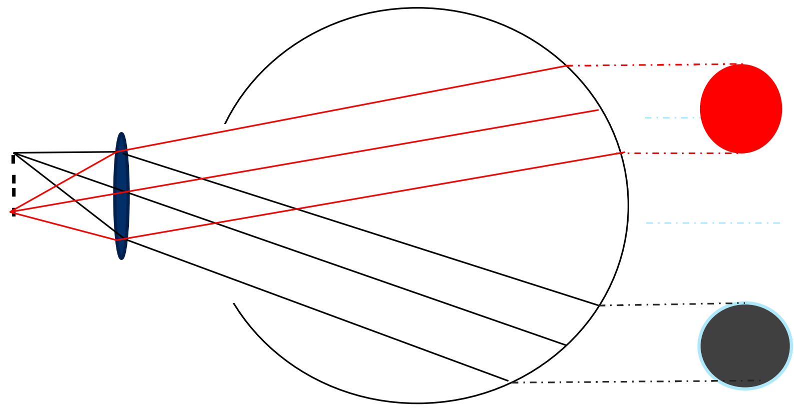
# Radiance Uniformity Definition by Optical System

- Uniformity pixel by pixel - For example

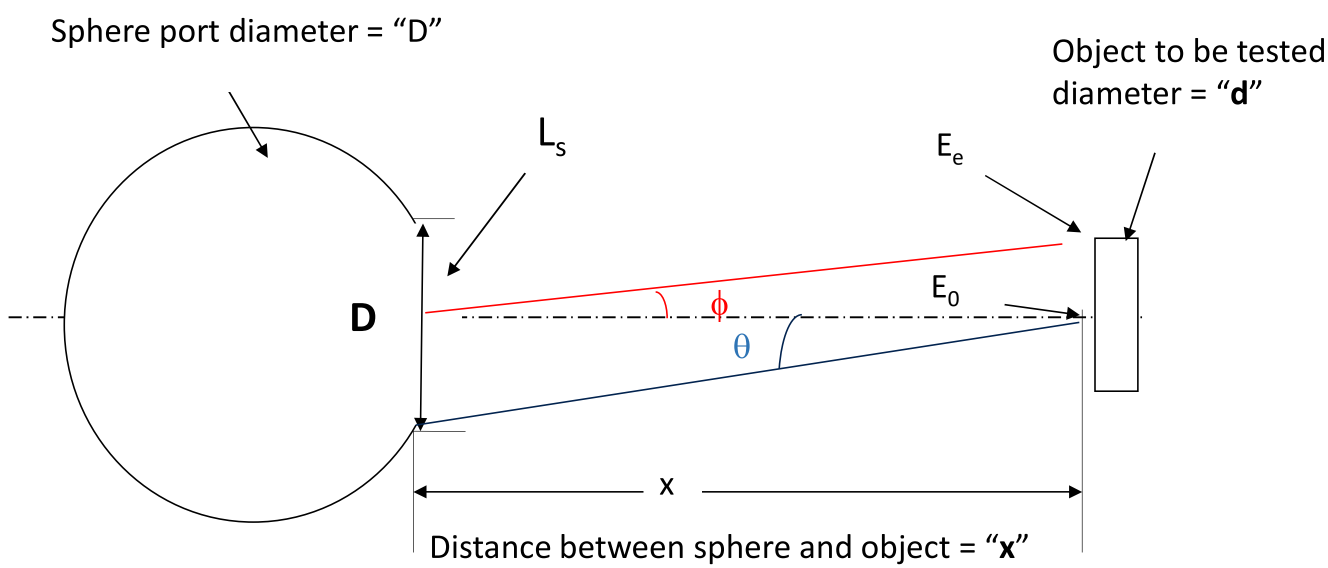


In case of uniformity of <98% both definitions will lead to similar uniformity.

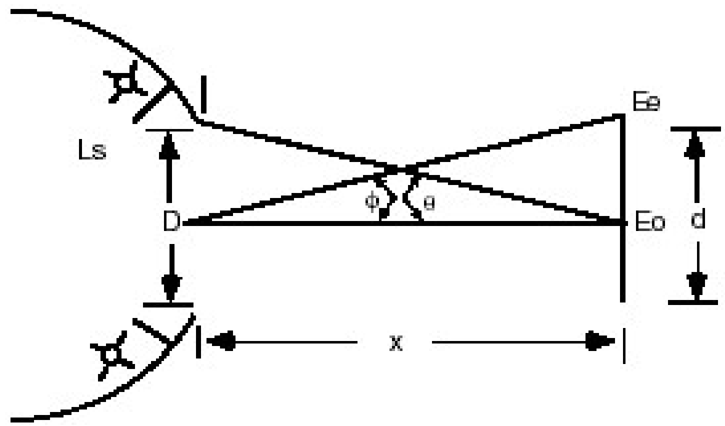
For uniformity >98%, measure uniformity as defined by optical system under test.

# Irradiance with a Sphere

- Size of Port (D), Size of Sensor (d), Distance between Sensor and Port (x).



# Irradiance Uniformity: d/D and x/D

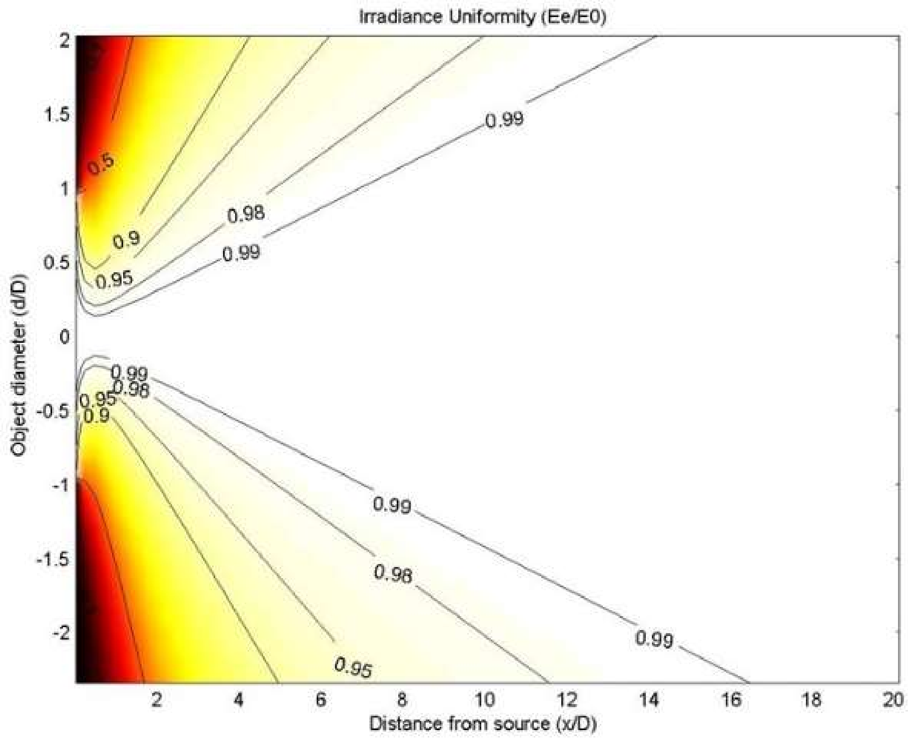



Irradiance Uniformity (Ee/Eo)
Distance from Source (x/D)

| Object Diameter d/D | 0.00 | 0.10 | 0.20 | 0.25 | 0.50 | 0.75 | 1.00 | 1.50 | 2.00 | 2.50 | 3.00 | 5.00 | 10.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.2 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.3 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.96 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 |
| 0.4 | 1.00 | 0.99 | 0.96 | 0.94 | 0.92 | 0.93 | 0.95 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 |
| 0.5 | 1.00 | 0.97 | 0.92 | 0.90 | 0.88 | 0.90 | 0.92 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 1.00 |
| 0.6 | 1.00 | 0.95 | 0.88 | 0.85 | 0.82 | 0.86 | 0.89 | 0.94 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 |
| 0.7 | 1.00 | 0.92 | 0.81 | 0.78 | 0.76 | 0.81 | 0.86 | 0.92 | 0.95 | 0.96 | 0.97 | 0.99 | 1.00 |
| 0.8 | 1.00 | 0.84 | 0.72 | 0.69 | 0.70 | 0.76 | 0.82 | 0.89 | 0.93 | 0.95 | 0.97 | 0.99 | 1.00 |
| 0.9 | 1.00 | 0.70 | 0.60 | 0.59 | 0.62 | 0.71 | 0.78 | 0.87 | 0.92 | 0.94 | 0.96 | 0.98 | 1.00 |
| $\sin^2\theta$ | 1.000 | 0.962 | 0.862 | 0.800 | 0.500 | 0.308 | 0.200 | 0.100 | 0.059 | 0.038 | 0.027 | 0.010 | 0.002 |
| $\pi\sin^2\theta$ | 3.142 | 3.021 | 3.708 | 2.513 | 1.571 | 0.967 | 0.628 | 0.314 | 0.185 | 0.121 | 0.085 | 0.031 | 0.008 |

Note: Boundary lines delineate regions of 98%, 95%, and 90% irradiance uniformity

# Irradiance Ratios: d/D and x/D

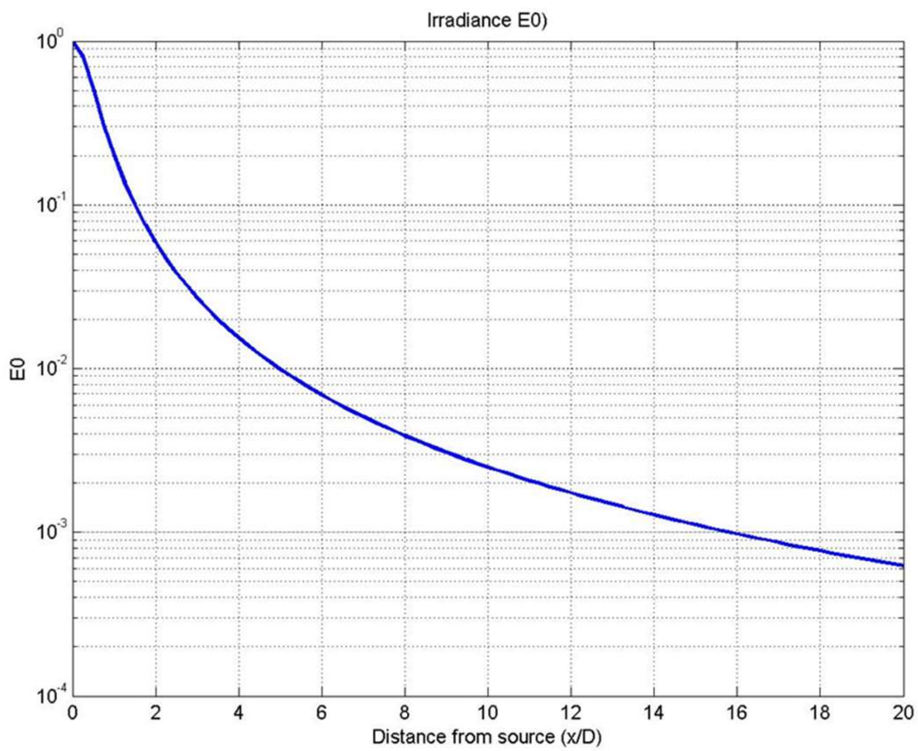



Irradiance is very uniform at sphere port, then degrades with distance.

Uniformity returns as distance increases (point source)

At distance, uniformity is proportional to the $\cos^4$ of the small angle ($\delta$)

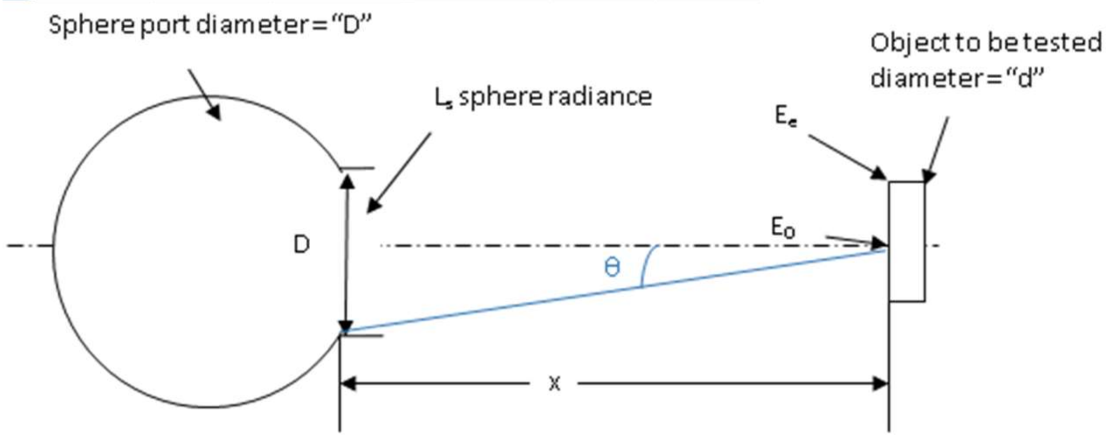
# Irradiance Decrease with Distance



# Irradiance Decrease with Distance

| | θ | | | | | |
|---|---|---|---|---|---|---|
| angle (°) | 1.8 | 3.6 | 7.2 | 14.5 | 30 | 45 |
| N.A. | 0.03 | 0.06 | 0.13 | 0.25 | 0.5 | 0.71 |
| f/# | 16 | 8 | 4 | 2 | 1 | 0.71 |
| π.sin²θ | 0.001 | 0.00 4 | 0.016 | 0.063 | 0.25 | 0.50 |

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

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# Irradiance and FOV (f/#)

When testing a detector for flat fielding or response, one wants certainly to use the same FOV as the one the detector will see when mounted in the camera.

The way to define a system with a sphere is:

- Define the uniformity needed on the detector
- Calculate the distance needed to get this uniformity using the $\cos^4$ rule
- When the distance is defined, then the FOV will determine the size of the port needed on the sphere

As an example :

Detector: 13mm diagonal – FOV : f/2 - requested irradiance uniformity : 98%

- Using the $\cos^4$ law angle should be 5.7° and the distance should be 65mm
- f/# of 2 means that the sphere port dia should be 33mm

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# Sphere vs. a Target: Why?

Main reasons:

- Uniformity:
  - Spatial <u>and</u> Angular (10cm port shown)
- Dynamic range (>100dB)
- Mix of sources (Solar, QTH, Laser)
- Monitoring of light levels and absolute measurements with known uncertainty
- Spheres are depolarized
- Low Uncertainty Calibration for Downwelling* / Upwelling Sensors

Table: 1

Uniformity Map: Spatial

| | -8.00" | -6.40" | -4.80" | -3.20" | -1.60" | -0.00" | 1.60" | 3.20" | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8.00" | | | | | -0.550% | -0.480% | -0.500% | | | | |
| 6.40" | | | 0.160% | 0.190% | -0.400% | -0.480% | -0.480% | -0.580% | -0.730% | | |
| 4.80" | | 0.170% | 0.120% | 0.130% | -0.010% | -0.430% | -0.520% | -0.740% | -0.860% | -0.910% | |
| 3.20" | | 0.160% | 0.080% | 0.150% | 0.230% | 0.050% | -0.360% | -0.640% | -0.700% | -0.680% | |
| 1.60" | 0.190% | 0.180% | 0.130% | 0.060% | 0.110% | 0.120% | 0.050% | -0.100% | -0.240% | -0.270% | -0.370% |
| 0.00" | -0.130% | -0.100% | -0.050% | -0.100% | -0.060% | 0.000% | 0.050% | -0.060% | -0.260% | -0.330% | -0.500% |
| -1.60" | 0.490% | -0.340% | -0.240% | -0.140% | -0.130% | -0.190% | -0.140% | -0.250% | -0.470% | -0.610% | -0.680% |
| -3.20" | | -0.650% | -0.530% | -0.420% | -0.360% | -0.340% | -0.390% | -0.540% | [illegible] | [illegible] | [illegible] |
| -4.80" | | -0.980% | -0.820% | -0.760% | -0.680% | -0.640% | -0.690% | -0.790% | [illegible] | [illegible] | [illegible] |
| -6.40" | | | -0.970% | -0.910% | -0.880% | -0.890% | -0.870% | -0.990% | [illegible] | [illegible] | [illegible] |
| -8.00" | | | | | -1.130% | -1.110% | -1.150% | | | | |

| | |
|---|---|
| Uniformity | 98.61% |
| Non Uniformity Deviation | 0.40% |

Table: 2

Uniformity Map: Angular

| | -17.50 deg | -14.00 deg | -10.50 deg | -7.00 deg | -3.50 deg | 0.00 deg | 3.50 deg | 7.00 deg | 10.50 deg | 14.00 deg | 17.50 deg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.50 deg | | | | | 1.180% | 1.150% | 1.170% | | | | |
| 14.00 deg | | | 0.800% | 0.810% | 0.840% | 0.960% | 0.930% | 0.760% | 0.690% | | |
| 10.50 deg | | 0.710% | 0.570% | 0.340% | 0.430% | 0.490% | 0.340% | 0.380% | 0.350% | 0.390% | |
| 7.00 deg | | 0.640% | 0.490% | 0.260% | 0.280% | -0.350% | -0.610% | -0.010% | 0.170% | 0.130% | |
| 3.50 deg | 0.440% | 0.490% | 0.500% | 0.280% | 0.270% | -0.350% | -0.600% | -0.100% | -0.030% | -0.040% | 0.060% |
| 0.00 deg | 0.270% | 0.160% | 0.110% | 0.040% | 0.030% | 0.000% | -0.190% | -0.400% | -0.360% | -0.390% | -0.220% |
| -3.50 deg | 0.090% | -0.250% | -0.420% | -0.410% | -0.350% | -0.340% | -0.580% | -0.820% | -0.810% | -0.680% | -0.490% |
| -7.00 deg | | -0.450% | -0.640% | -0.620% | -0.620% | -0.680% | -0.860% | -1.000% | -1.030% | -0.990% | |
| -10.50 deg | | -0.590% | -0.780% | -0.760% | -0.830% | -0.950% | -1.100% | -1.180% | -1.190% | -1.180% | |
| -14.00 deg | | | -0.870% | -0.930% | -0.930% | -1.010% | -1.040% | -1.120% | -1.180% | | |
| -17.50 deg | | | | | -0.960% | -0.990% | -1.000% | | | | |

| | |
|---|---|
| Uniformity | 97.63% |
| Non Uniformity Deviation | 0.66% |

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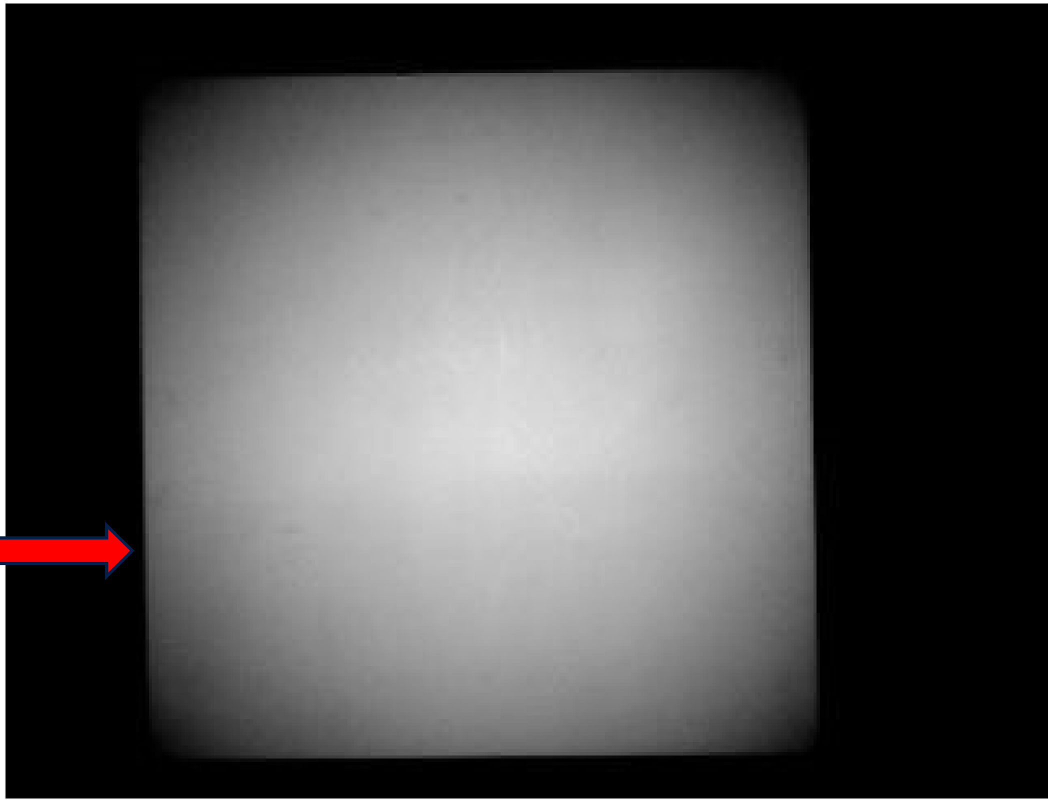
# Uniformity & Level of a Target

The uniformity in radiance will depend on the uniformity in irradiance of the source projected at the target. OK for small targets or large distances….not OK for short distance or large targets.

Examples:

Lamp @ 50cm and 10cm Target
Irradiance ~Cos^3
Uniformity ~+/-1.5% (97%)

Lamp @ 50cm and 30cm Target
Irradiance ~Cos^3
Uniformity ~+/-12% (86%)



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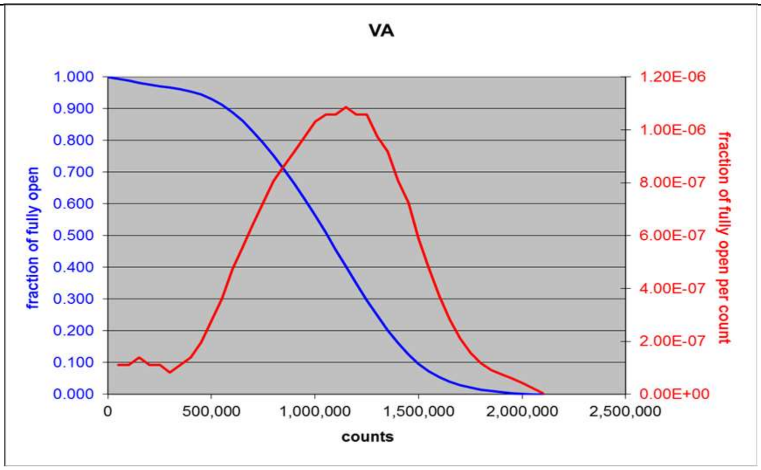
# Spheres: Dynamic Range (DR)

- Units:

  dB : $20*\log_{10}(DR)$

  bits : $\log_2(DR)$

  decades : $\log_{10}(DR)$

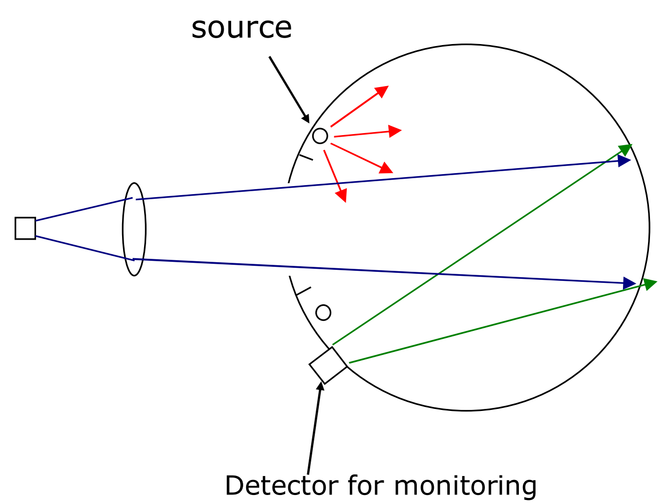



Dynamic range with target using combination of grey target and distance to the target: 0-40dB

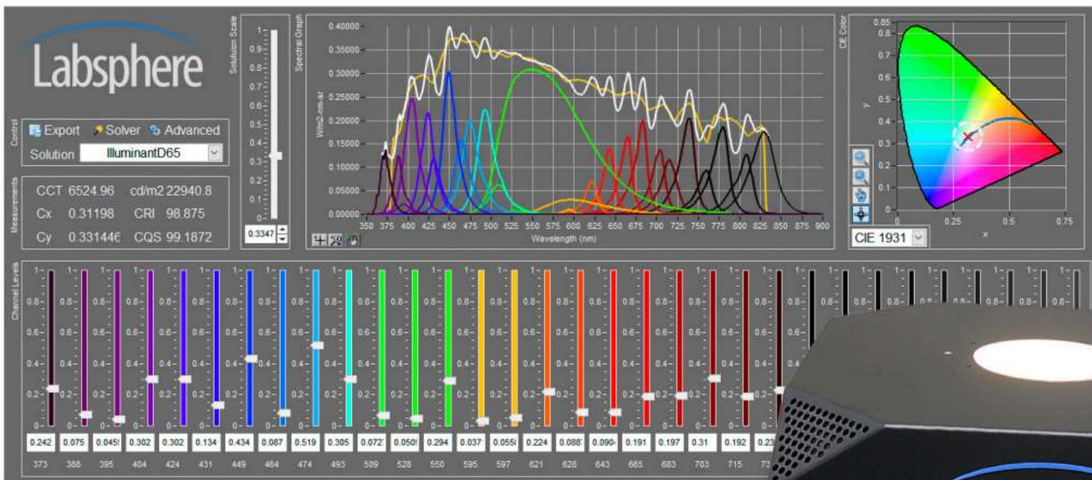
Dynamic range with a sphere system: 40-160dB+

# Sphere: Monitoring & Absolute Measurements with Known Uncertainty

Detector on the sphere can be calibrated to reflect the radiance or irradiance delivered by the sphere



# Spheres - Creating Light Mixing or Tuneable Sources





Accurately reproduce almost any spectrum from 390 nm to 1000 nm

- Large Arrays of LEDs
  - Provide high radiance in spheres
- Spectral Shaping for Tunability Systems
  - Independent control and flux integration
  - Global optimization using spectral fit objective functions provide match to target spectra
  - Can emulate many different sources including broadband through the visible and NIR

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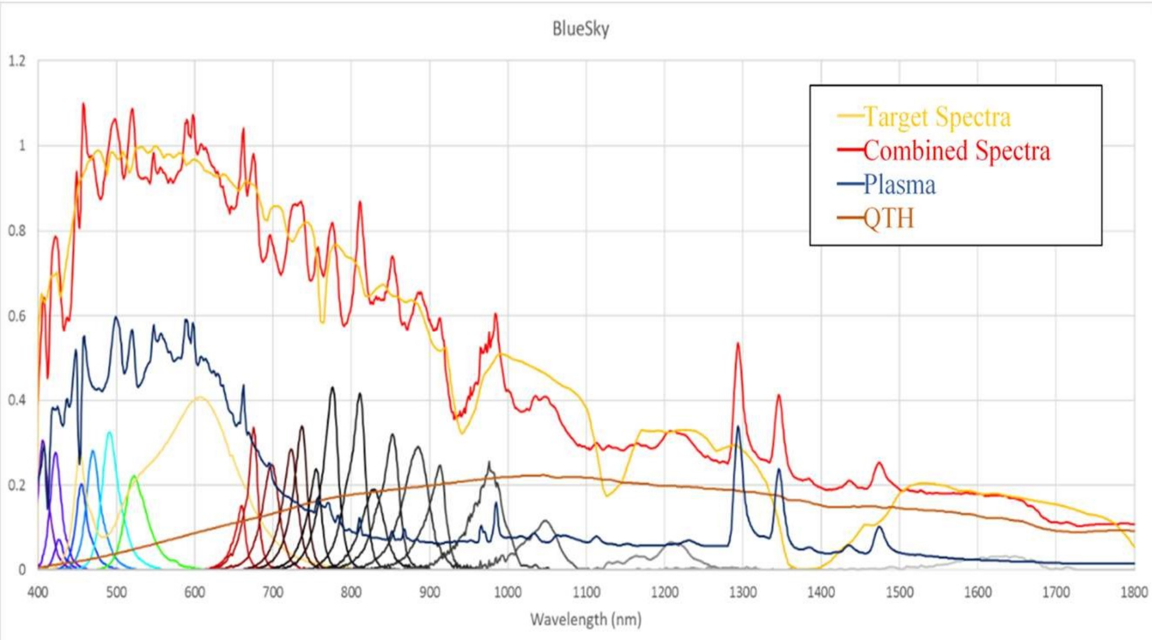
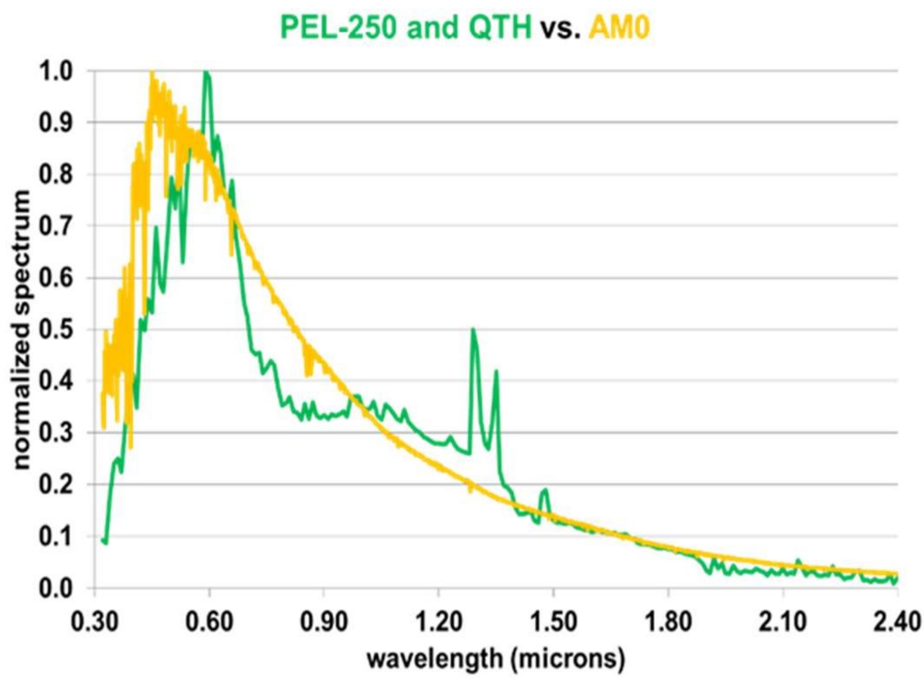
# Combining Broadband and Other sources – Solar examples

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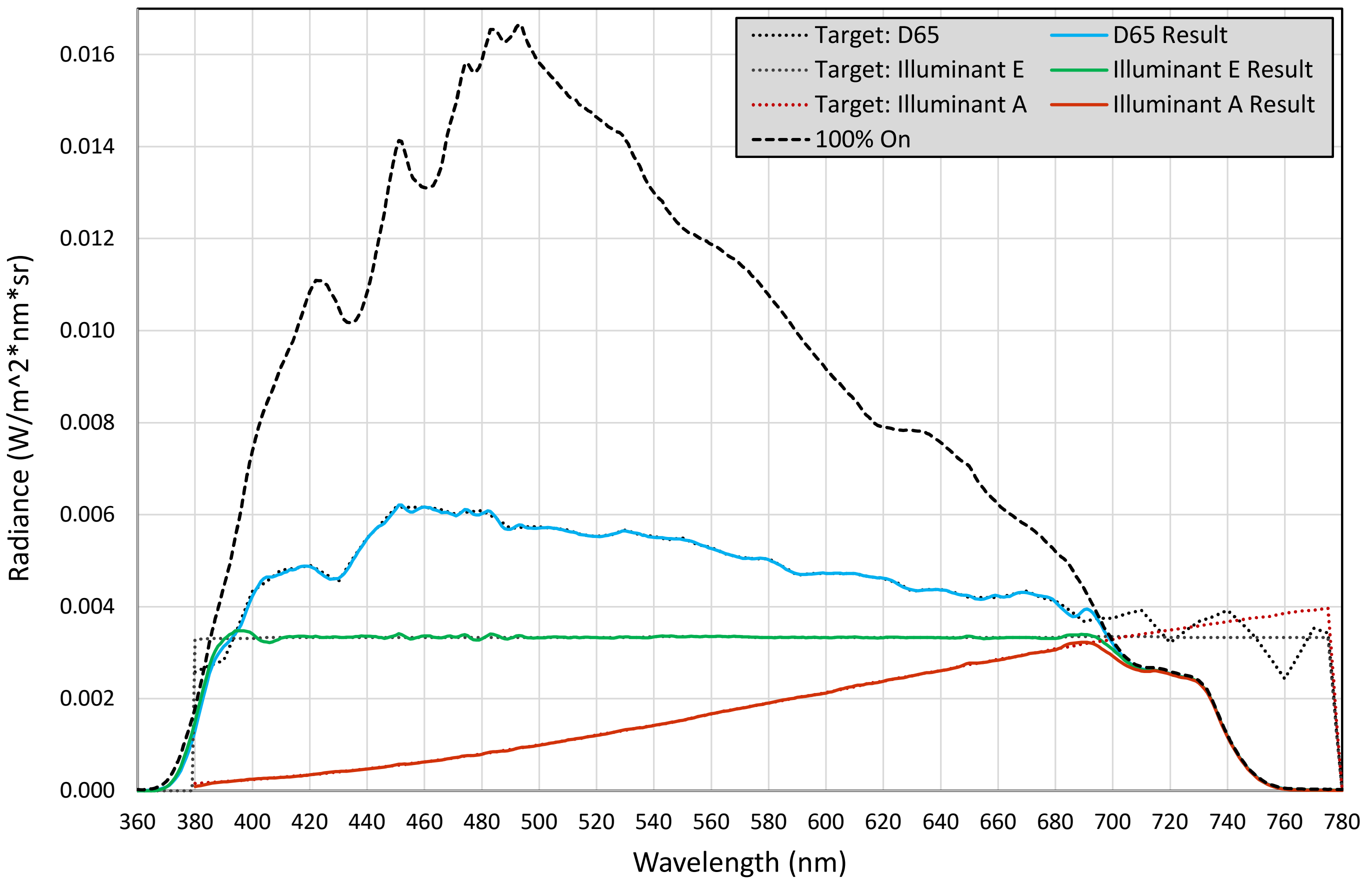
# Polychromator:  Standard Illuminants matching

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# Calibration of Integrating Spheres

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- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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## Sphere Calibrations

**The reflectance of the sphere cannot be known with low enough uncertainty to calculate throughput accurately enough for calibration.**

**Therefore, all sphere calibrations are SOURCE BASED calibrations.**

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# Calibration of Spheres

**Radiometers/photometers**

**Reflectance/transmittance measurements**

**Uniform source**

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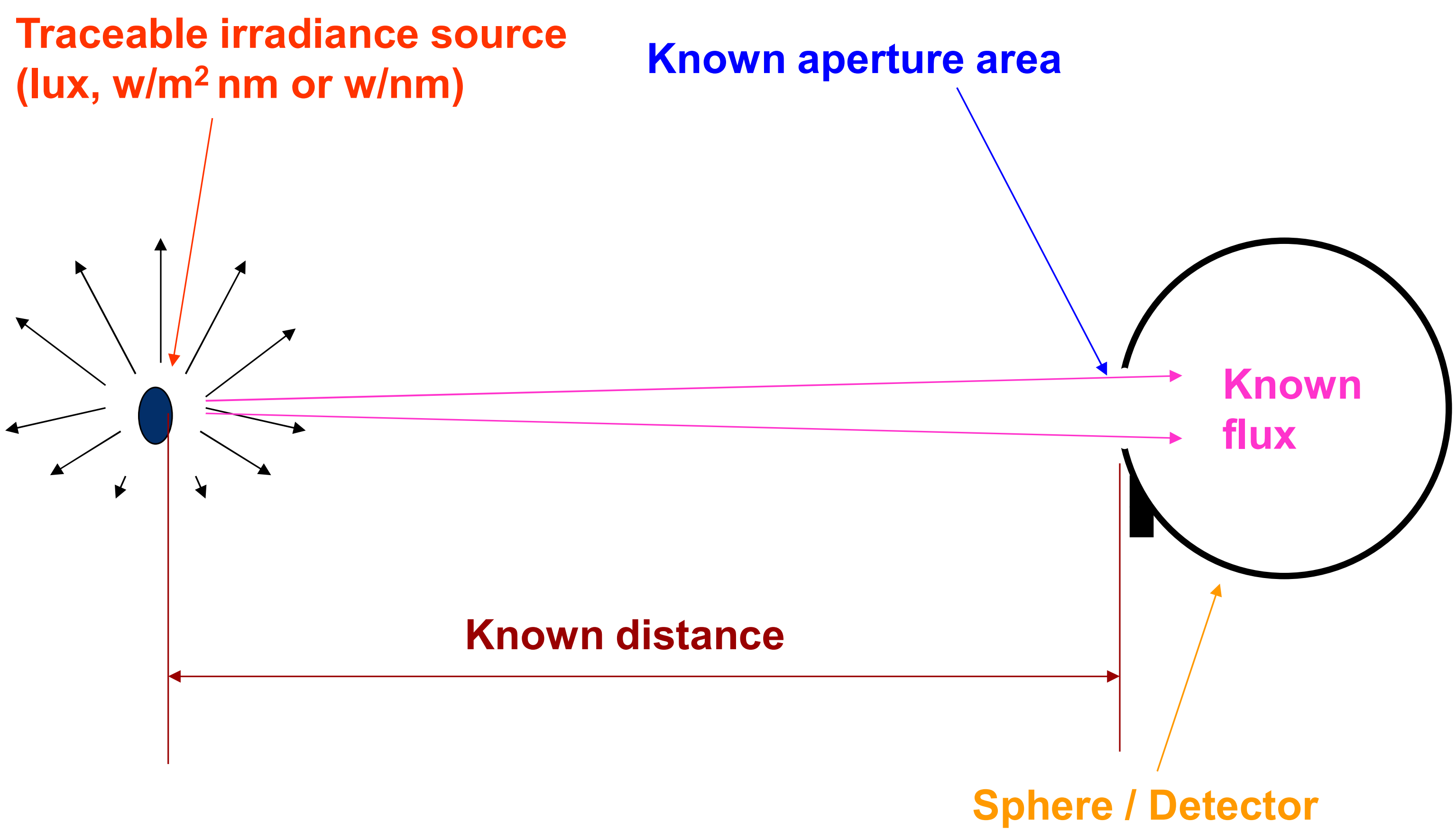
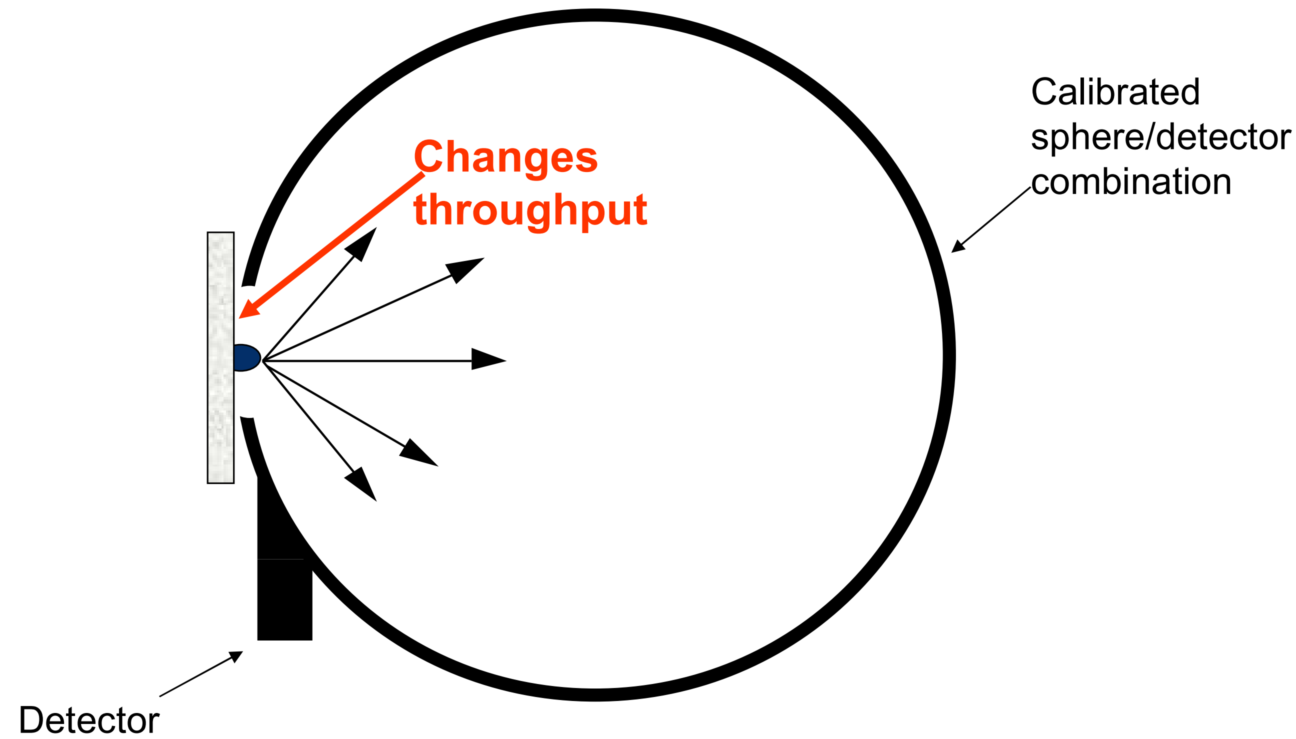
# Calibration of Radiometers/Photometers/Laser Power



# LED / Laser Substitution Error

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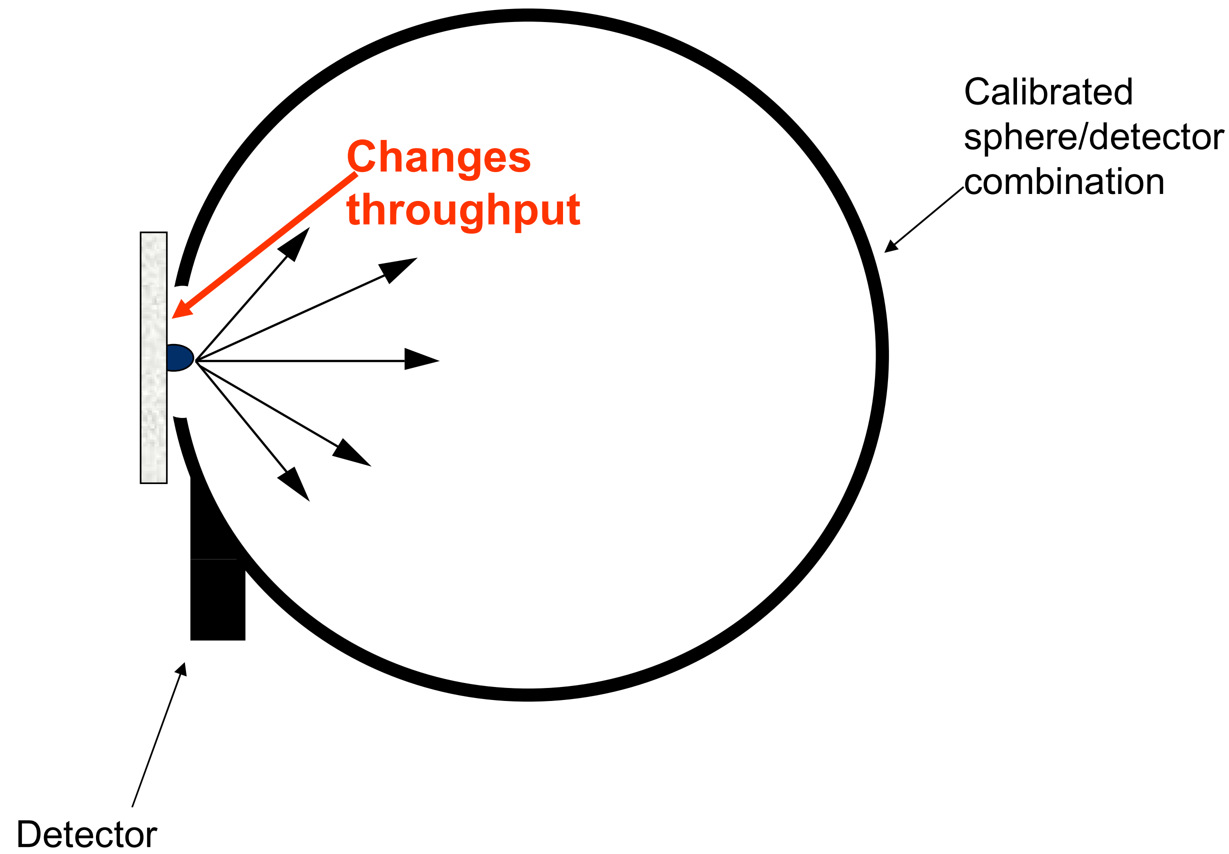
# LED / Laser Substitution Error

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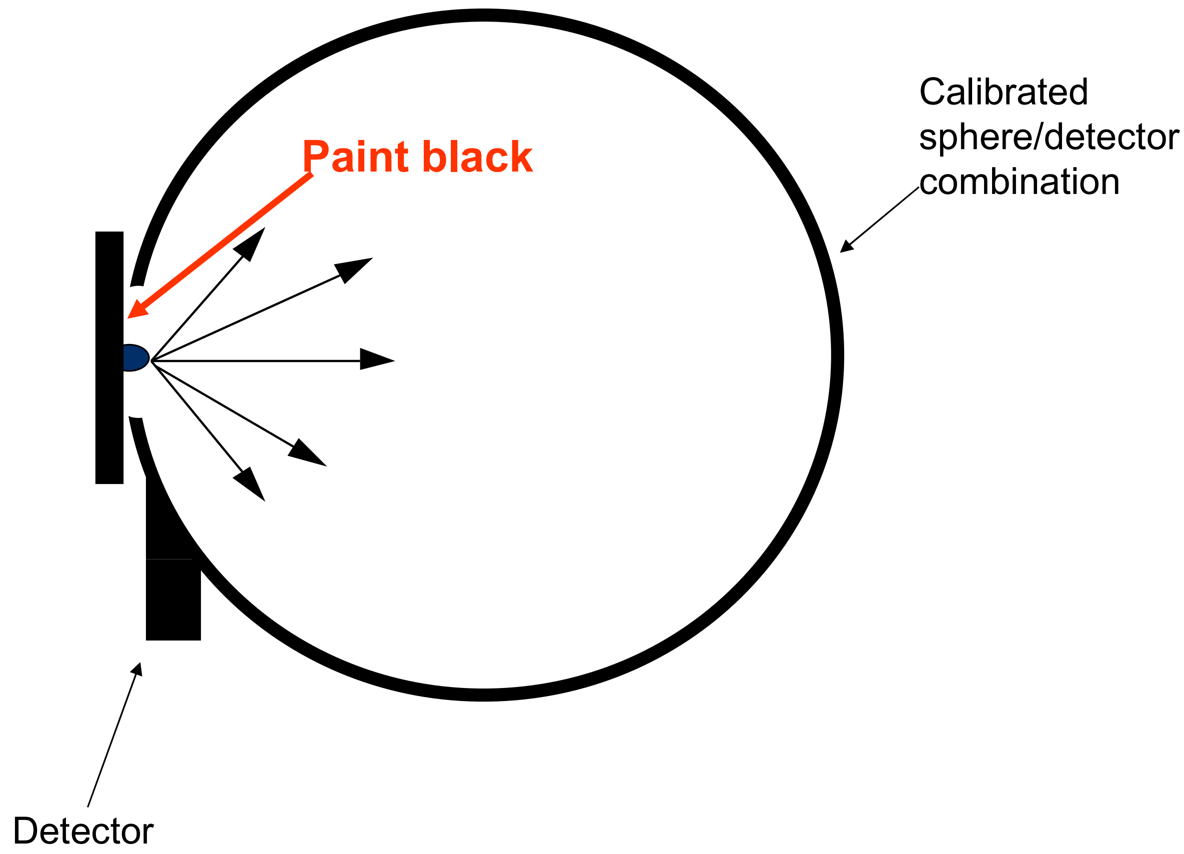
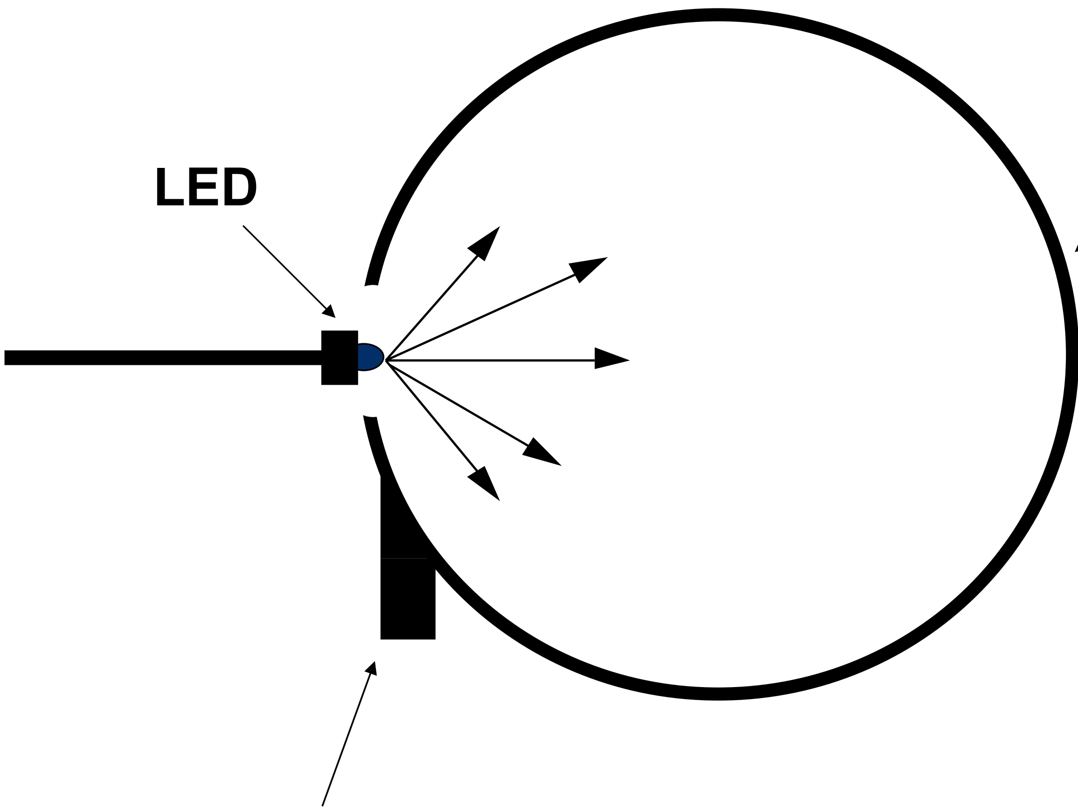
# LED / Laser Substitution Error



# LED / Laser Substitution Error

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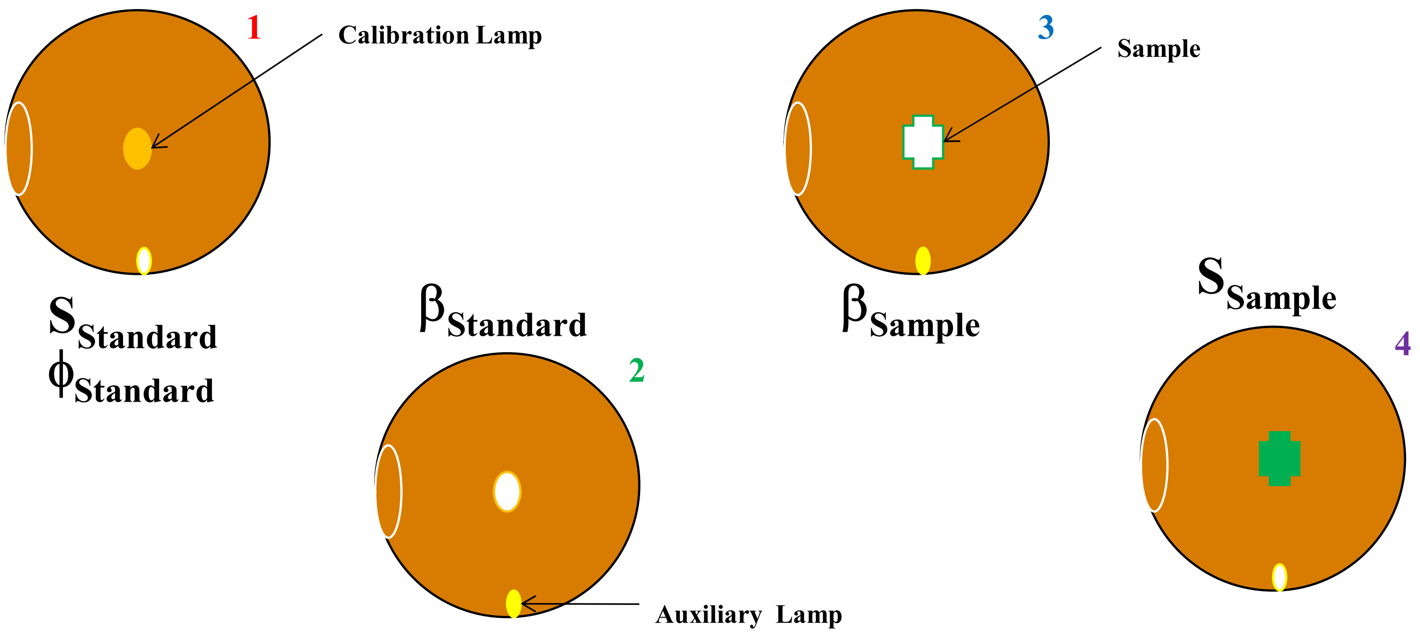
# Internal/External Lamp Measurement Calibration




$$\phi_{Sample}(\lambda) = \frac{S_{Sample}^{4}(\lambda)}{S_{Standard}^{1}(\lambda)} * \frac{\beta_{Standard}^{2}(\lambda)}{\beta_{Sample}^{3}(\lambda)} * \phi_{Standard}^{1}(\lambda)$$

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# Sphere Calibration

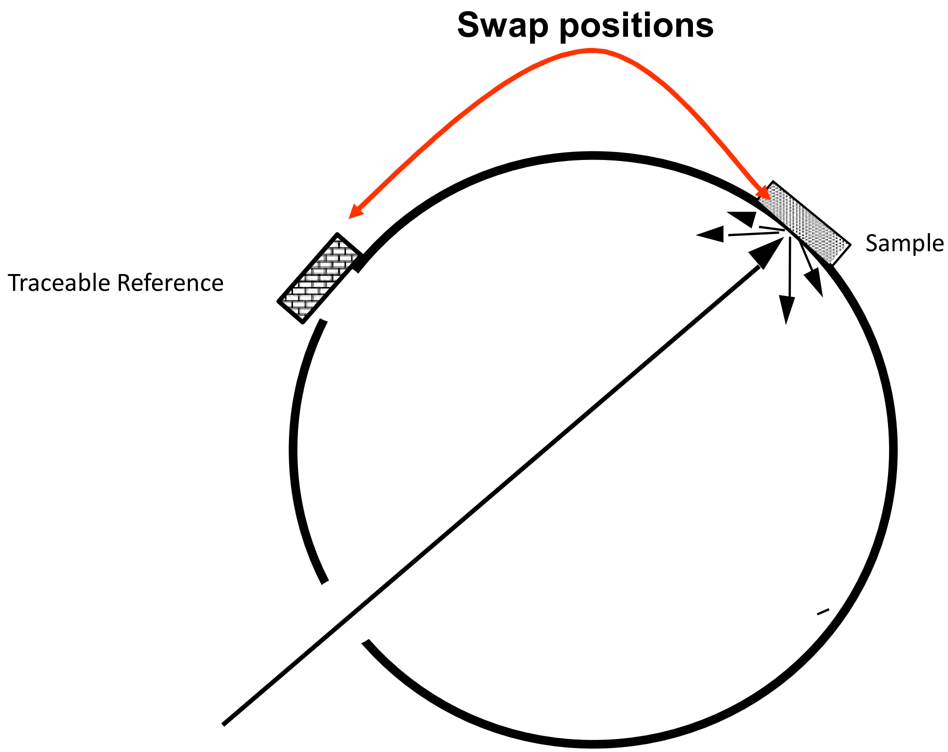
Radiometers/photometers

Reflectance/transmittance measurements

Uniform source

Labsphere

# Reflectance Calibration




**Both Sample Stay on Sphere during each measurement – no substitution error.**

# Sphere Calibration

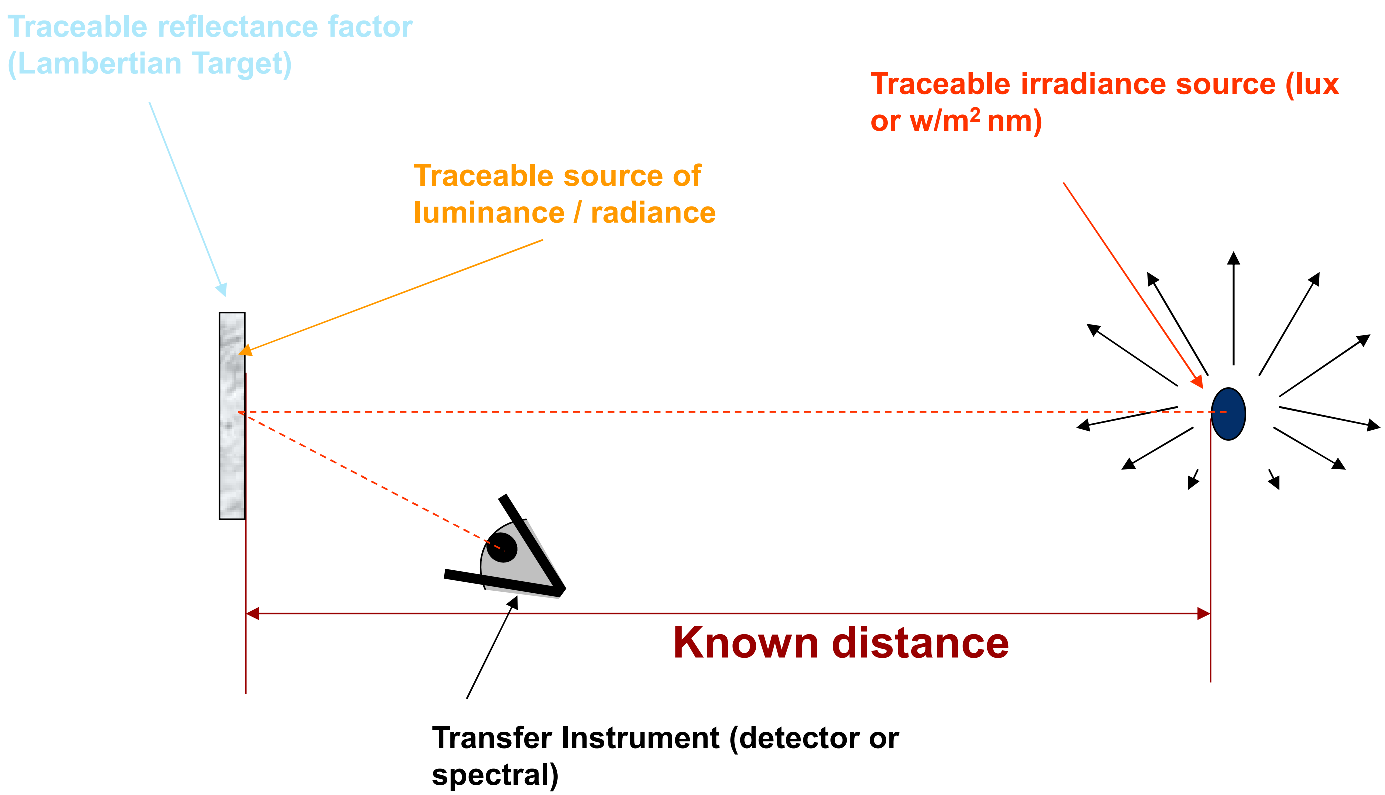
Radiometers/photometers

Reflectance/transmittance measurements

Uniform source

Labsphere

# Uniform Source Calibration

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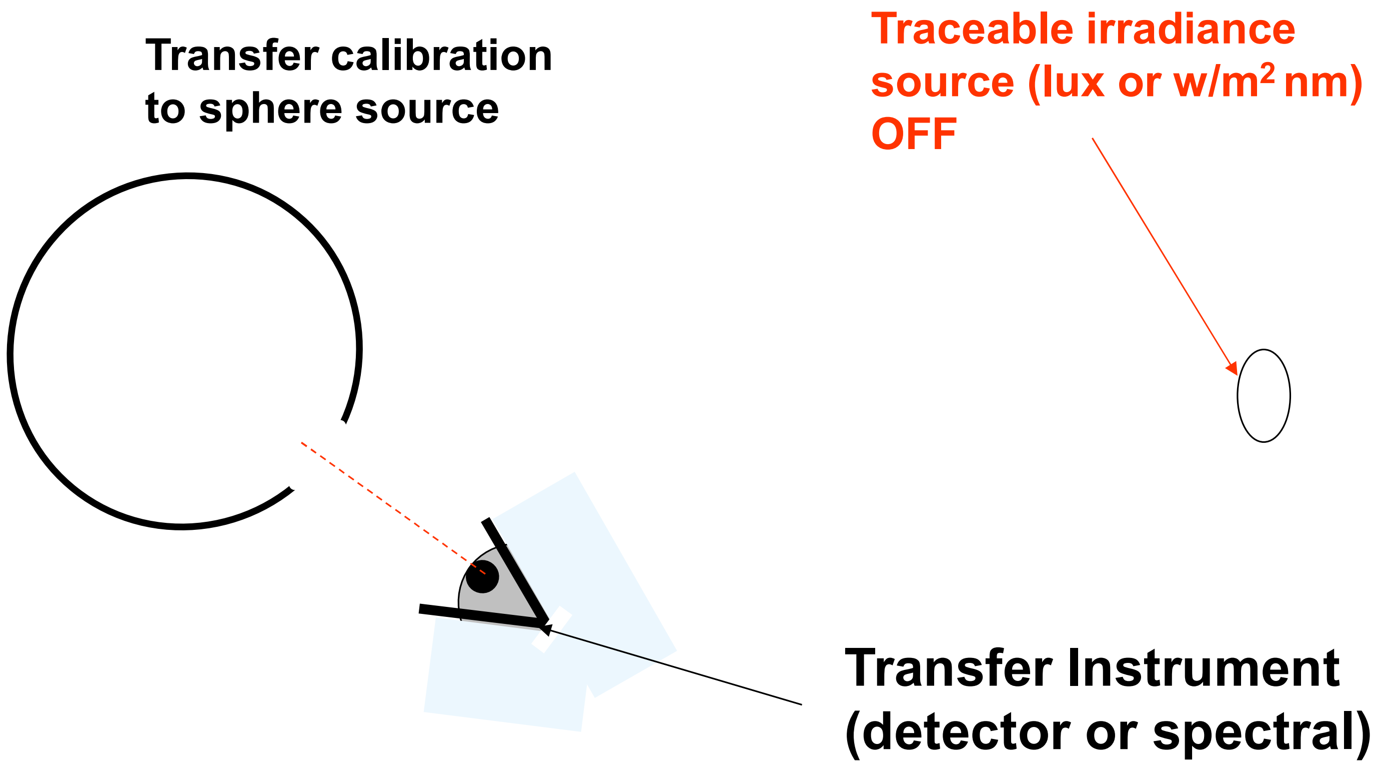
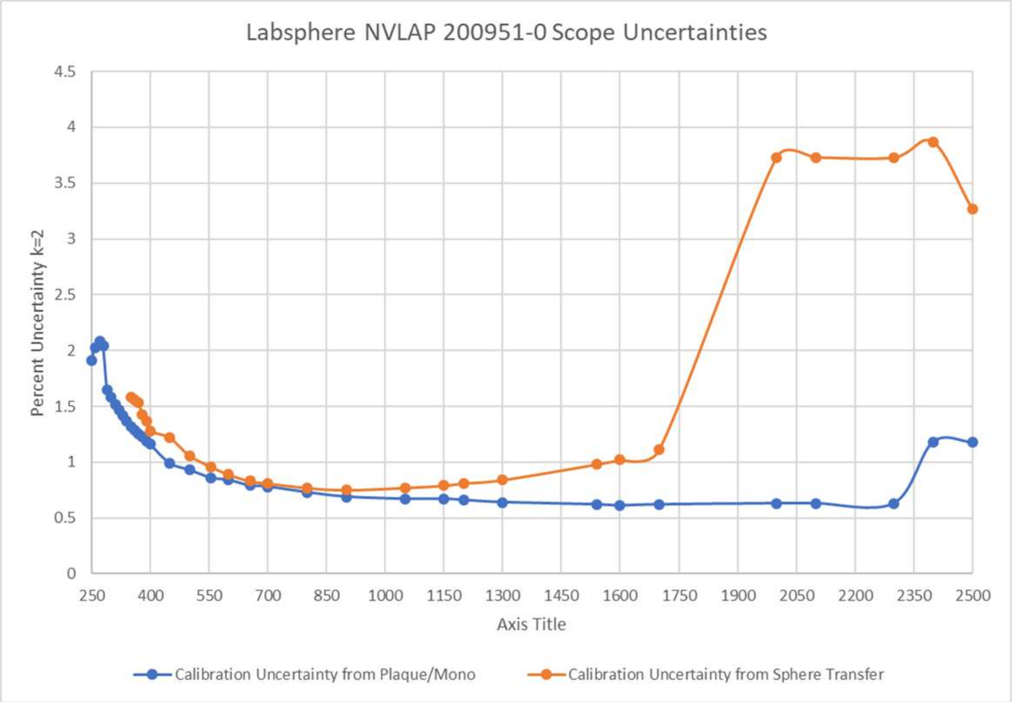
# Uniform Source Calibration



# Traceability for Integrating Sphere Calibration Source

- Begins with SI Units and the National Metrology Institutes
  - Transfer from NIST primary irradiance source off calibrated Lambertian plaque to monochromator detector
- Increases in NMI accuracy improves uncertainty across industry/EO community
  - NIST recently added (2018) 2500 nm, extends our capability
- Traceability chain to NIST - <1% relative uncertainty 555 – 1600 nm

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# Uniform Source Case Studies
# (If time permits…)

# Landsat 8 & 9 OLI Calibration System

- 100% QTH
- >160dB Dynamic Range
- Extraterrestrial Sunlight Levels to Night Vision.
- Spectral and Band Monitoring
- >98% Uniformity over 8 decades.
- 1% variation in Uniformity at each level
- Water-Cooled

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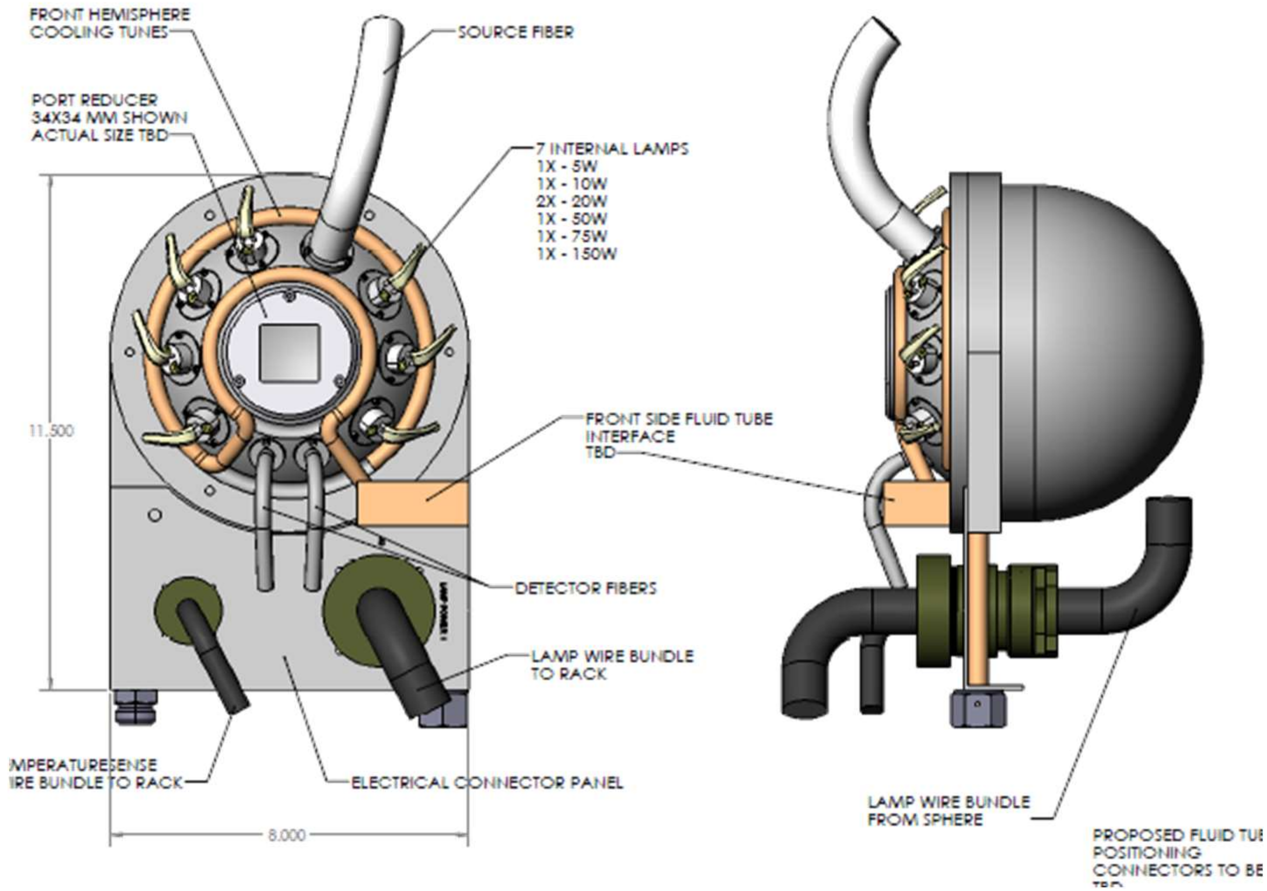
# Water cooled, vacuum-ready, variable output source – OLI 8/9

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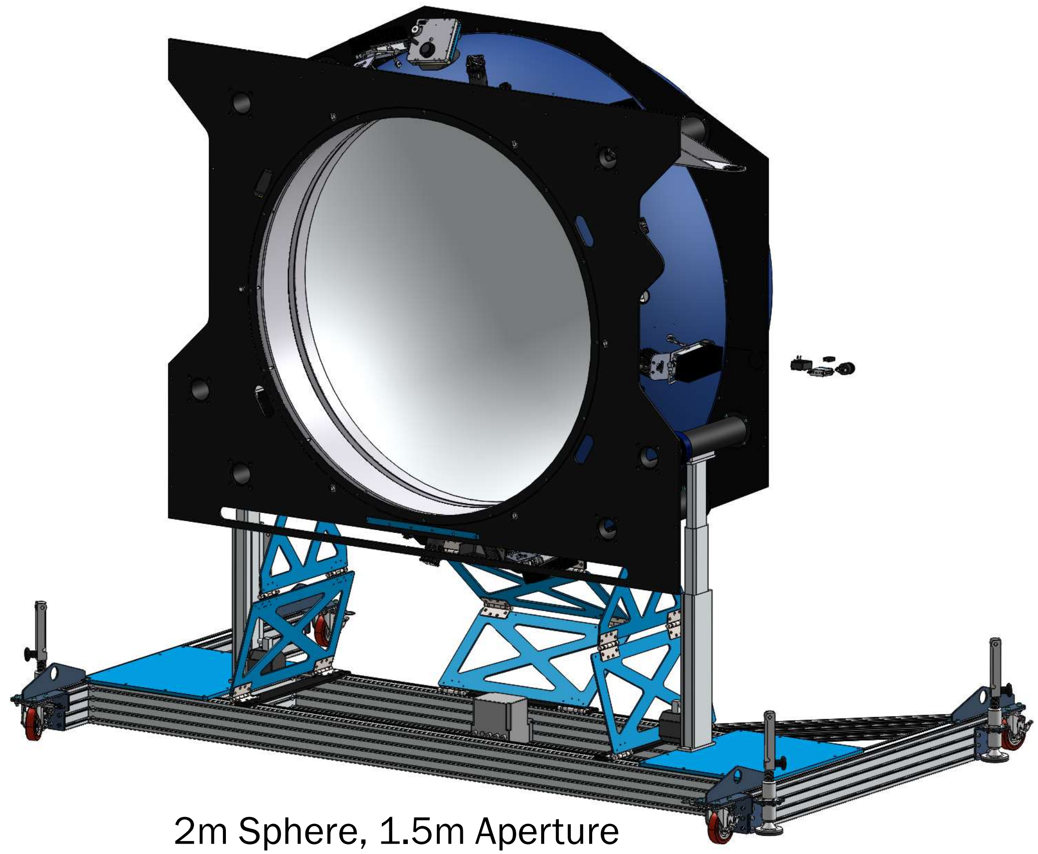
# Japan & India – 2m Next Generation Satellite Calibrators


2m Sphere, 1.2m Aperture QTH



2m Sphere, 1.5m Aperture
Plasma, Laser and QTH

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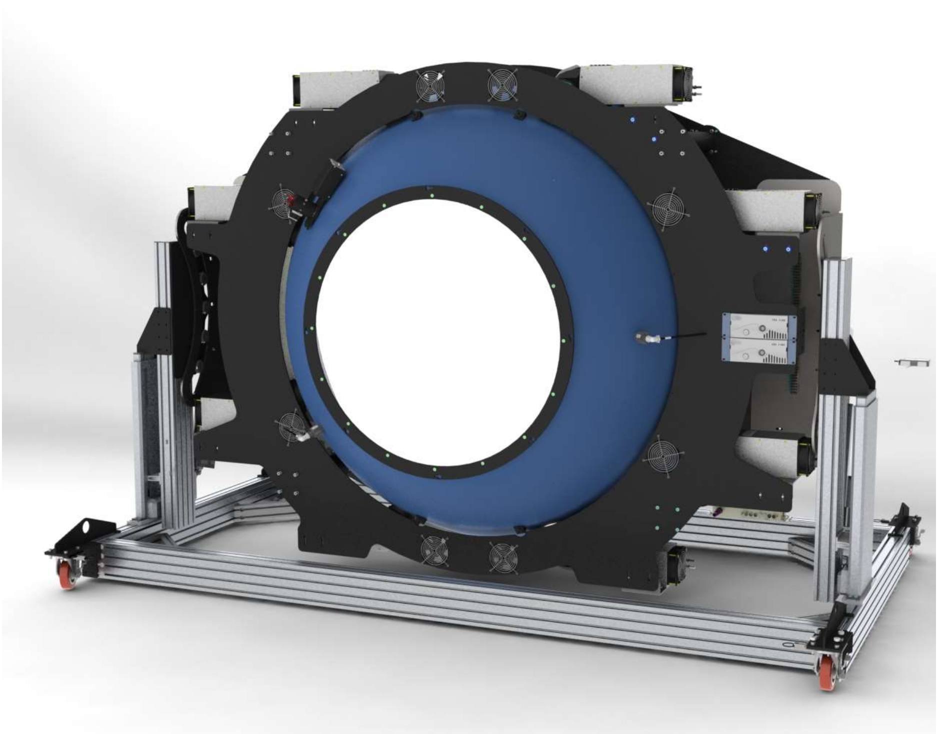
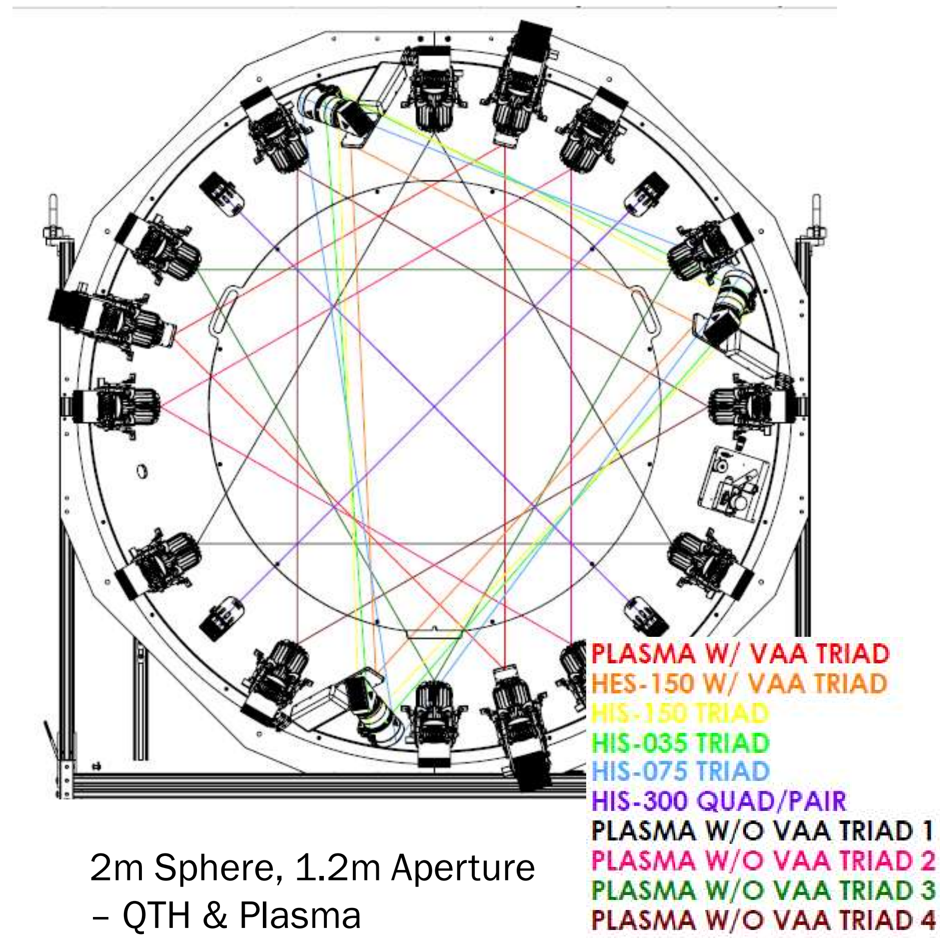
# China & Korea – Next Generation



2m Sphere, 1.2m Aperture – QTH & Xenon




2m Sphere, 1.2m Aperture – QTH & Plasma

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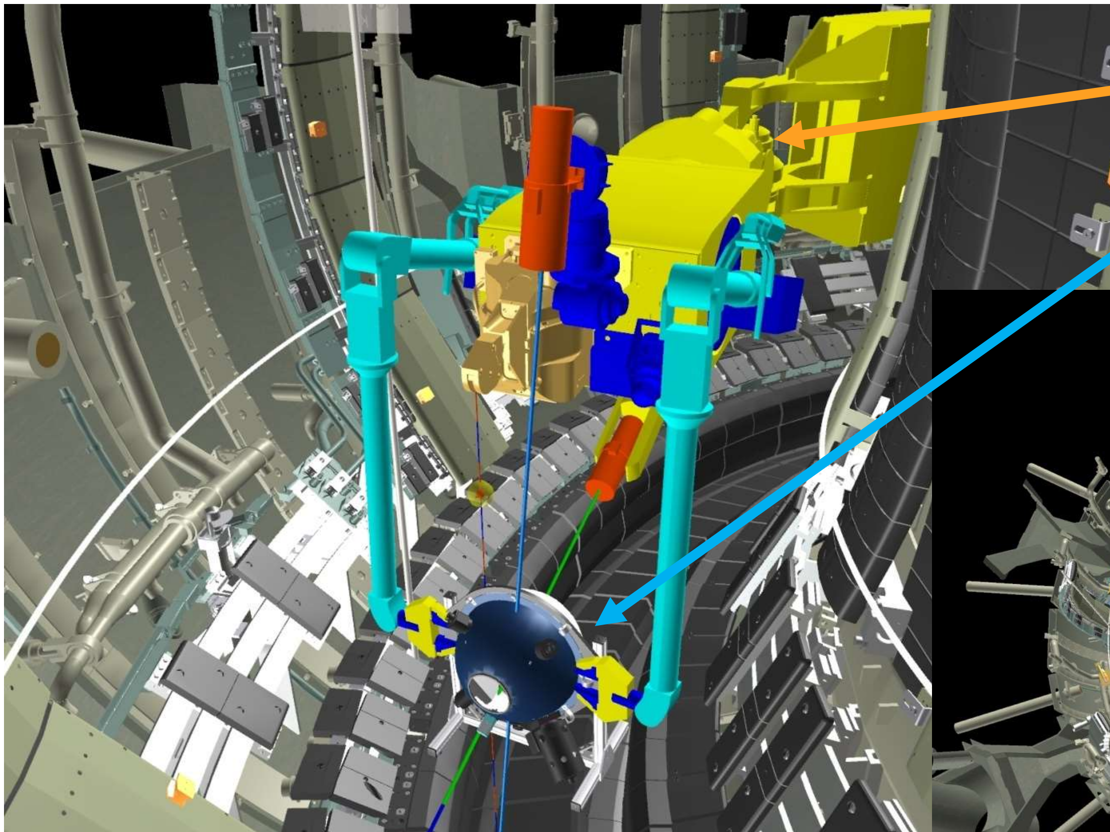
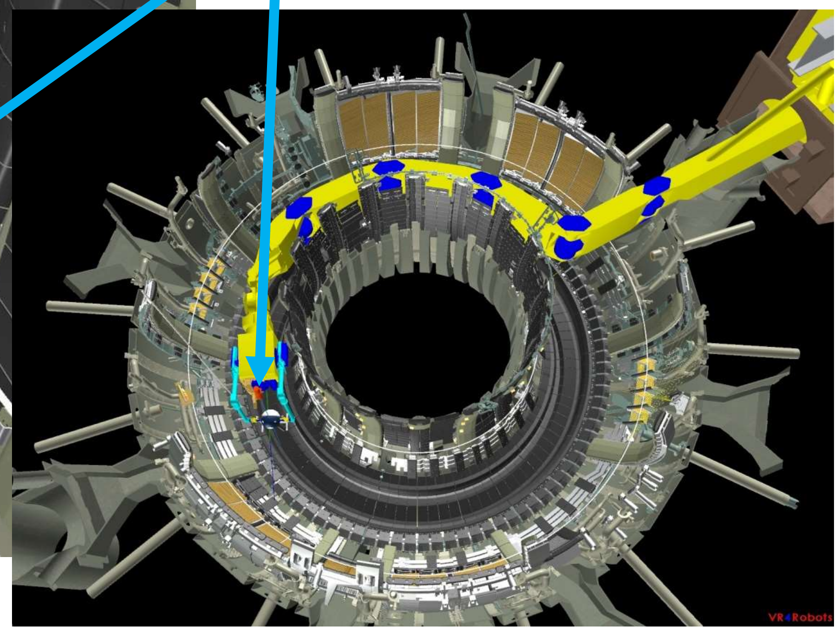
# Joint European Torus (JET) – Calibration Sphere





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# VIRTUAL COFFEE BREAK

(10 Minutes)

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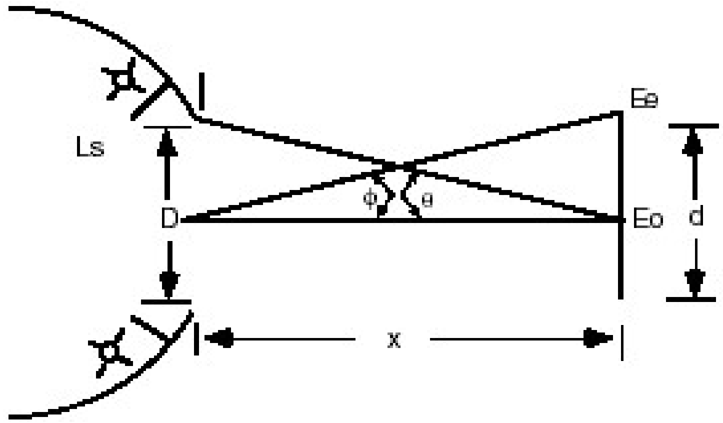
# Irradiance Uniformity: d/D and x/D




Irradiance Uniformity (Ee/Eo)
Distance from Source (x/D)

| Object Diameter d/D | 0.00 | 0.10 | 0.20 | 0.25 | 0.50 | 0.75 | 1.00 | 1.50 | 2.00 | 2.50 | 3.00 | 5.00 | 10.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.2 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.3 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.96 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 |
| 0.4 | 1.00 | 0.99 | 0.96 | 0.94 | 0.92 | 0.93 | 0.95 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 |
| 0.5 | 1.00 | 0.97 | 0.92 | 0.90 | 0.88 | 0.90 | 0.92 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 1.00 |
| 0.6 | 1.00 | 0.95 | 0.88 | 0.85 | 0.82 | 0.86 | 0.89 | 0.94 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 |
| 0.7 | 1.00 | 0.92 | 0.81 | 0.78 | 0.76 | 0.81 | 0.86 | 0.92 | 0.95 | 0.96 | 0.97 | 0.99 | 1.00 |
| 0.8 | 1.00 | 0.84 | 0.72 | 0.69 | 0.70 | 0.76 | 0.82 | 0.89 | 0.93 | 0.95 | 0.97 | 0.99 | 1.00 |
| 0.9 | 1.00 | 0.70 | 0.60 | 0.59 | 0.62 | 0.71 | 0.78 | 0.87 | 0.92 | 0.94 | 0.96 | 0.98 | 1.00 |
| $\sin^2\theta$ | 1.000 | 0.962 | 0.862 | 0.800 | 0.500 | 0.308 | 0.200 | 0.100 | 0.059 | 0.038 | 0.027 | 0.010 | 0.002 |
| $\pi\sin^2\theta$ | 3.142 | 3.021 | 3.708 | 2.513 | 1.571 | 0.967 | 0.628 | 0.314 | 0.185 | 0.121 | 0.085 | 0.031 | 0.008 |

Note: Boundary lines delineate regions of 98%, 95%, and 90% irradiance uniformity

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# Performance Considerations for Uniform Source Specifications

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# Workshop Agenda (All times in MDT)

- 0730-0840 Sphere Theory and Applications (Durell)
- 0840-0910 Uniform Source Tutorial (Durell)
- 0910-0920 Sphere Calibrations (Durell)
- 0920-0930 (Virtual) Coffee Break
- 0930-1010 Considerations for Uniform Source Specifications (Scharpf)
- 1010-1020 Commercial considerations (Scharpf)
- 1020-1040 NASA GLAMR Case Study (Brendan McAndrew, NASA GSFC)
- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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# Performance Considerations for Uniform Source Specifications

- Imaging v. Sensor Applications
- Size requirements
- Uniformity
- Output levels
  - Adjustability
  - Min/Max
- Spectral requirements
  - In-band
  - Spectral shape
  - Color temperature
- Stability
- Accuracy/Uncertainty

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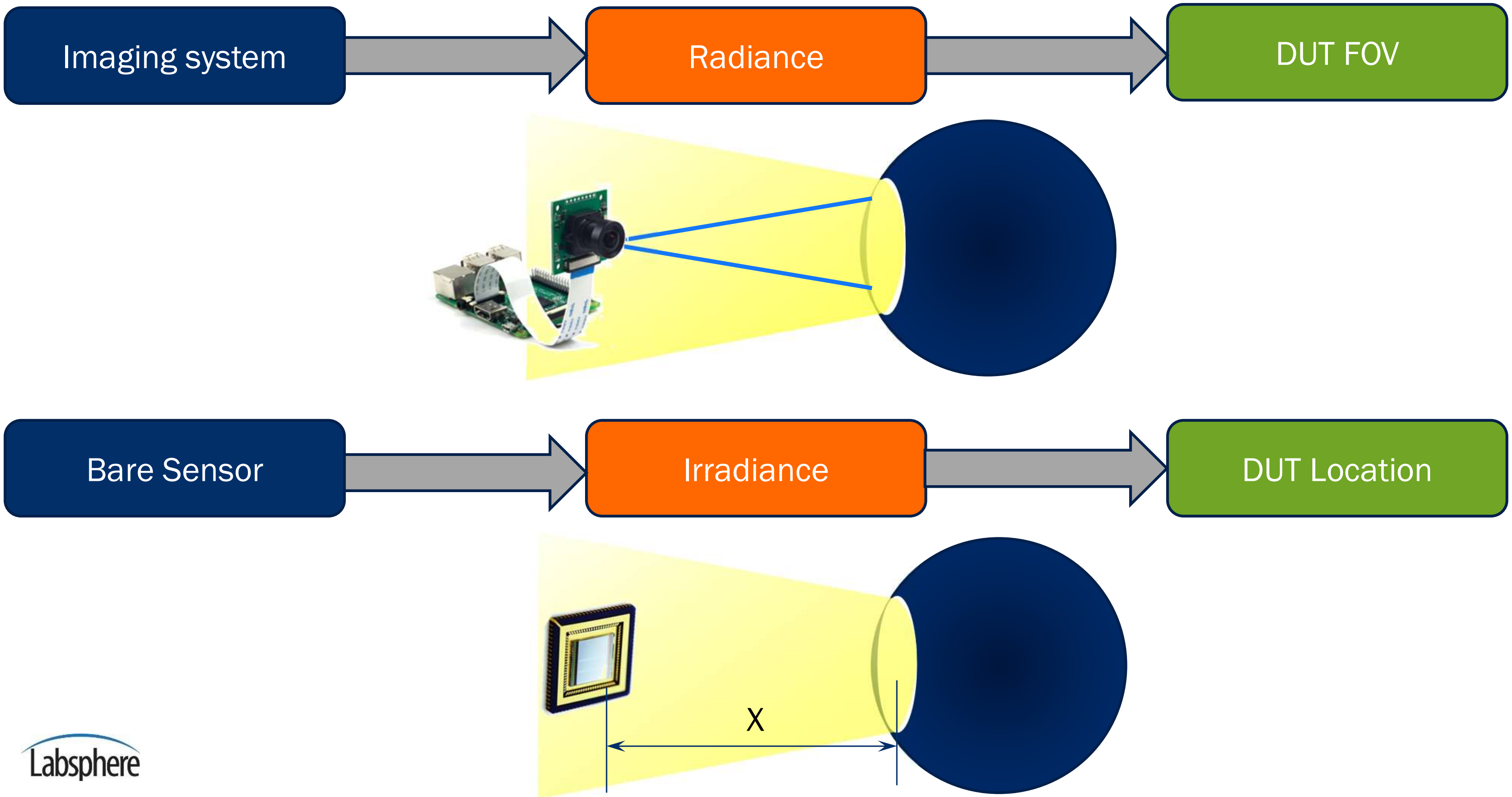
# DUT: Imaging Device or Bare Sensor?

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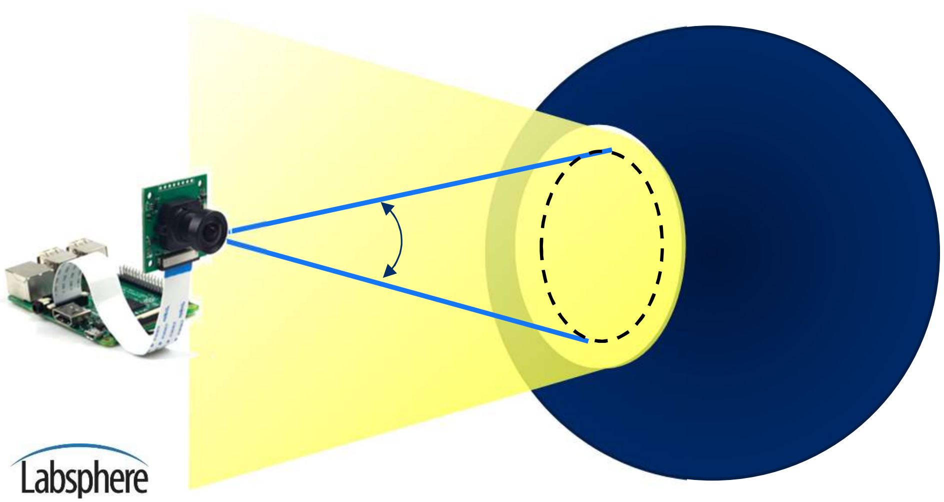
# Sphere Design for Imaging Device

- Port dia. Is based on FOV
  - Determine DUT location
  - Calculate dia at sphere location
  - FOV set to < 90% of port Dia.
- Use Radiance Requirement to determine Flux




## Design Steps

Define FOV

Calculate Exit Port Dia.

Define Sphere Dia with $f < 5\%$

Calculate Required Flux, $\phi_i$

$$L = \frac{\phi_i}{\pi A_s} \frac{\rho_0}{1 - \rho_0(1 - f)}$$

# Sphere Design for Bare Sensor

- Define Irradiance at DUT Location
  - Iterate on $D_{sphere}$, $D_{port}$
  - Constraints:
    - $f < 5\%$
    - Uniformity at sensor
- Calculate Required Flux

Irradiance Uniformity (Ee/Eo)

| Object Diameter d/D | Distance from Source (x/D) 0.00 | 0.10 | 0.20 | 0.25 | 0.50 | 0.75 | 1.00 | 1.50 | 2.00 | 2.50 | 3.00 | 5.00 | 10.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.2 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 0.3 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.96 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 |
| 0.4 | 1.00 | 0.99 | 0.96 | 0.94 | 0.92 | 0.93 | 0.95 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 |
| 0.5 | 1.00 | 0.97 | 0.92 | 0.90 | 0.88 | 0.90 | 0.92 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 1.00 |
| 0.6 | 1.00 | 0.95 | 0.88 | 0.85 | 0.82 | 0.86 | 0.89 | 0.94 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 |
| 0.7 | 1.00 | 0.92 | 0.81 | 0.78 | 0.76 | 0.81 | 0.86 | 0.92 | 0.95 | 0.96 | 0.97 | 0.99 | 1.00 |
| 0.8 | 1.00 | 0.84 | 0.72 | 0.69 | 0.70 | 0.76 | 0.82 | 0.89 | 0.93 | 0.95 | 0.97 | 0.99 | 1.00 |
| 0.9 | 1.00 | 0.70 | 0.60 | 0.59 | 0.62 | 0.71 | 0.78 | 0.87 | 0.92 | 0.94 | 0.96 | 0.98 | 1.00 |
| $\sin^2\theta$ | 1.000 | 0.962 | 0.862 | 0.800 | 0.500 | 0.308 | 0.200 | 0.100 | 0.059 | 0.038 | 0.027 | 0.010 | 0.002 |
| $\pi\sin^2\theta$ | 3.142 | 3.021 | 3.708 | 2.513 | 1.571 | 0.967 | 0.628 | 0.314 | 0.185 | 0.121 | 0.085 | 0.031 | 0.008 |

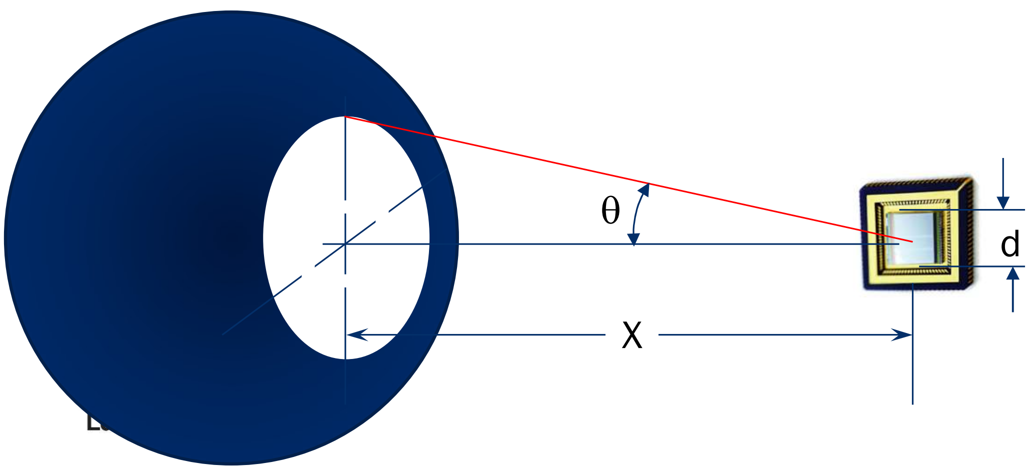
## Design Steps

Define Irradiance at DUT

Iterate to calculate port Dia., Sphere Dia

Sphere Dia with f<5%

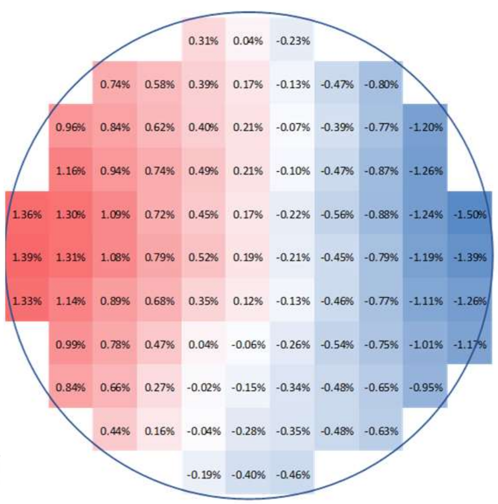
Calculate Required Flux

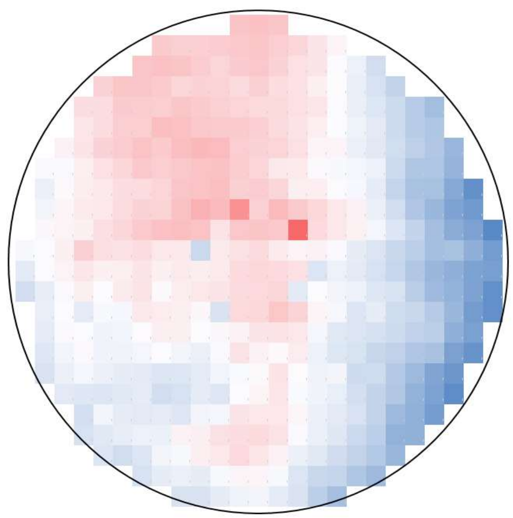


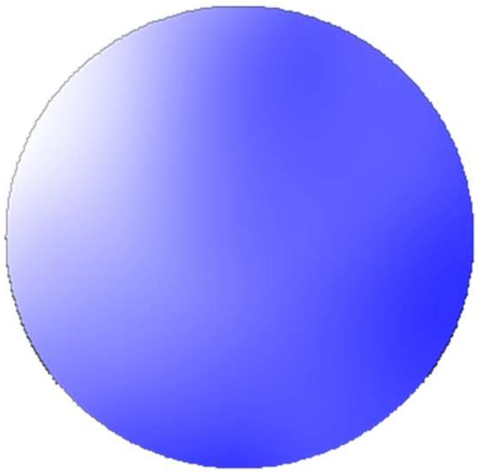

$$E = \frac{\phi_i}{A_s}\frac{\rho_0}{1-\rho_0(1-f)}\sin^2\theta$$

# Uniformity Requirements

- Define the uniformity calculation
- Will the uniformity map data be used for correction?
- Define the required uniformity map resolution
- Quantify the required uniformity
- Uniformity for each operating condition?





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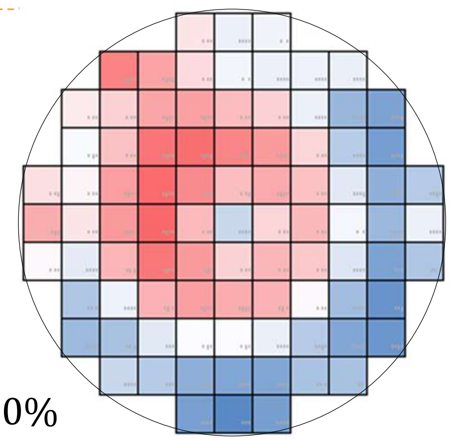
# Quantifying Uniformity

- Divide source area into sub-elements

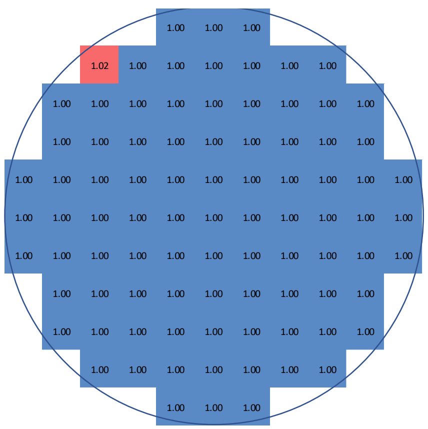


1. Max Deviation Method $$U_{Max\ Deviation} = \frac{Min}{Max} \times 100\%$$
2. Mean Deviation Method $$U_{Mean\ Deviation} = 1 - \frac{\left(\frac{Max - Min}{2}\right)}{Mean} \times 100\%$$
3. Deviation Method $$U_{Deviation} = 1 - \frac{(Max - Min)}{Mean} \times 100\%$$
4. CoV Method $$U_{COV} = \left(1 - \frac{\sigma_L}{\bar{L}}\right) \times 100\%$$

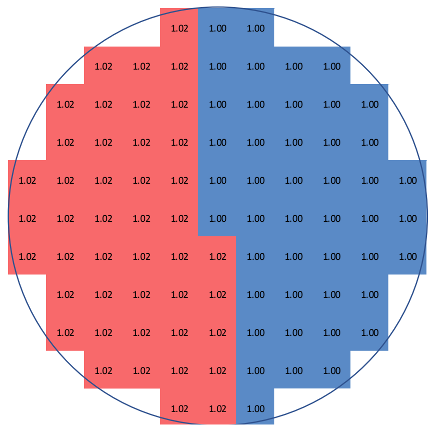
Labsphere

# Uniformity Examples

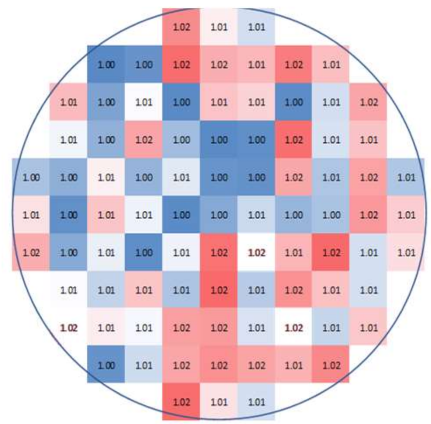
2% Spike



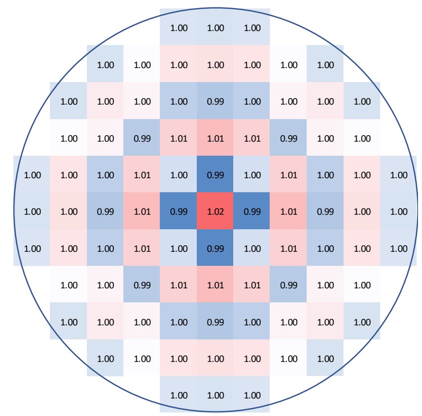
2% Split



2% Random

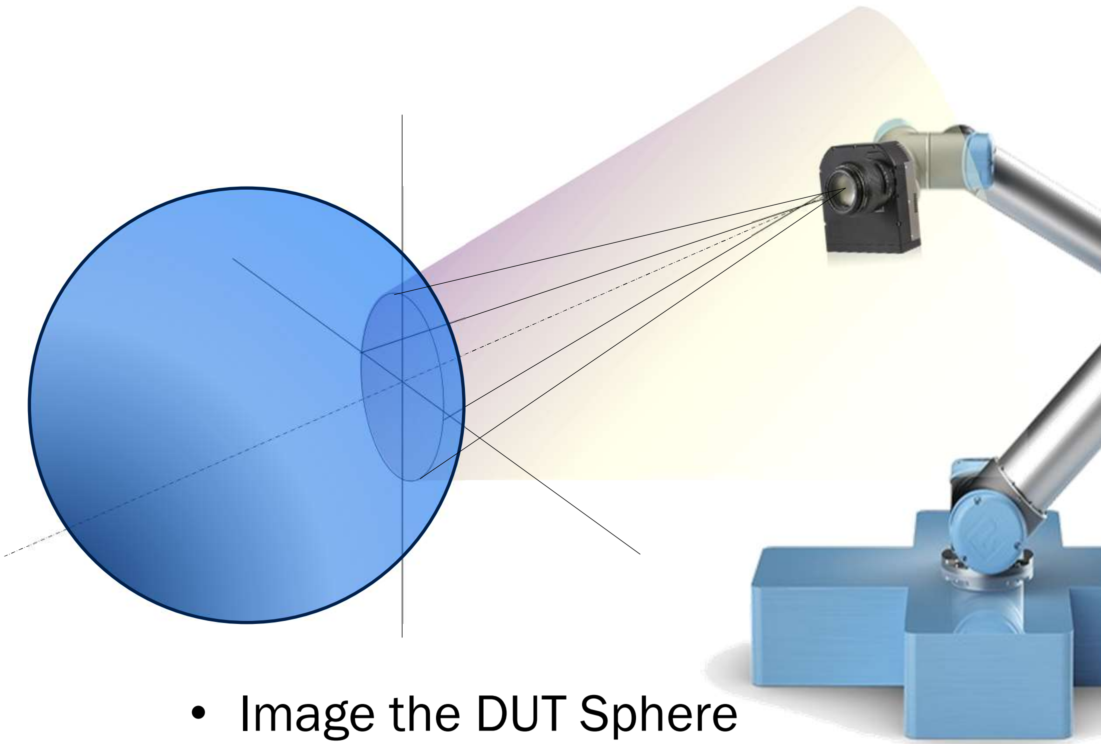


2% Damped

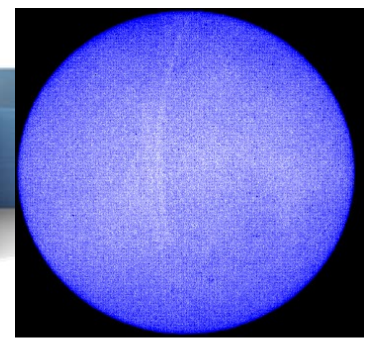


| | 2% Spike | 2% Split | 2% Random | 2% Damped | |
|---|---|---|---|---|---|
| Max Deviation | 98.0% | 98.0% | 98.1% | 96.7% | $\frac{L_{min}}{L_{max}}$ |
| Deviation Method | 98.0% | 98.0% | 98.0% | 96.7% | $1 - \frac{L_{max} - L_{min}}{L_{mean}}$ |
| Mean Deviation | 99.0% | 99.0% | 99.0% | 98.3% | $1 - \frac{(L_{max} - L_{min})/2}{L_{mean}}$ |
| (CoV) | 99.8% | 99.0% | 99.4% | 99.5% | $1 - \frac{s_L}{L_{mean}}$ |

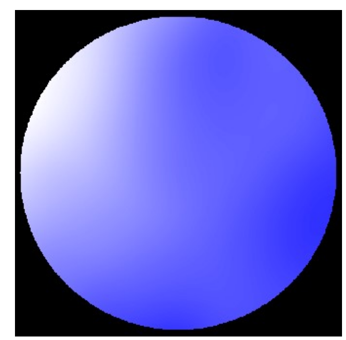
# Measuring Radiance/Luminance Uniformity



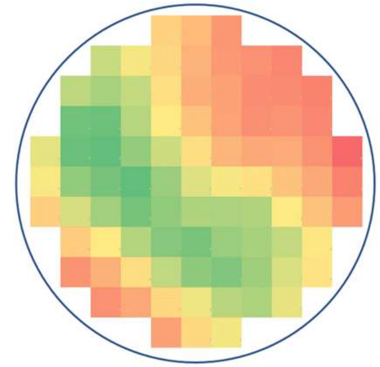
- Image the DUT Sphere
- Apply Flat Field Correction
- Discretize to sub grid



Raw Camera Image



Corrected Image



Discretized Image

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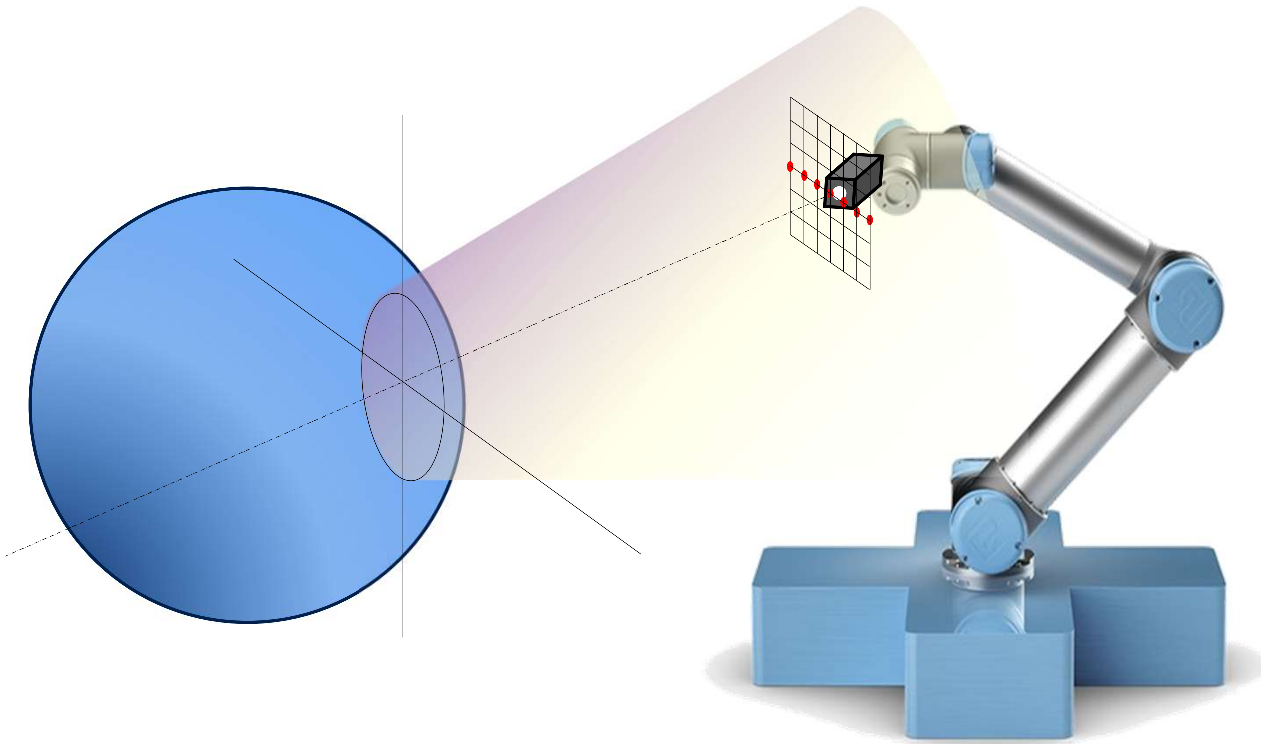
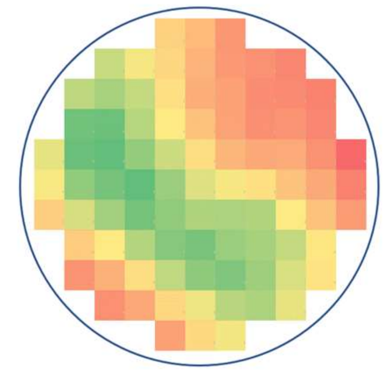
# Measuring Irradiance Uniformity





Discretized Image

- Define Sensor distance
- Define spacing at sensor location
- Traverse sensor in xy-plane

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# Defining Sphere Output Requirements

- Spectral or In-Band?
- Units
- Min/Max Levels
- Dynamic Range
- Spectral Shape
  - Blackbody
  - Smoothness – Peak-peak variation, RMS,
- Wavelength Range

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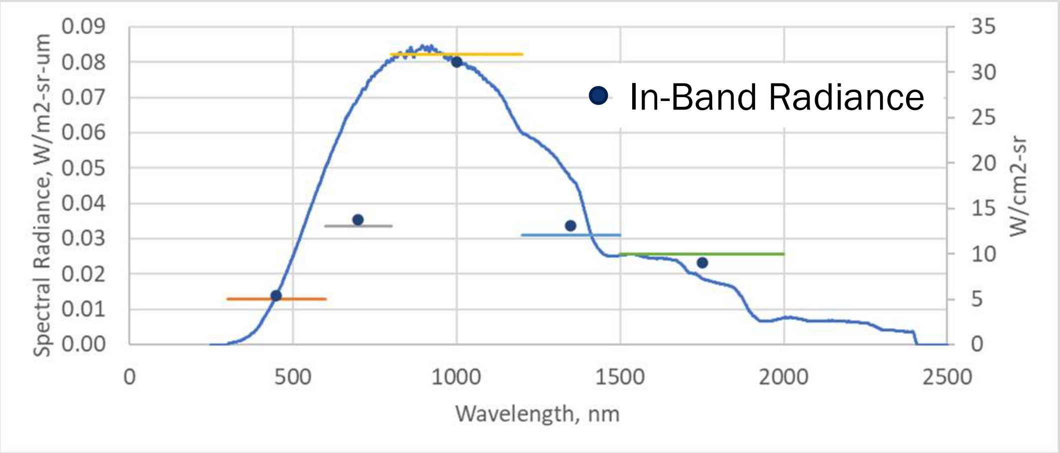
# Defining Sphere Output: In-Band integrated values

- Define the bands
- Define the units
  - Radiance: [W/m$^2$-sr], [photons/s-m$^2$-sr]
  - Irradiance [W/m$^2$]
- Define the requirements
  - All in-band requirements to be met simultaneously?
  - In-band requirements to be met individually?
  - Integrated value in band must exceed minimum
  - Integrated value in band must fall between min and max




| Band, nm | Min Radiance, W/cm2-sr |
|---|---|
| 300 - 600 | 5 |
| 600 - 800 | 13 |
| 800 - 1200 | 32 |
| 1200 - 1500 | 12 |
| 1500 - 2000 | 10 |

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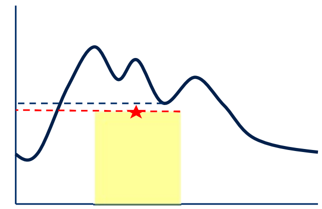
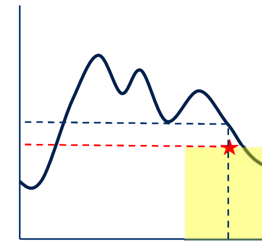
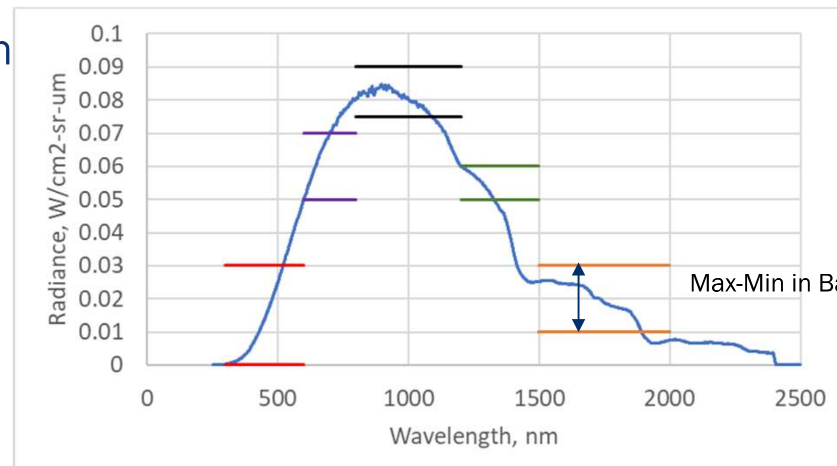
# Defining Sphere Output: Spectral Levels

- Define the Units
  - Radiance: [W/m²-sr-μm], [photons/s-m²-sr-μm]
  - Irradiance [W/m²-μm]
- Within the Band of interest:
  - All spectral values to exceed the minimum within band
  - The level at the center wavelength should exceed the value prescribed for the band
  - All spectral values to fall between min and max within range
  - All in-band requirements to be met simultaneously
  - In-band requirements to be met individually
  - Value must exceed min at center wavelength in band
- Can the sphere output filtered?





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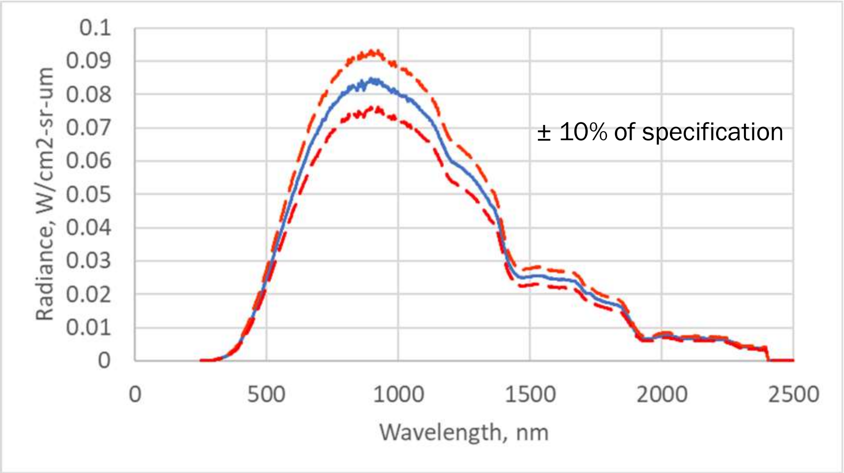
# Defining Output Levels: Spectral Shapes

- Provide a tolerance across the band:
  - All values to be within ± 10% of nominal value within the band.
- Provide an RMSE value:
  - The RMSE between the measured and prescribed spectrum shall be < 5%
- Blackbody curve
  - Provide CCT
  - Provide allowable deviation as defined above

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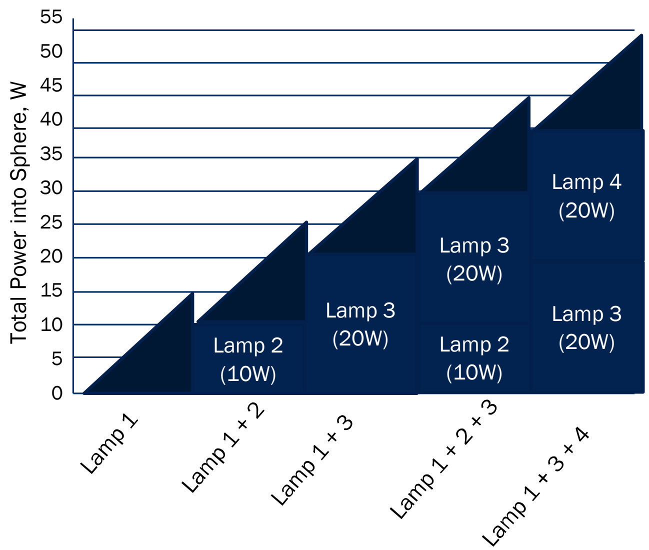
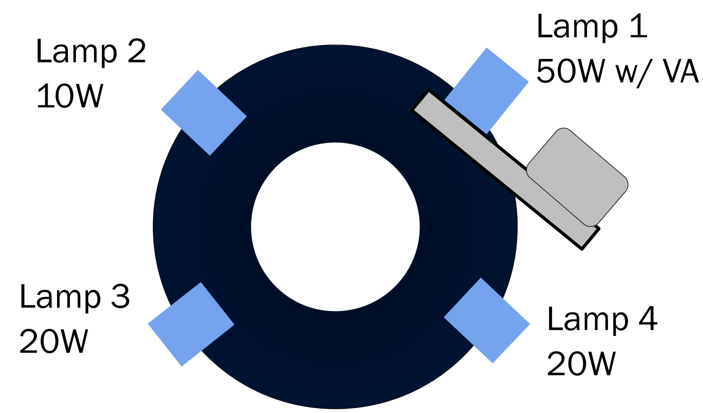
# Defining Output Levels: Adjustability

- What is dynamic range of system?
  - Define the min and max levels
- Is continuous adjustability required?



# Sphere Output: Defining Required Stability

- Define the use case:
  - Will it run for hours at one condition?
  - Sweep through dynamic range?
  - Is time required to capture output on the order of minutes, hours, days?
- What is the effect of stability on the DUT measurement?
- Define the stability requirement
  - Max allowable peak-peak variation
  - %RMS over time period (CoV)
- Short-Term or Long-Term requirements?
- CCT Stability?
- Define sampling frequency for system validation testing

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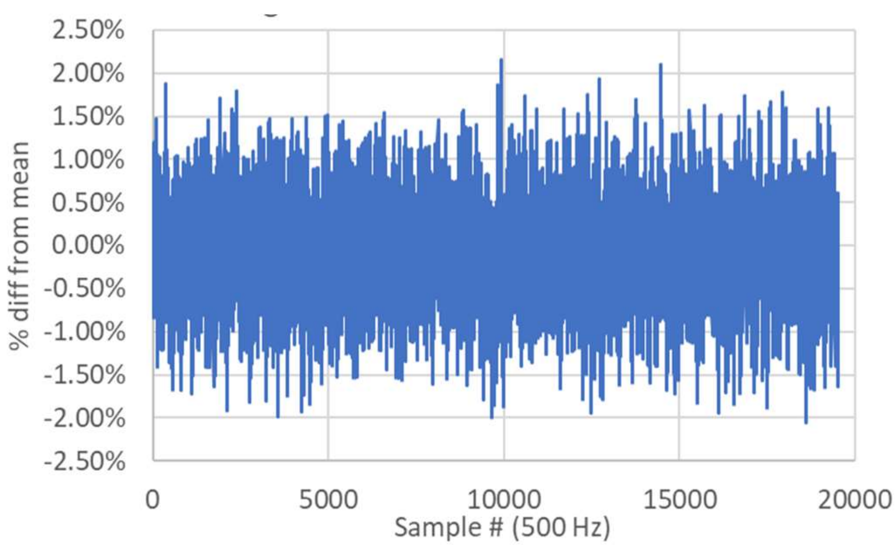
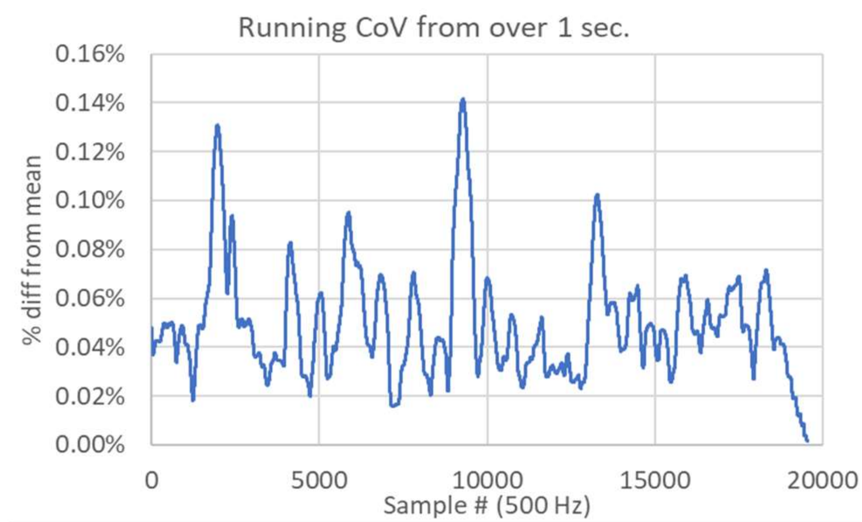
# Sphere Output: Xe Lamp Stability Example

Peak-Peak ~ ±2%




CoV < 0.15%

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# Sphere Output: Accuracy and Uncertainty

- Accuracy – Closeness of a measured value to the true value
- Uncertainty – parameter, associated with the result of a measurement, that characterizes the dispersion of values that could reasonably be attributed to the thing being measured*.
  - Refers to the measurement at a given instance in time, NOT the instrument.
- Uncertainty values are provided with the calibration of the system.
  - Measured spectral radiance
  - Detector response
  - Uniformity

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* NPL, https://www.npl.co.uk/resources/q-a/difference-accuracy-uncertainty

# Commercial Considerations for Uniform Source Specifications

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- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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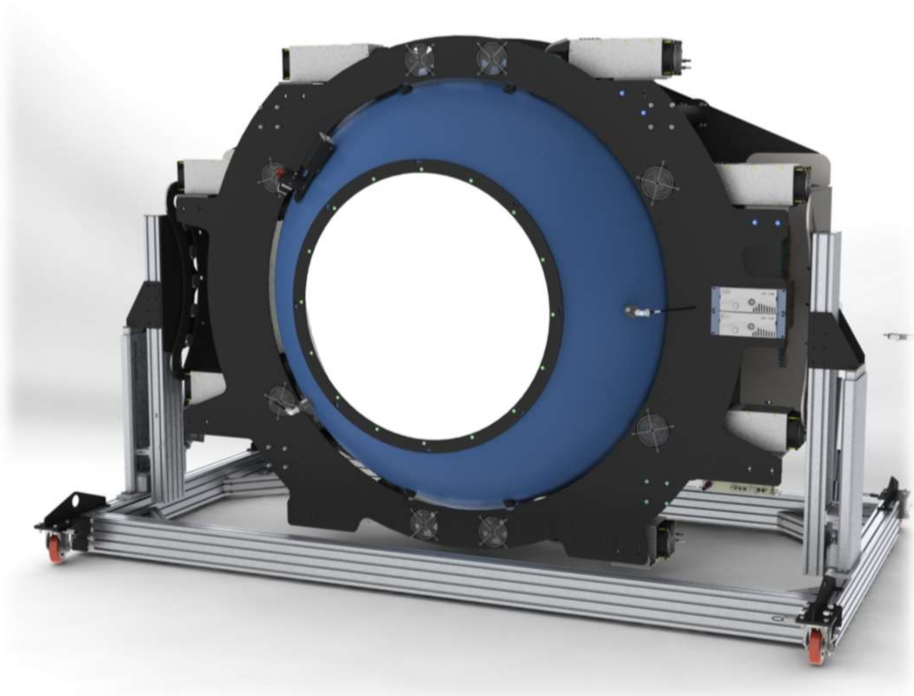
# Commercial Considerations

- Sphere Material
- Sphere Size
- Spectral Requirements
- Source Types
  - Plasma, Xe, LED, Lasers, QTH, UV/IR
- Spectral Range
- Dynamic Range
- Lead Time
- Uncertainty
- Mechanical features
- Stability and Control
- Software Modifications
- Theory v. Practice
- Thermal Control
- Environmental



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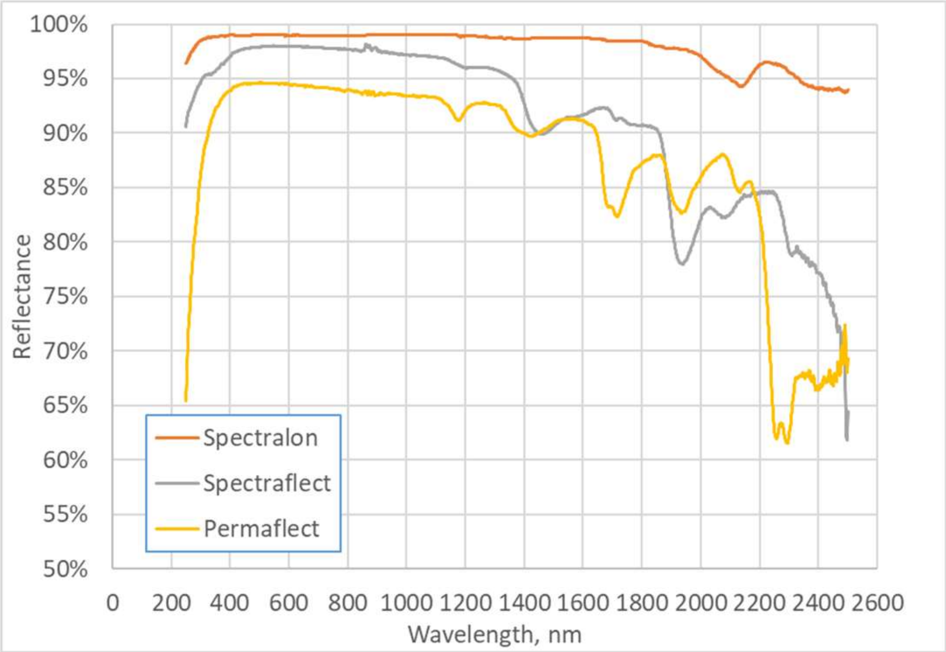
# Cost Drivers – Materials

- Spectralon (machined PTFE)
  - Needed for UV, and high reflectance in blue
  - Space applications – vacuum baked
- Spectraflect (spray coating)
  - General purpose
  - Wide spectral range
- Permaflect
  - Cleanable
  - Harsh environments
- Gold
  - IR applicaitons

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# Cost Drivers: Spectral Requirements

- Spectral Matching
  - Requires multiple lamp types
  - Tight specifications may require filters on sources
- High Blue Content
  - Multiple plasma
  - LEDs
- High NIR ( >1200nm)
- Simultaneously meeting levels in multiple bands

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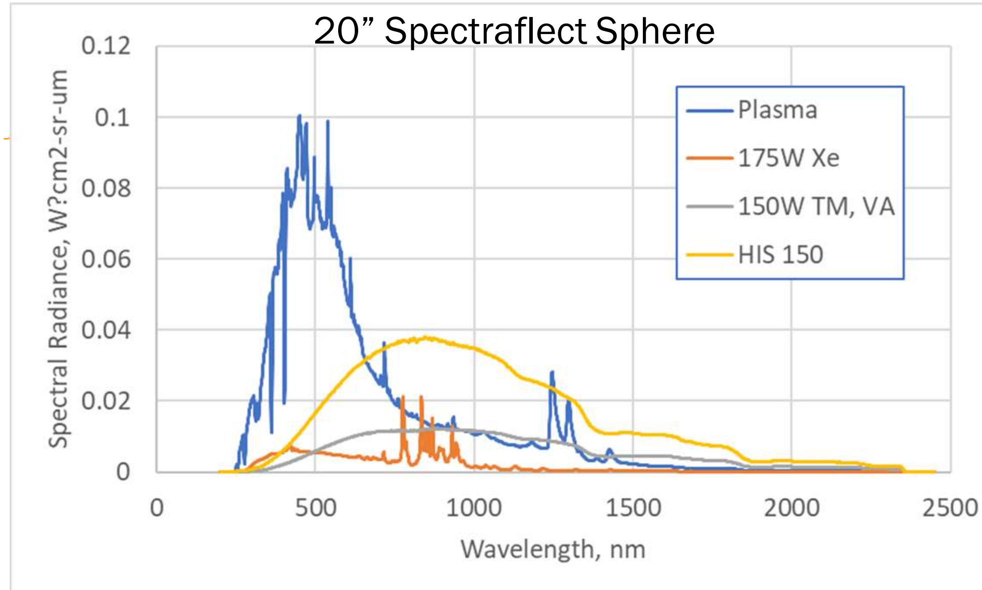
# Cost Drivers: Lamp Types

Increasing $

- Xenon $$$$
- Plasma $$$
- Lasers $$ - $$$
  - May require de-speckler
- LED $$$
- External QTH $$
- Internal QTH $




## Cost Considerations

- Each lamp typically requires a dedicated power supply
- High # of lamps:
  - increases electronics rack complexity
  - increases power consumption and complexity
  - May introduce thermal issues and control
- Continuous Adjustability requires multiple lamps

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# Cost Drivers: Spectral Range

- Wide ranges may span multiple detector ranges:
  - Si 320nm – 1100nm
  - InGaAs 900 – 1700nm, or 700 – 2600nm
- Filters on detectors for specific bands
  - Rolloff
  - Cutoff
  - Leakage
- Wide spectral range may require multiple lamp types



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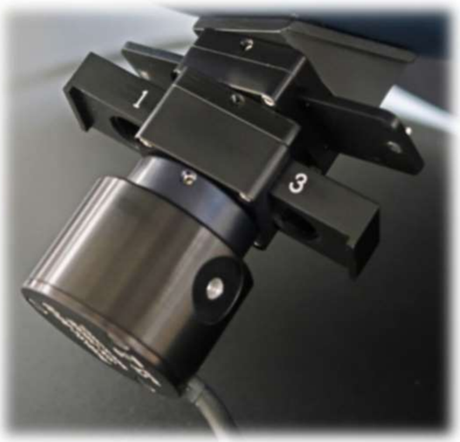
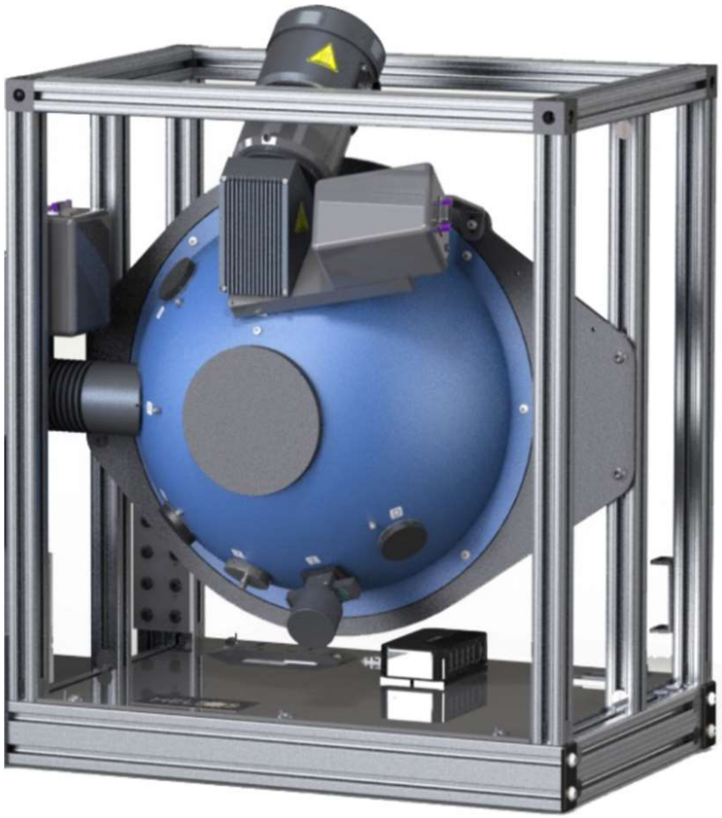
# Cost Drivers: Dynamic Range

- Requires multiple lamps
- Continuous adjustability
  - Variable Attenuator (VA) required
- May require apertures on detectors
  - May require additional calibrations for each configuration



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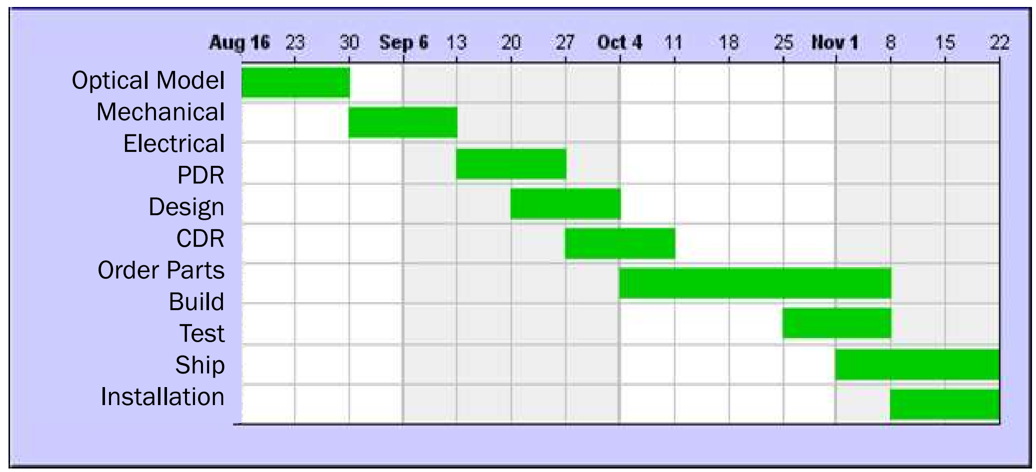
# Cost Drivers: Schedule and Lead Time

- Standard systems – quickest delivery
- Custom
  - add time for NRE and custom parts
- Advanced Custom
  - NRE, Custom parts, Design Reviews
- Special components
  - Gold coating
- Special calibrations
- 3rd party components
- 3rd party calibration
- Special Filter Orders
- Shipment: Air/Land
- Installation and Training
- Readiness of installation site

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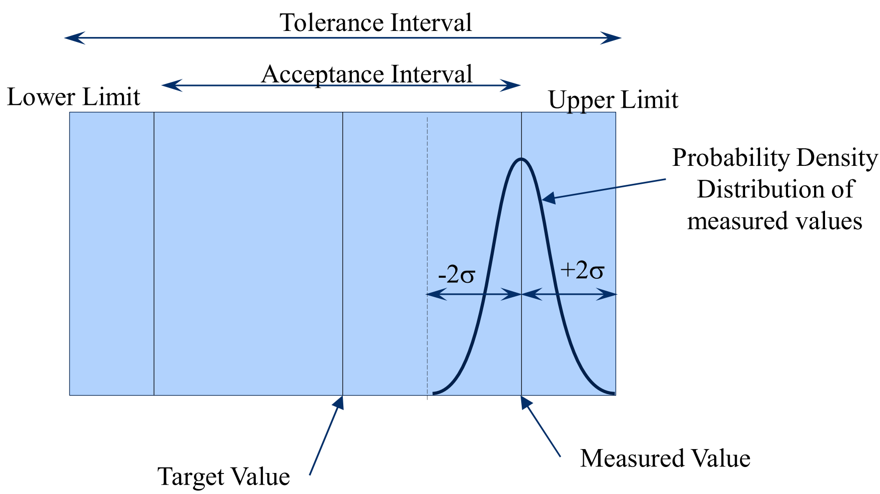
# Commercial Considerations: Uncertainty

- Uncertainty is on the measurement at the time of the measurement
- Standard Calibrations include uncertainty estimates
- Custom Calibrations/Measurements
  - Add ~ 1-2 weeks of NRE for uncertainty
- New systems and components that require uncertainty
  - Add ~ 1-4 weeks of NRE for uncertainty
  - May require additional measurements and characterization of new components

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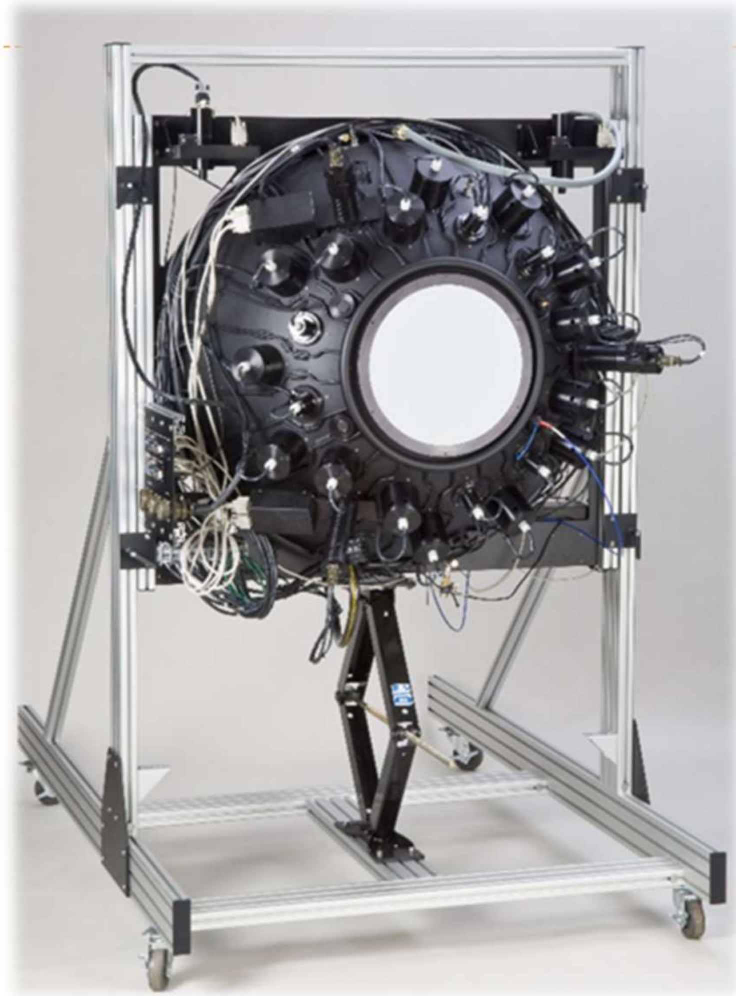
# Mechanical Features that Add Cost

- Height Adjustment
- Additional Port reducers
- Rotation
- Alignment features
- Shutters
- Clean Room Requirements
- Cable Lengths
- Thermal management
  - Fans
  - Insulation
- Weight Limitations
- Space Constraints



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# Commercial Considerations: Stability and Control

- Stability needs to be defined over a time period

- QTH lamps are very stable (~ 0.04% P-P)
- Plasma Stability
  - Short term (<1 min) ±0.4% P-P, 0.3% CoV
  - Long Term (> 1min) ±0.4% P-P, 0.2% CoV
  - Long Term ~ 30 min w/ 15 plasma lamps: < ±0.7% P-P, 0.2% CoV
  - Improved stability with multiple lamps
- Improved stability over baseline requires additional control

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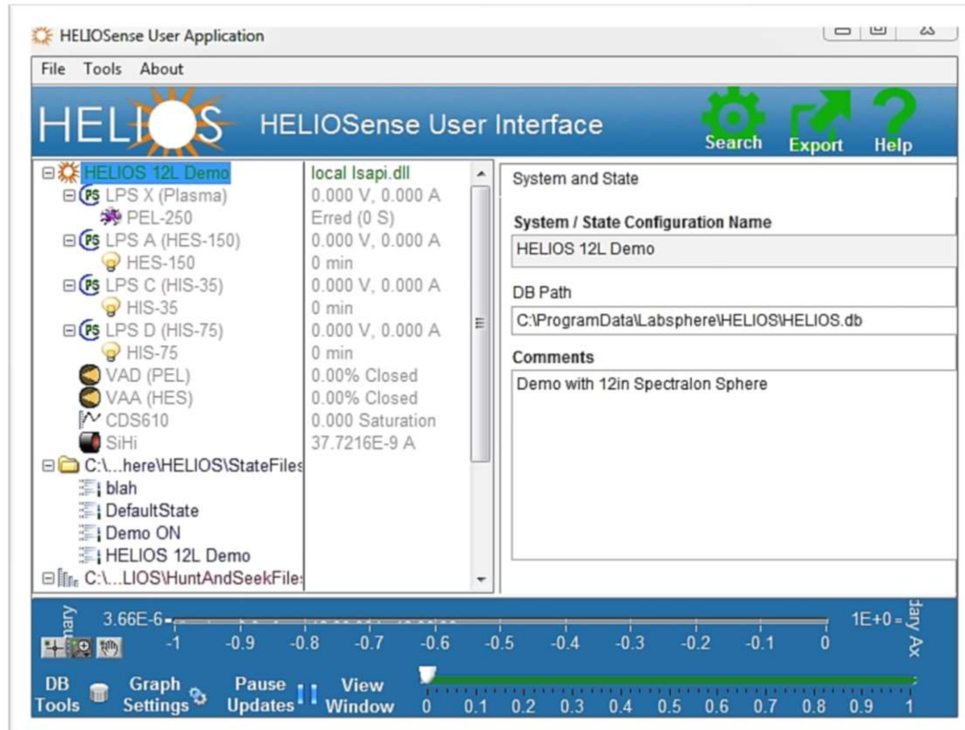
# Commercial Considerations: Software

- SDK available
- NRE required for:
  - Addition of new features
  - Addition of new hardware controls
  - SDK development assistance
  - Integration to automated system

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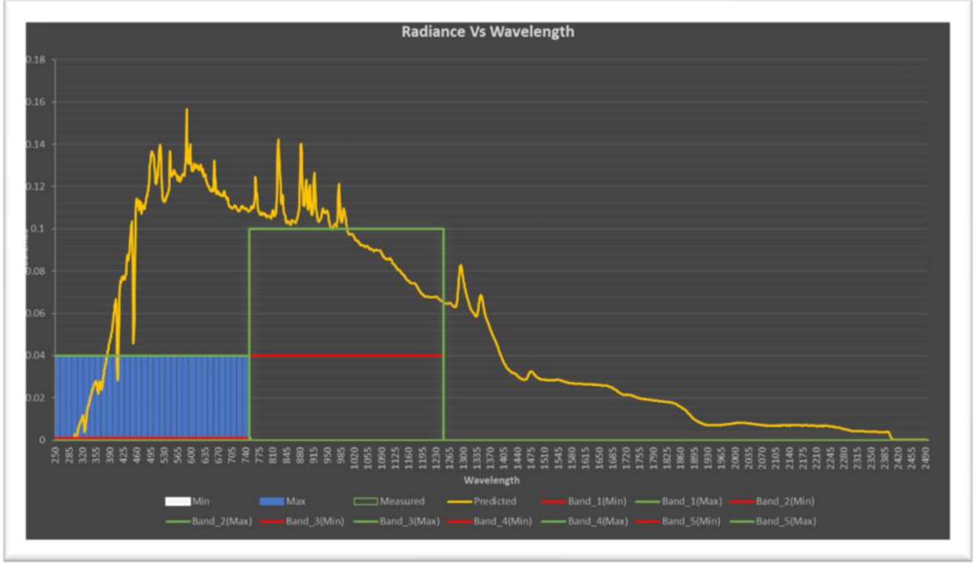
# Commercial Considerations: Theory v. Practice

- QTH Lamp supply is constantly changing
- LED Specifications and Binning
- Material variations
- Machine Tolerances
- Always deal with design tradeoffs
  - Prioritize the Requirements

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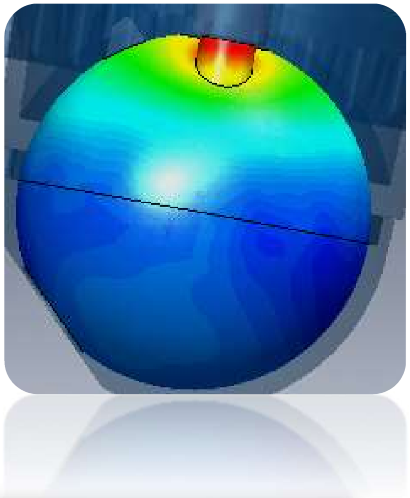
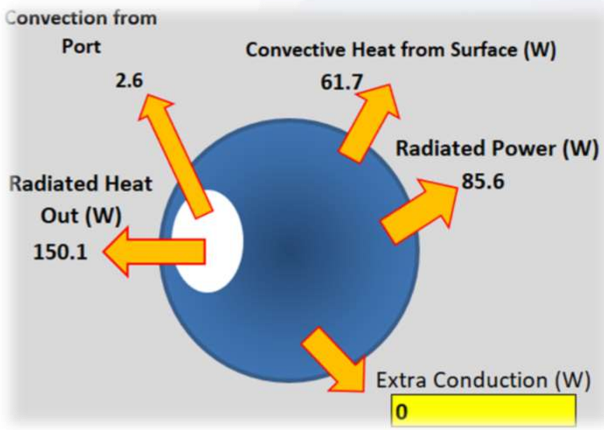
# Commercial Considerations: Thermal Control

- Many lamps turns sphere into an oven
- Thermal limits on coating:
  - Spectraflect ~ 100C
  - Spectralon ~ 400C
- Labsphere models for bulk temperature of sphere
- Detailed analysis using CFD
- Cooling methods
  - External fans
  - Directed fans/blowers
  - Cooled filters
  - Liquid cooling



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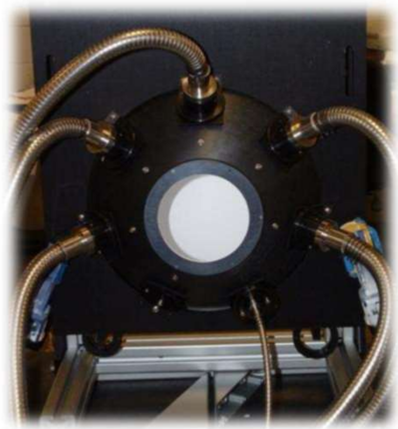
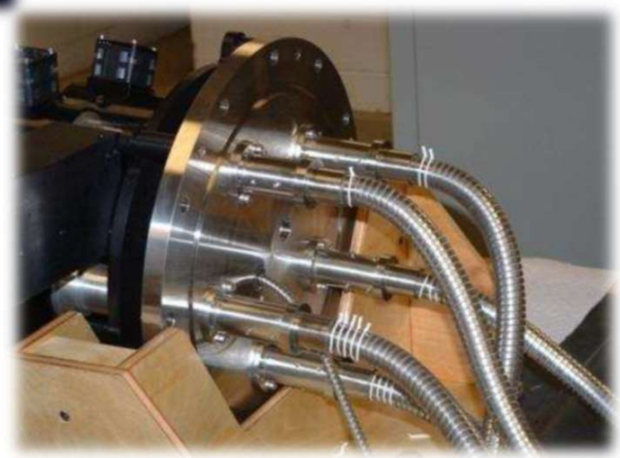
# Commercial Considerations: Environmental

- Harsh Environments
  - Tarmac
  - Flight Lines
  - Desert
  - On-board
- Clean Rooms
  - Material constraints
  - ISO Class
- Vacuum
  - Material limitations (outgassing)
  - Instrument and lamp changes
  - Fiber feeds
  - Optical Fibers
  - Bulkhead design





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# Commercial Considerations: Summary

- Cost Adders
  - Custom
  - High output
  - Large spheres
  - UV
  - Thermal management
  - Spectral Monitoring
  - Vacuum or environmental
- Complexity
  - Spectral matching
  - Matching multiple spectral ranges
  - Tight specifications
  - Extended range
- Cost controls
  - Prioritize the requirements
  - Identify areas for flexibility
  - Use standard product when possible
  - Quantify specs and define calculations prior to design
  - Understand use case

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# Workshop Agenda (All times in MDT)

- 0730-0840 Sphere Theory and Applications (Durell)
- 0840-0910 Uniform Source Tutorial (Durell)
- 0910-0920 Sphere Calibrations (Durell)
- 0920-0930 (Virtual) Coffee Break
- 0930-1010 Considerations for Uniform Source Specifications (Scharpf)
- 1010-1020 Commercial considerations (Scharpf)
- 1020-1040 NASA GLAMR Case Study (Brendan McAndrew, NASA GSFC)
- 1040-1050 If time permits: Uniform Source Case Studies (Durell)

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