UNEP-*lites.asia* Laboratory Training Workshop

Beijing, China

22-25 April 2015

Measurement of Directional Lamps in an Integrating Sphere

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Introduction & Basic Theory

- Integrating sphere used to measure total luminous flux of light sources
- Measured by comparison with a luminous flux standard lamp (substitution method)

Basic principle:

- The illuminance of the internal surface will be spatially uniform and temporally constant when illuminated by an omni-directional light source
- The luminous flux is related to the indirect illuminance on the internal surface of the integrating sphere (ie no light is directly incident on the detector)

Formula

$$\Phi = E_{ind} \times \frac{1-\rho}{\rho} \times A$$

Where

- E_{ind} is the indirect illuminance on the internal surface of the sphere
- ρ is the luminous reflectance of the internal surface
- A is the internal surface area

$$f_s = \frac{1-\rho}{\rho} \times A$$

- f_s is known as the sphere responsivity factor

Note: these functions work on the basis of uniform reflectivity, omni-directional light source and no obstructions

The Real World of integrating spheres

- Non uniform reflectivity
  - the coating may not be applied uniformly to all parts of the sphere
  - The door seams create light captures (lower reflectivity)
  - Internal structures (eg supports, baffles) may have different reflectances
  - Dust gravitates to the lower surfaces within the sphere altitudinally lowering the reflectance of this region
- Internal obstructions
  - Internal structures (eg supports, baffles) cause shadowing

Sphere responsivity factor

- Because of real world effects on the sphere, the sphere responsivity factor, f_s, cannot be calculated according to theory.
- But it can be determined using a reference light source

$$f_s = \frac{\Phi_{Ref}}{E_{ind,Ref}}$$

Where

- Φ_{Ref} is the luminous flux of the standard reference lamp
- $E_{ind,Ref}$ is the indirect illuminance (on the detector) due to the luminous flux Φ_{Ref}

Measuring total luminous flux

$$\Phi_{test} = f_s \times E_{ind,\,test}$$

- Where f_s has been determined from the standard reference lamp

BUT

- The standard reference lamp MUST have the same relative intensity distribution as the test lamp.

- This is because the light directly incident on each part of the internal surface will undertake a different series of reflections (to different parts of the internal surface with varying reflectance and obstructions) before reaching the detector.

Measuring partial sphere response

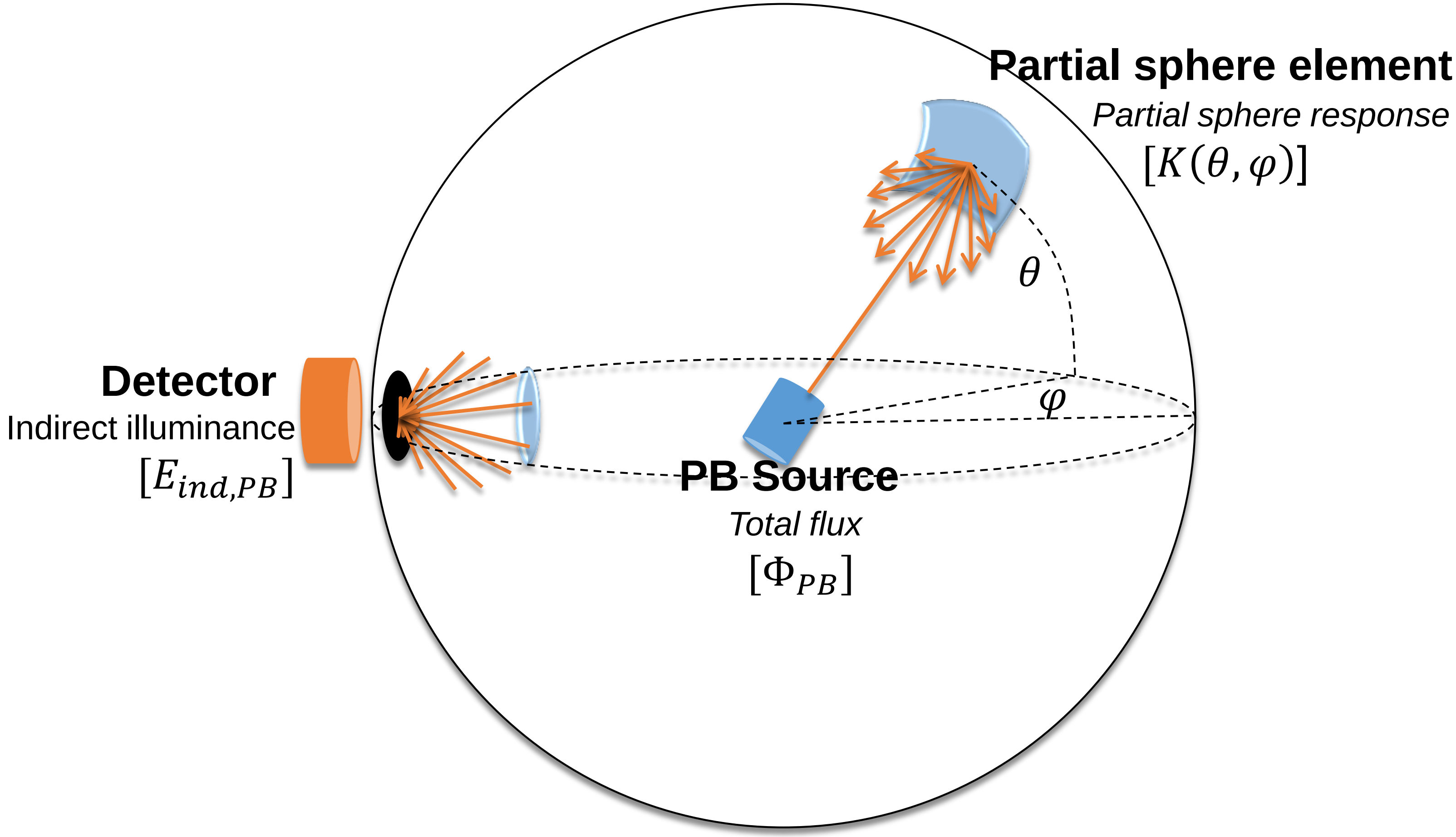
$$\Phi_{test} = f_s \times E_{ind,\,test}$$

So

- Let's consider the "partial sphere response" to a small parallel beam (PB) of light incident in one direction (orientation (θ, φ)) on every part of the sphere internal surface.

$$f_{s,PB(\theta,\varphi)} = \frac{\Phi_{PB}}{E_{ind,PB}}$$

Measuring partial sphere response



Spatial Response Distribution Function

- In order to ascertain the spatial response within the entire sphere the beam is rotated (scanned) to every orientation inside the sphere.
- This is effectively producing an isotropic light source (equal intensity in all directions) of intensity, I_{PB}, with a total flux of $4\pi\ I_{PB}$
- This collective result is the Spatial Response Distribution Function (SRDF) or $K(\theta, \varphi)$ to a theoretical isotropic source of $4\pi\ I_{PB}$ lumens.
- In order to compare different sphere arrangements this function needs be a normalised Spatial Response Distribution Function (creates a function independent of light source intensity)

Normalised Spatial Response Distribution Function

- The normalised SRDF, $K^*(\theta,\varphi)$ is achieved by determining the $K(\theta,\varphi)$ at each orientation relative to the average $K_{ave}(\theta,\varphi)$

$$K^*(\theta,\varphi) = \frac{K(\theta,\varphi)}{K_{ave}(\theta,\varphi)}$$

where

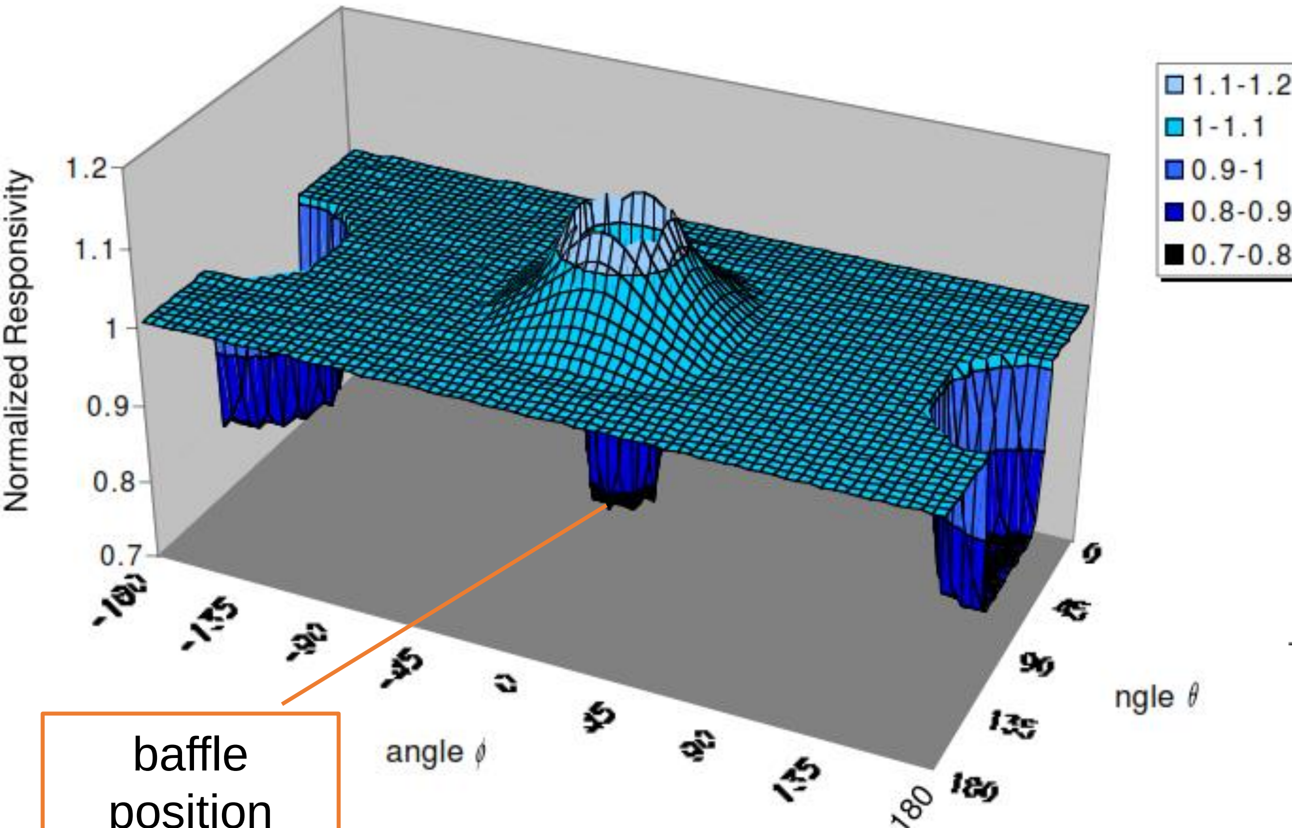
$$K_{ave}(\theta,\varphi) = \frac{\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} K(\theta,\varphi)\, sin\theta\, d\theta\, d\varphi}{4\pi}$$

Therefore

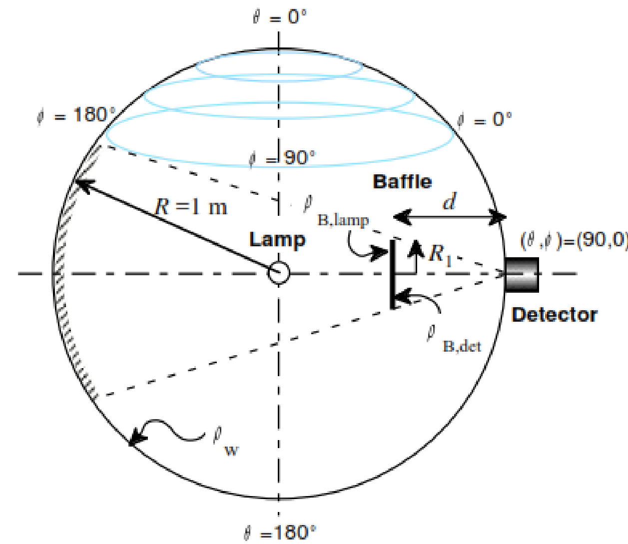
$$K^*(\theta,\varphi) = \frac{4\pi\, K(\theta,\varphi)}{\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} K(\theta,\varphi)\, sin\theta\, d\theta\, d\varphi}$$

Example of a 3 dimensional SRDF

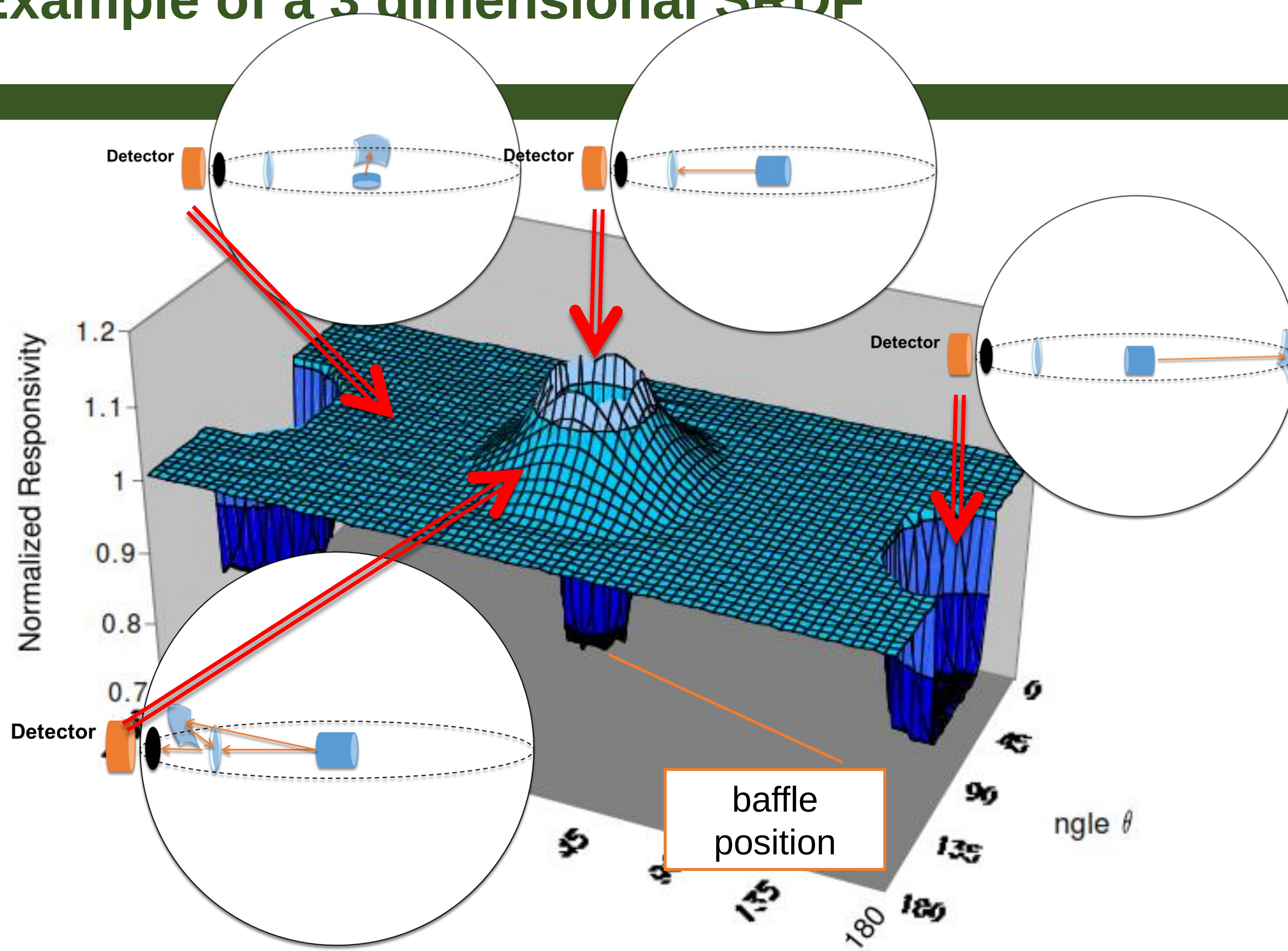
- $\rho = 0.80$



baffle position

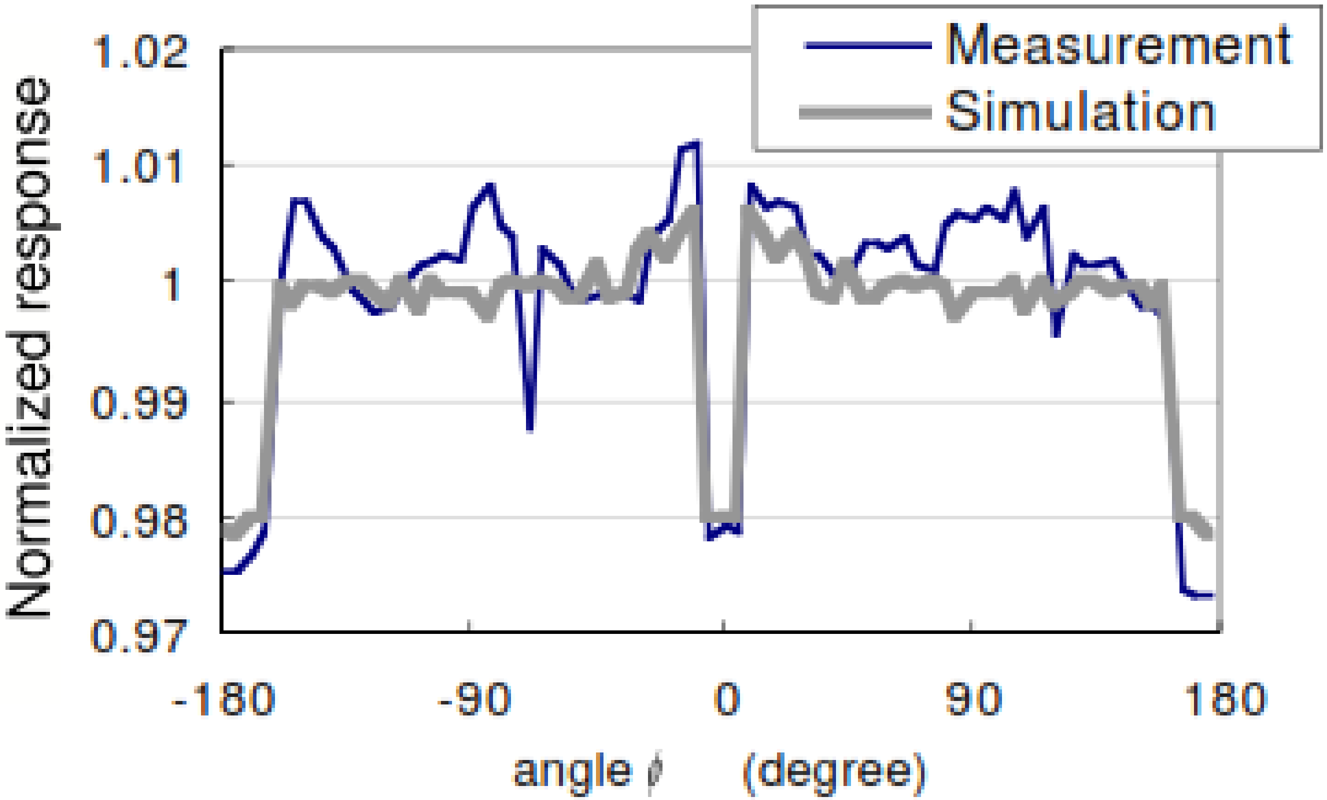


Example of a 3 dimensional SRDF



Example of SRDF – in horizontal plane

- Simulation vs actual measurement
- $\rho = 0.98$



Calculating the sphere response factor

- The sphere response to a light source is the summing of the product of the relative intensity of a light source in each direction $I_{rel}(\theta,\varphi)$ and the relative (partial) spatial response of sphere in that direction $K^*(\theta,\varphi)$, as a proportion of the total flux of the lamp.
- The sphere response factor (ie normalised response) is then:

$$f_s = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) K^*(\theta,\varphi) sin\theta \; d\theta \; d\varphi}{\Phi_{Rel}}$$

$$f_s = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) K^*(\theta,\varphi) sin\theta \; d\theta \; d\varphi}{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) \; sin\theta \; d\theta \; d\varphi}$$

The sphere response factor

If the sphere was a perfect sphere with the same response at the detector regardless of the orientation (θ, φ) of the light,

then the partial sphere response for all orientations is

$$K(\theta, \varphi) = K_{ave}(\theta, \varphi)$$

making the normalised partial sphere response

$$K^*(\theta, \varphi) = \frac{K(\theta, \varphi)}{K_{ave}(\theta, \varphi)} = 1$$

for all orientations (θ, φ).

The sphere response factor

Thus

$$f_s = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi)\cancel{K^*(\theta,\varphi)} sin\theta \, d\theta \, d\varphi}{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) \, sin\theta \, d\theta \, d\varphi}$$

becomes

$$f_s = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) sin\theta \, d\theta \, d\varphi}{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) \, sin\theta \, d\theta \, d\varphi}$$

$f_s = 1$ (for a perfect sphere)

BUT no sphere is optically perfect!

Practical situation: Sphere response factor

- If we normalise the sphere response factor, $f_s = 1$, for a particular sphere when calibrated with an isotropic light source
- The measurement error for each test lamp is then given by:

$$f_s - 1$$

- The errors associated with various light intensity distributions, $I_{rel}(\theta, \varphi)$, can be evaluated by the sphere response factor.

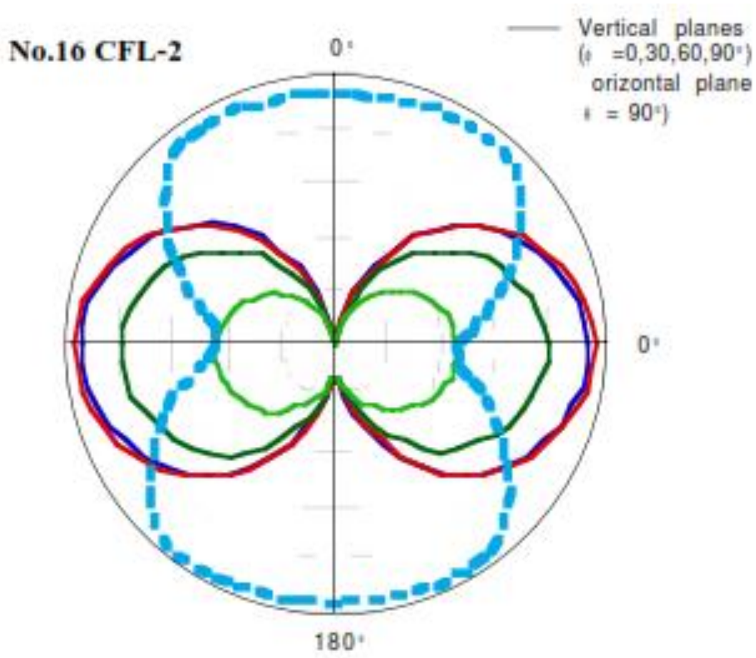
Understanding the errors due to angular distribution of lamp

- These measurement errors can be observed by rotation of a lamp in the sphere.

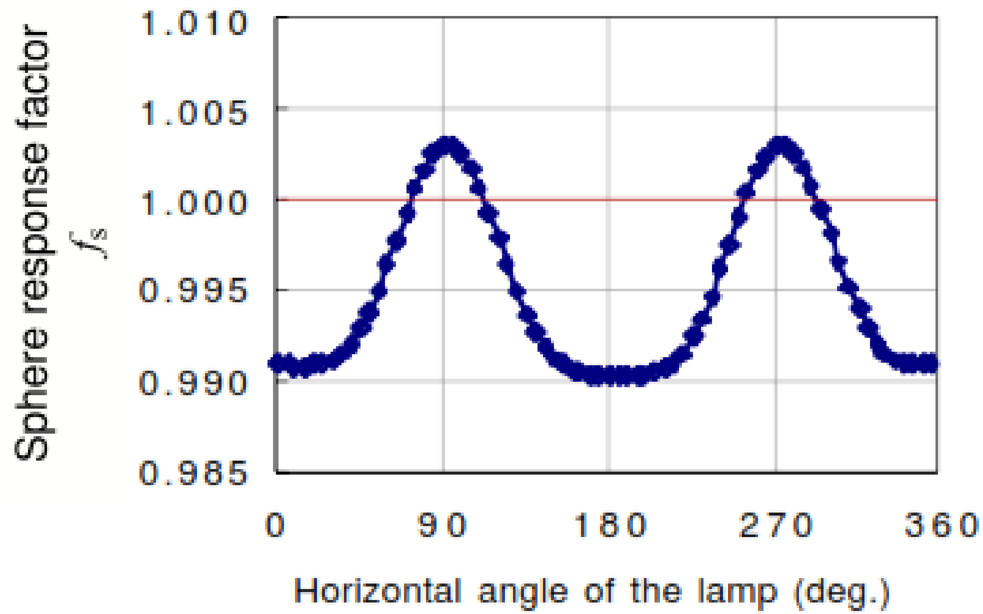
- The magnitude of the error is influenced by a number of parameters.
  - Reflectivity of the internal sphere surface
  - Baffle, size, position, reflectance
  - Detector angular response

Understanding the error due to angular distribution of lamp

- Simulated horizontal rotation of a twin CFL in 2m sphere and $\rho = 0.80$

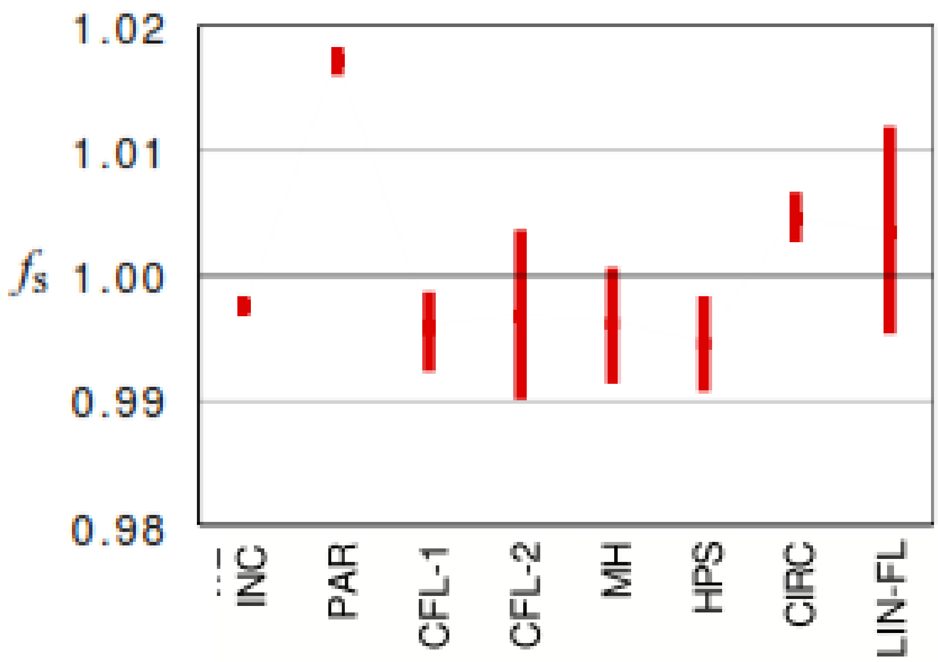


Intensity distribution



Understanding the error due to angular distribution of lamp

- Range of sphere response factors from simulations when different types of lamps are rotated horizontally

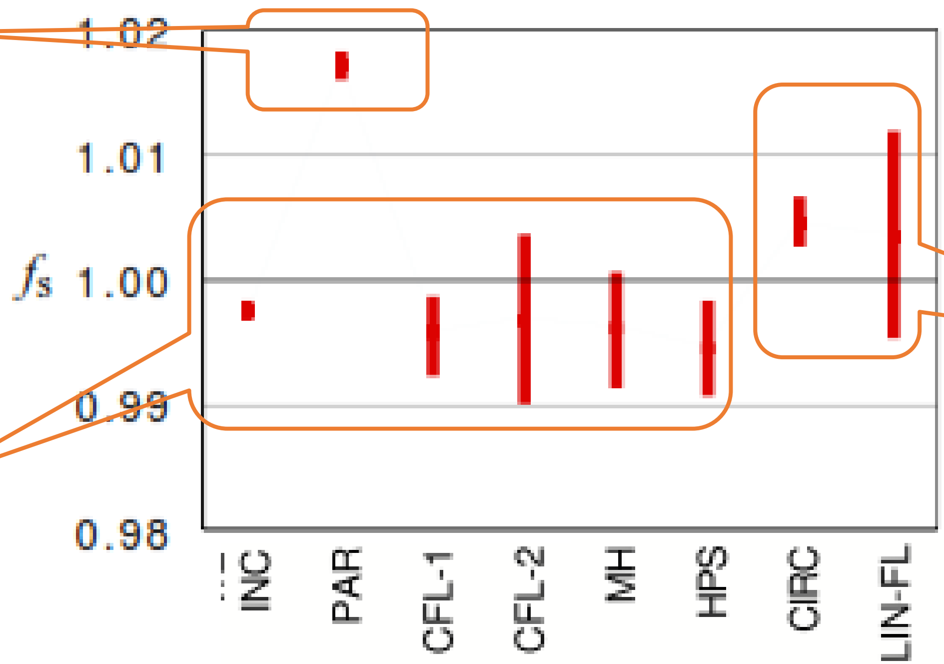


Understanding the error due to angular distribution of lamp

- Range of sphere response factors from simulations when different types of lamps are rotated horizontally

Group 3
Downward dominant intensity

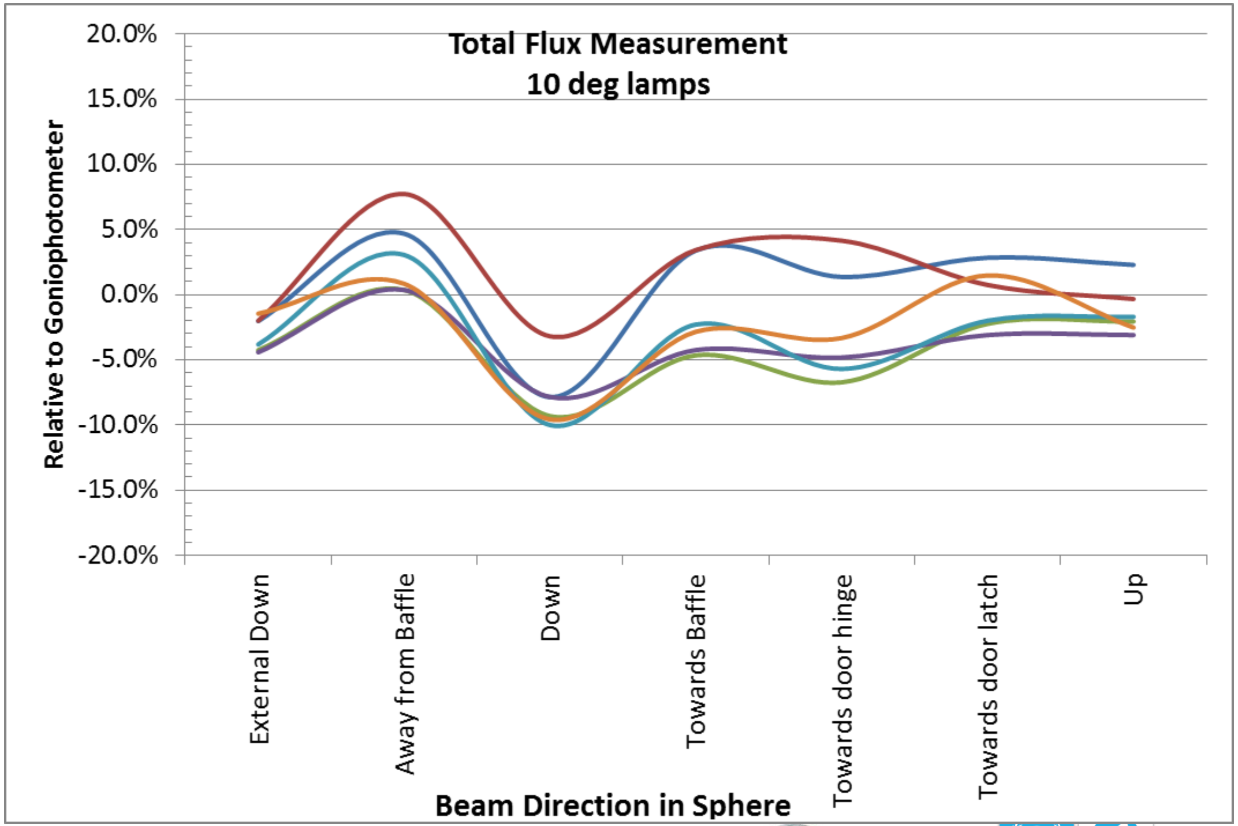
Group 1
Horizontally dominant intensity



Group 2
Vertically dominant intensity

Understanding the error due to angular distribution of lamp

- Actual measurements relative to goniophotometer
- Sphere
  - Dia = 1.5m
  - $\rho = 0.95$



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Understanding the error due to angular distribution of lamp

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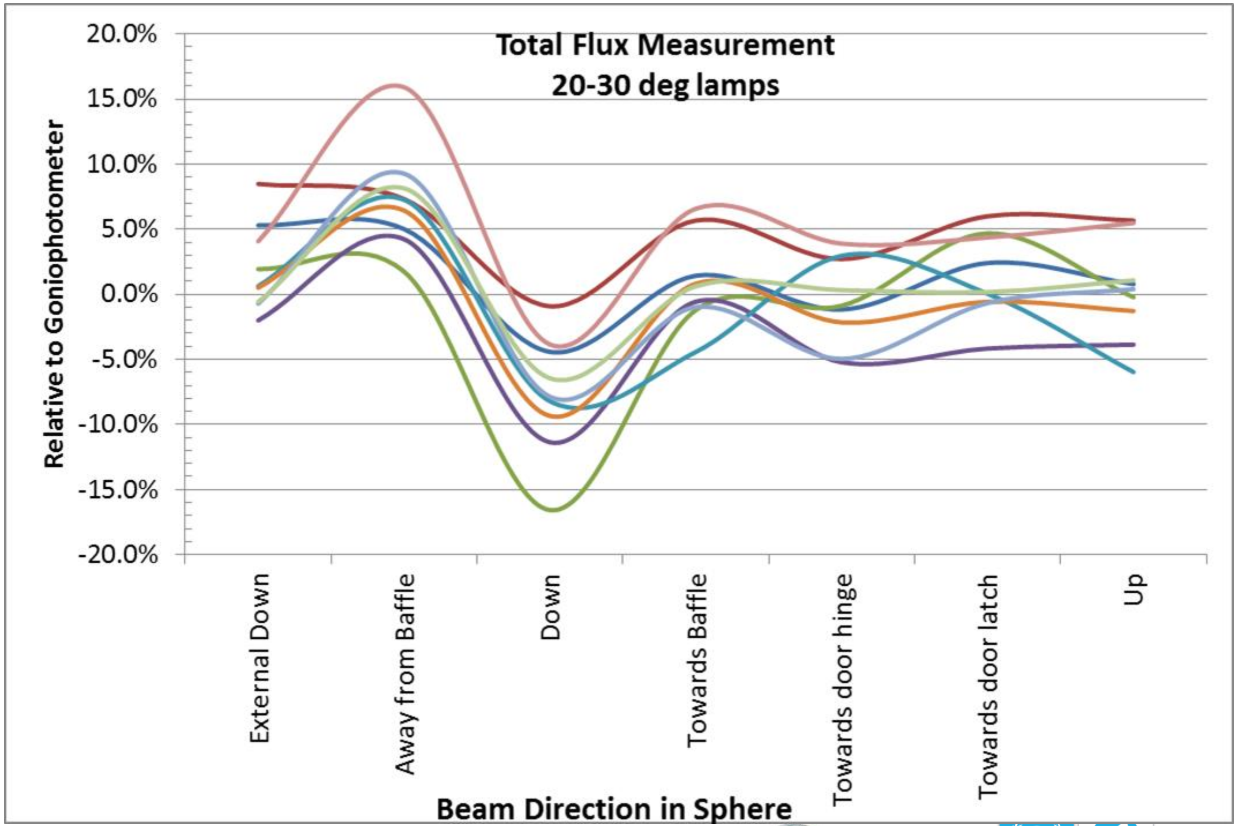

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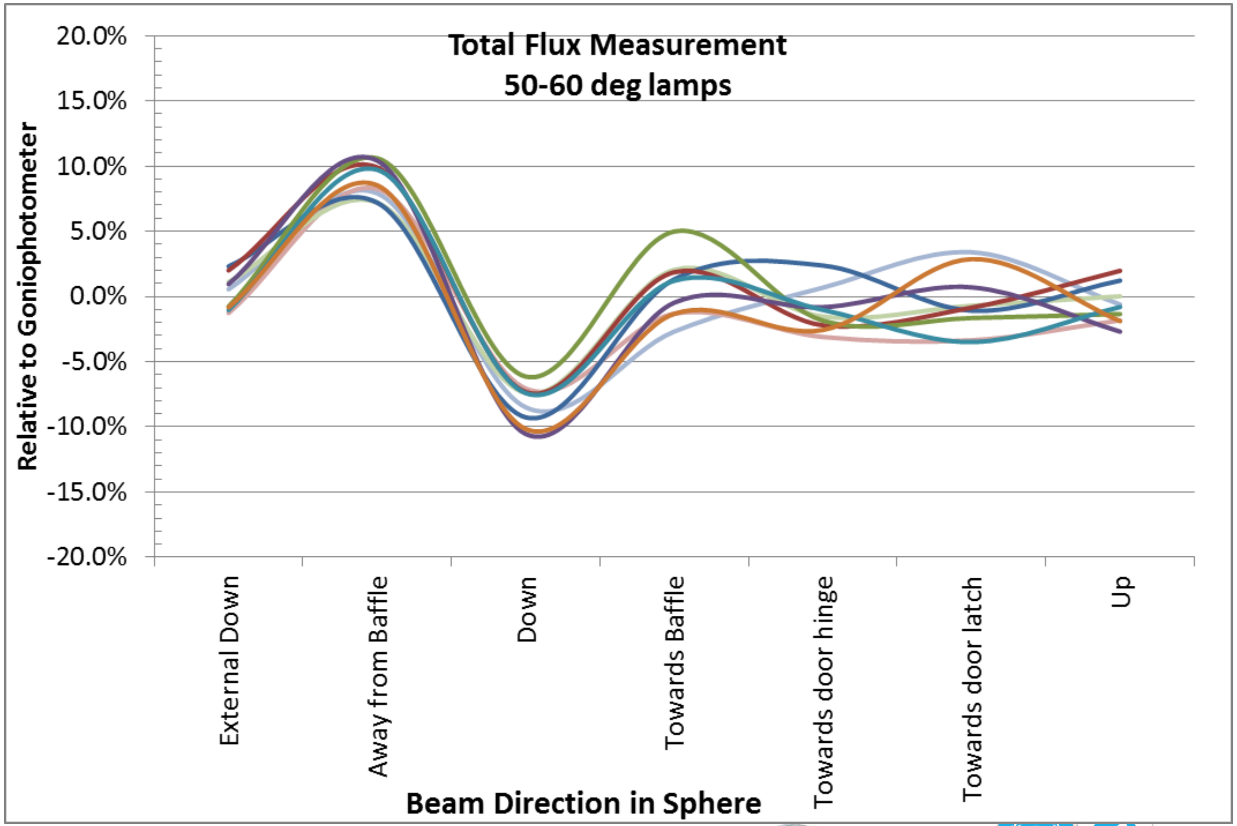
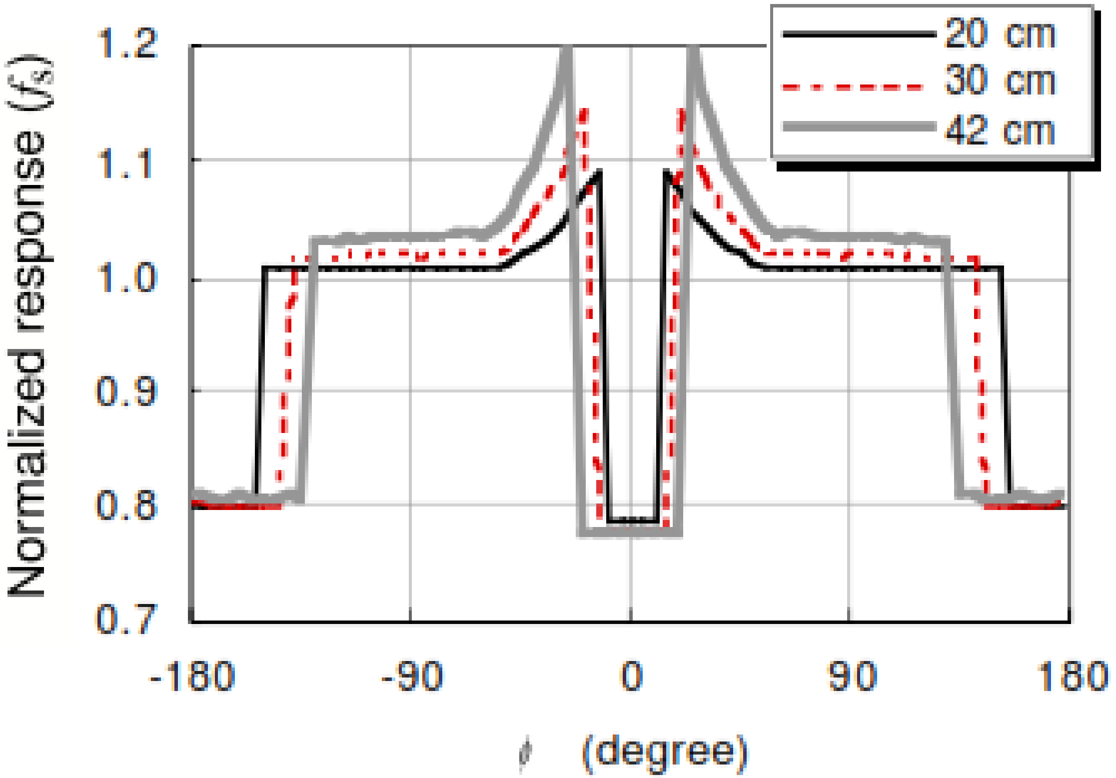


Understanding magnitude of errors: influencing factors

- Baffle Size
- Baffle Size/Location
- Reflectance of sphere wall
- Detector angular response

Understanding magnitude of error due to: Baffle Size

- Investigation of simulated SRDF curves for different baffle sizes



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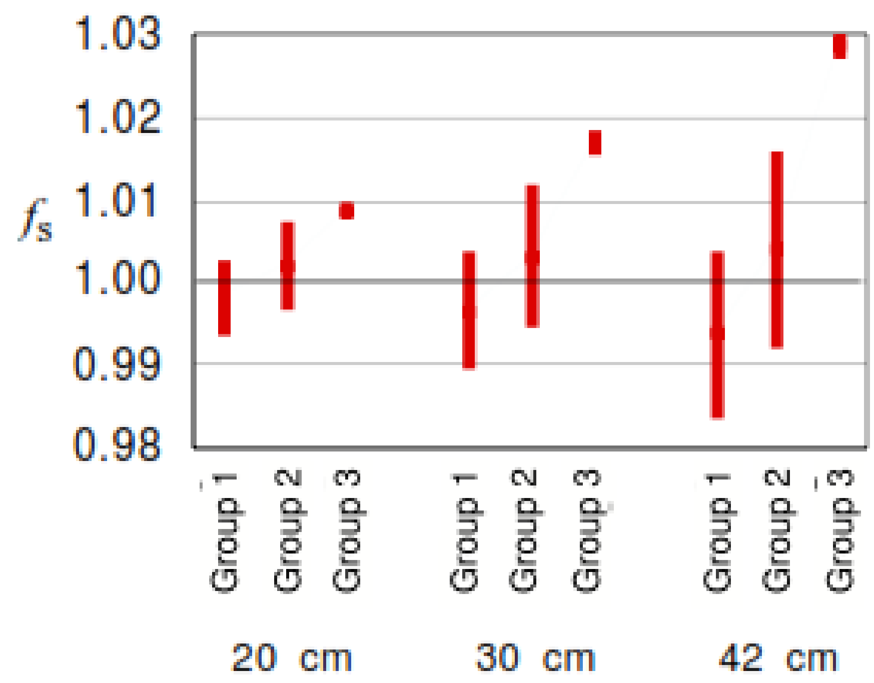
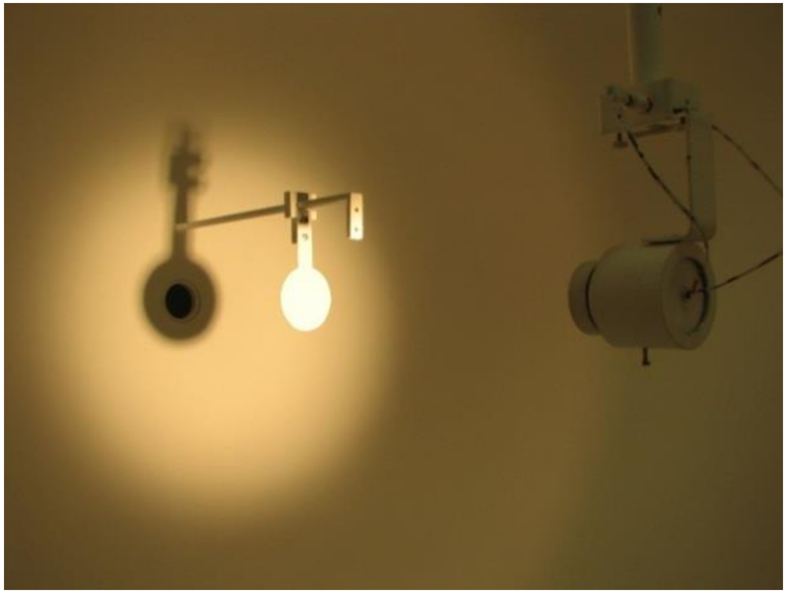
Understanding magnitude of error due to: Baffle Size

- Indicates that errors in the sphere response factor, f_s increase with increasing baffle size
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly directional



Understanding magnitude of error due to: Baffle Size/Location

- Different baffle sizes/locations change shadow cone size around detector



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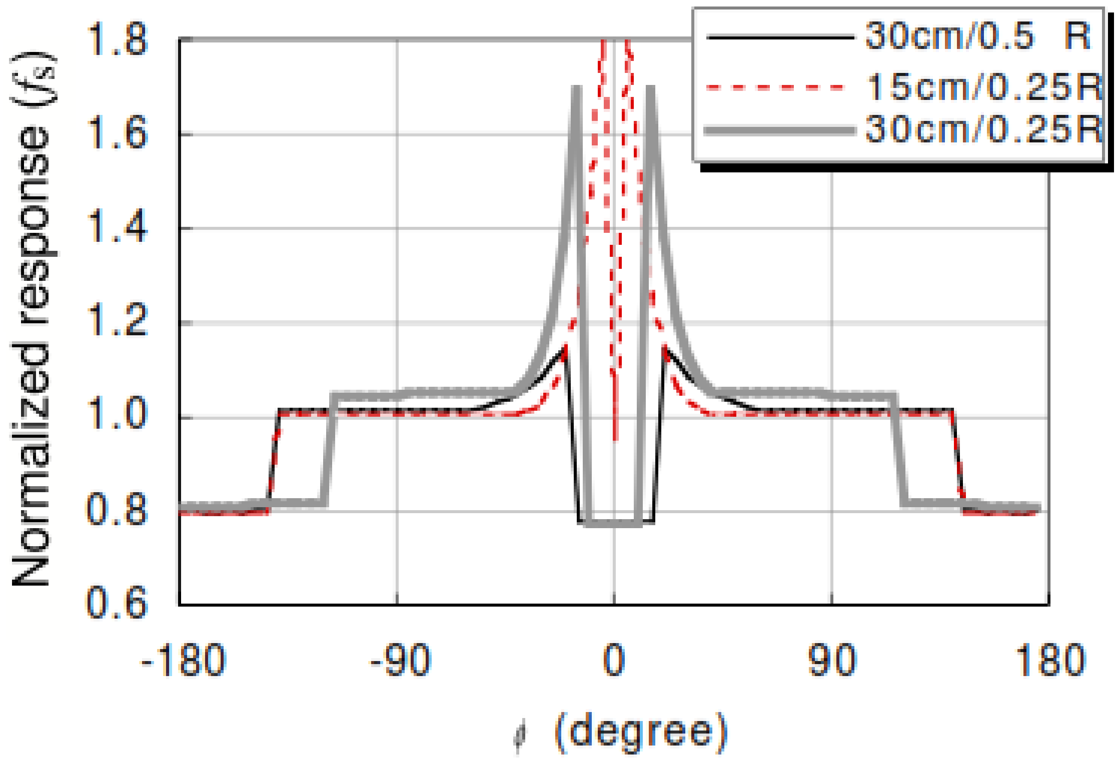
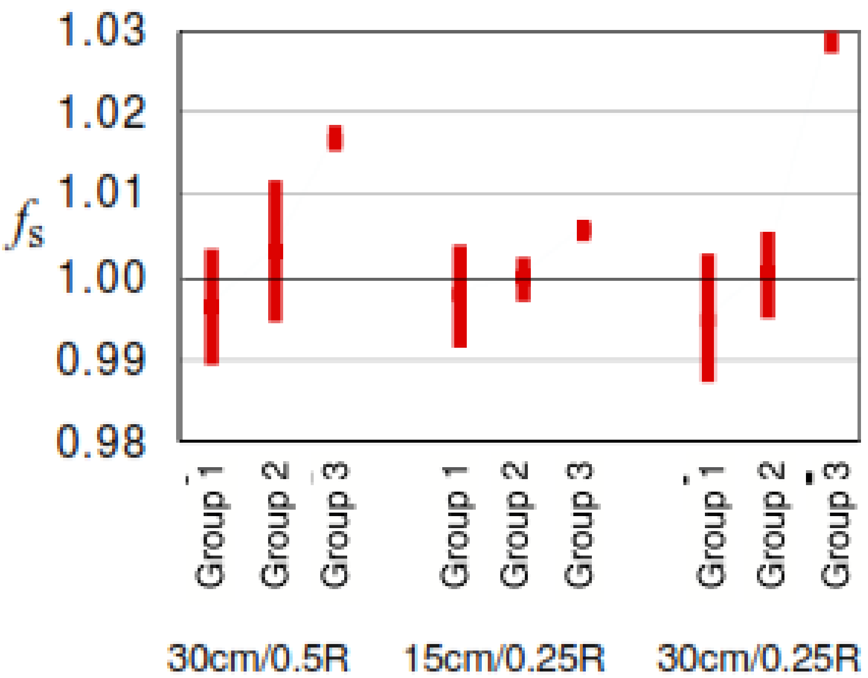
Understanding magnitude of error due to: Baffle Size/Location

- Investigation of simulated SRDF curves for different baffle sizes/locations



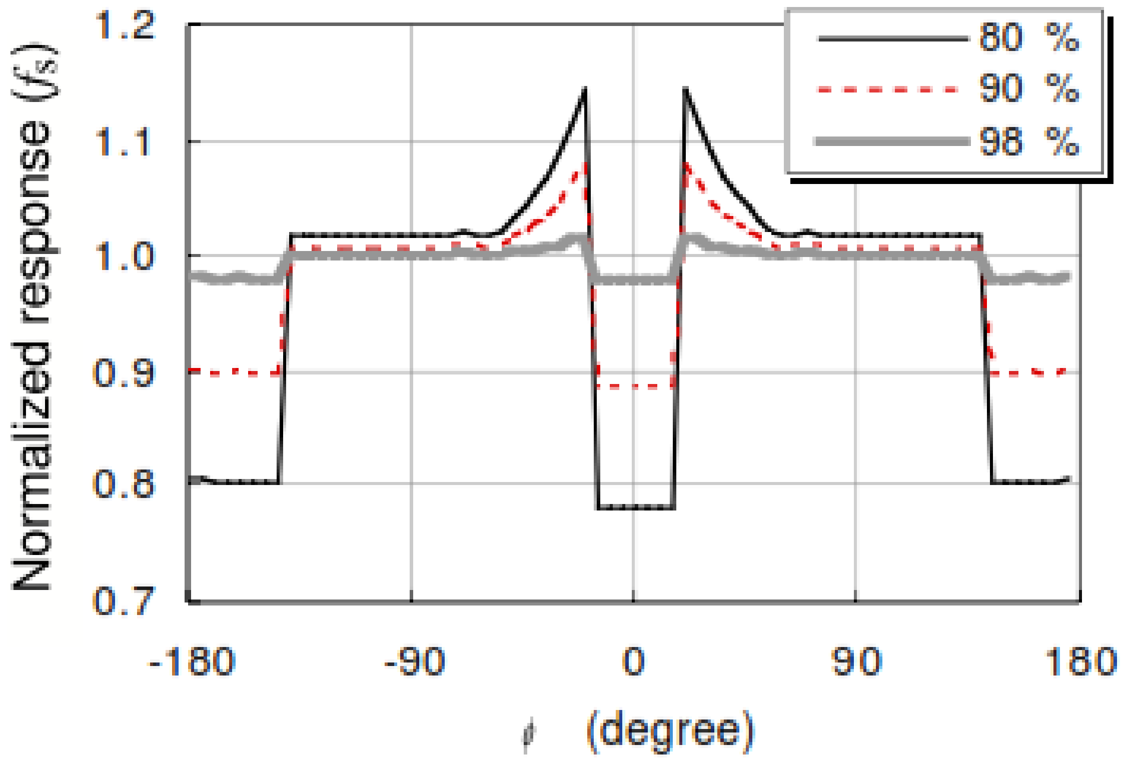
Understanding magnitude of error due to: Baffle Size/Location

- Indicates that errors in the sphere response factor, f_s increase with 1/3 R to 1/2 R placement of the small baffle from detector
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly directional



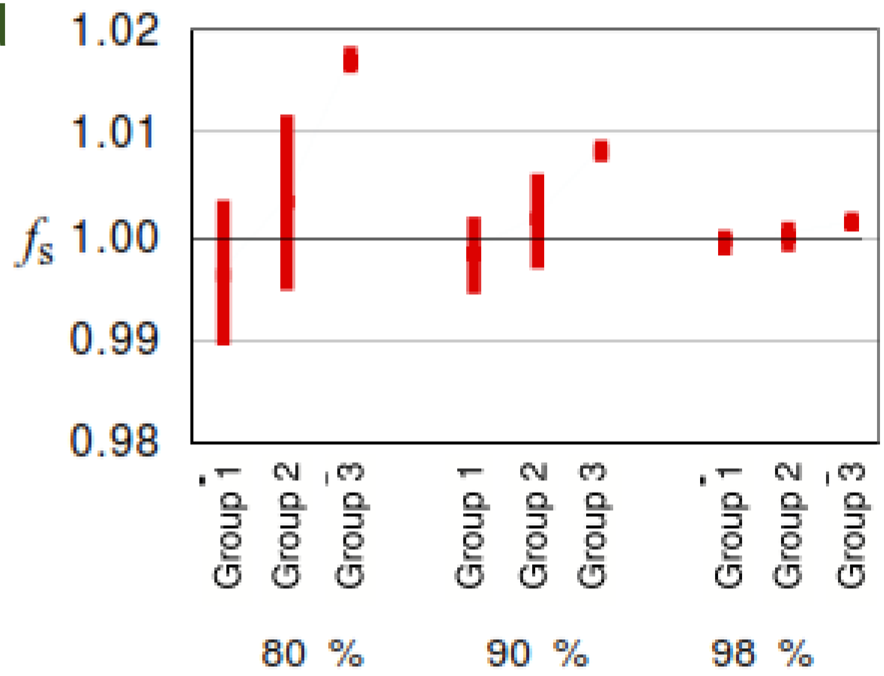
Understanding magnitude of error due to: reflectance of sphere wall

- Investigation of simulated SRDF curves for different reflectances in the recommended range (> 80%)



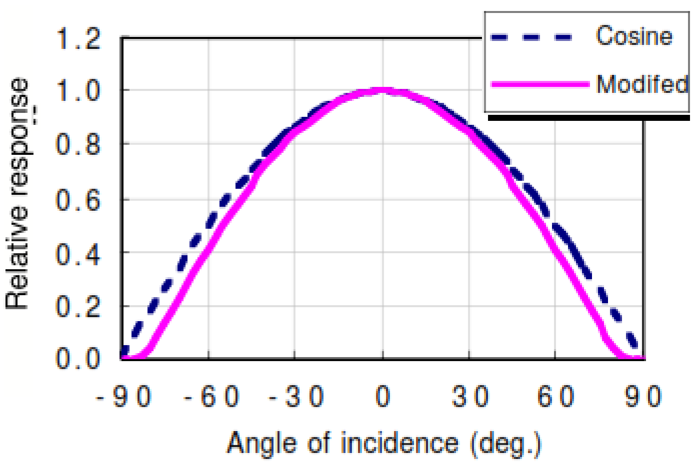
Understanding magnitude of error due to: reflectance of sphere wall

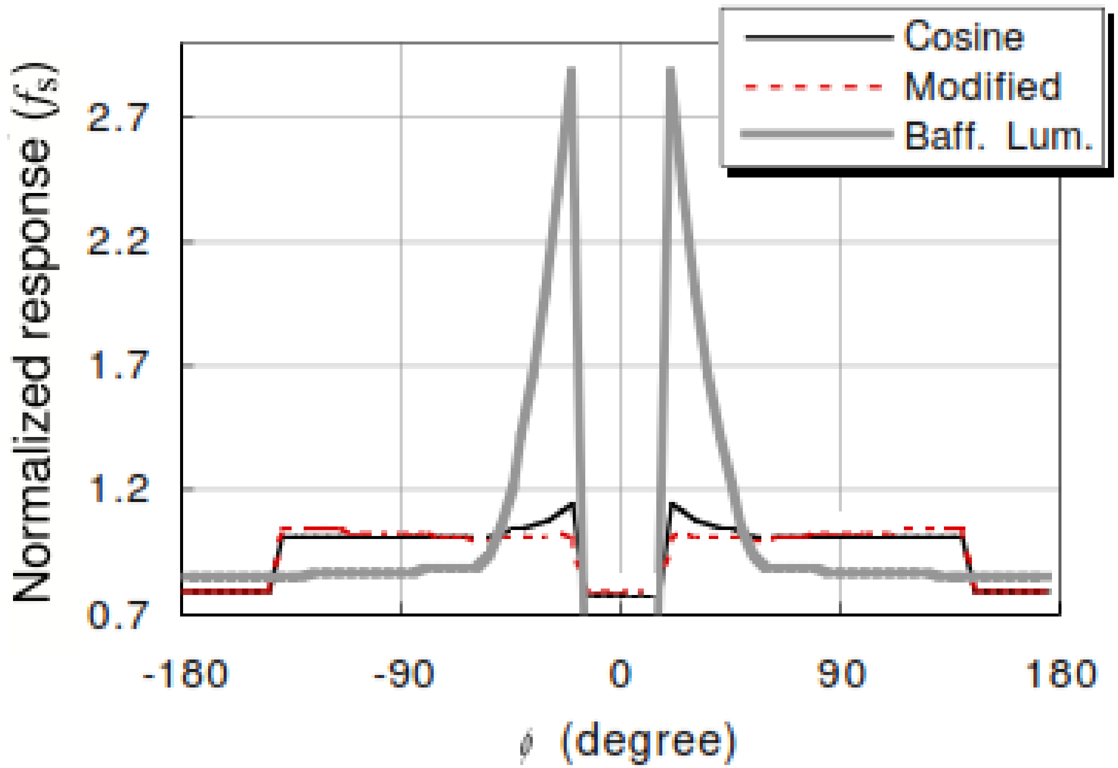
- Indicates that errors in the sphere response factor, f_s decrease with increasing reflectance
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly directional



Understanding magnitude of error due to: detector angular response

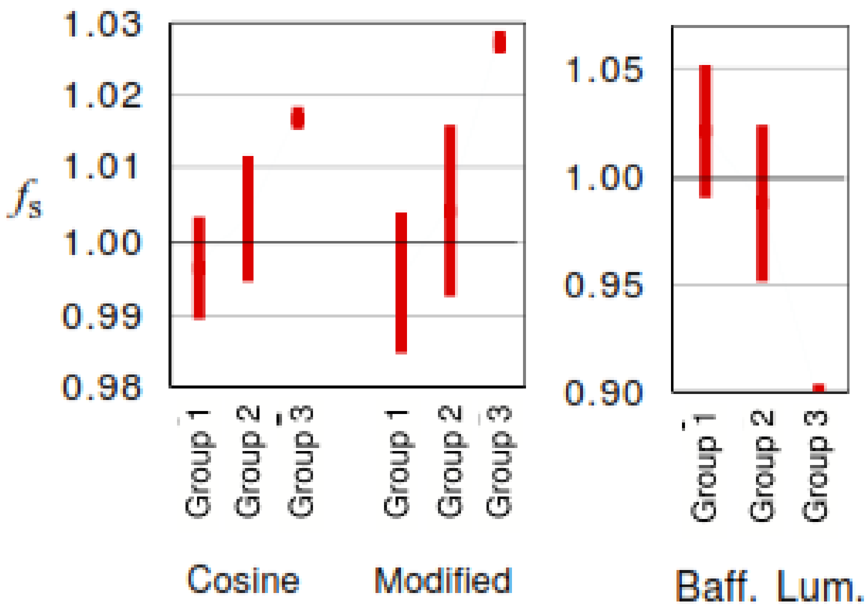
- Investigation of simulated SRDF curves for cosine, modified cosine and baffle FOV response





Understanding magnitude of error due to: detector angular response

- Indicates that errors in the sphere response factor, f_s decrease with increased reduction in cosine response
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly directional



Findings of the investigation

- Variation in the error level in the sphere response factor is apparent due to the comparative difference between different lamp distribution types and the isotropic light source.
- This is also the case for the real world situation of an omni-directional standard reference lamp. (It is not a perfect isotropic source! It has a dead zone due to the cap.)
- So these errors could be reduced by using a standard reference lamp with a light distribution replicating the test lamp.

Practical considerations

- Test lamps should only be measured against standard reference lamps with the very similar angular distribution.
- Then firstly need to know the beam angle of the test lamp.
- Can we accept the rated beam angle of the test lamp in order to select an appropriate standard reference lamp?

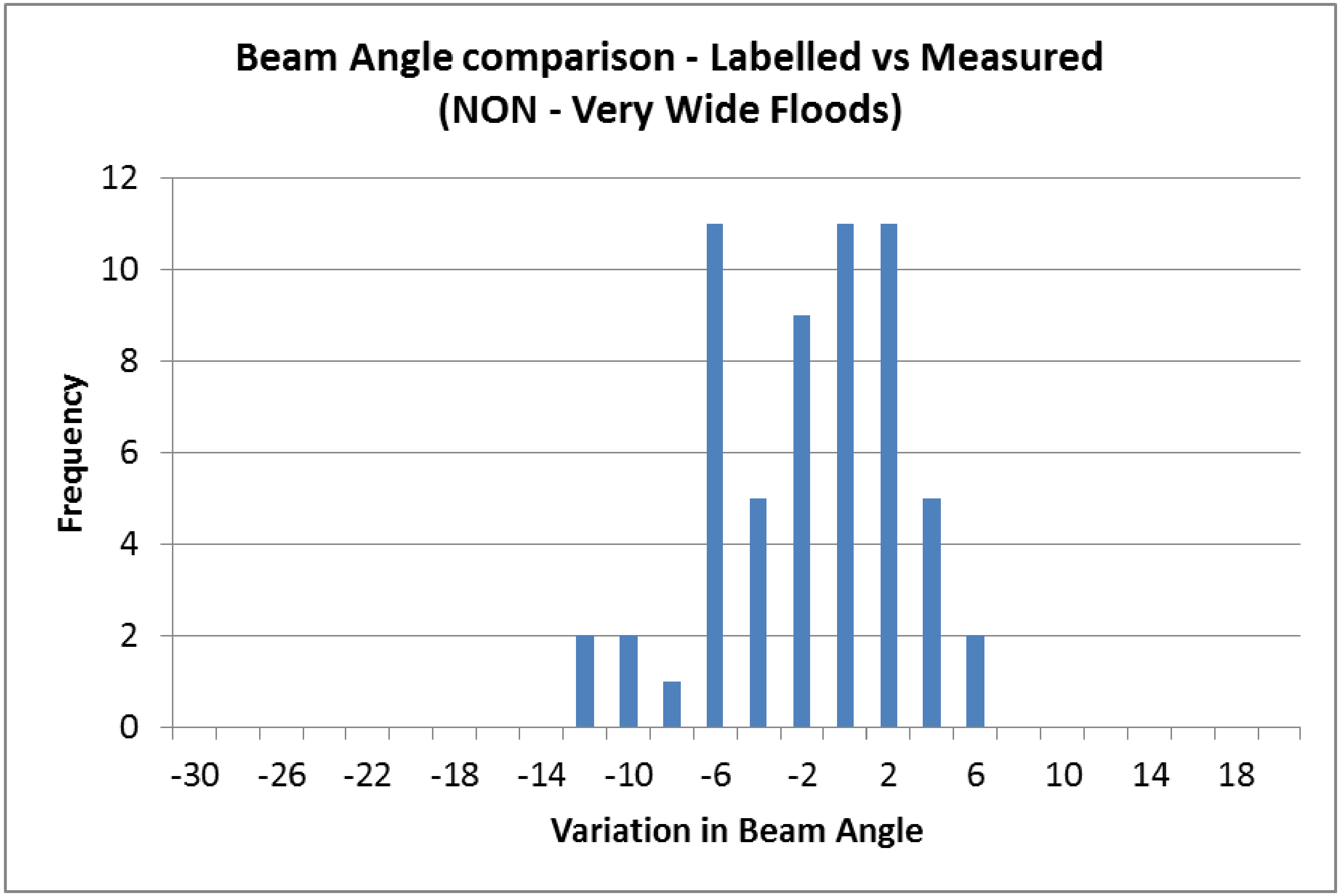
Beam Angle Variations

- Cannot assume that the rated beam angle is correct

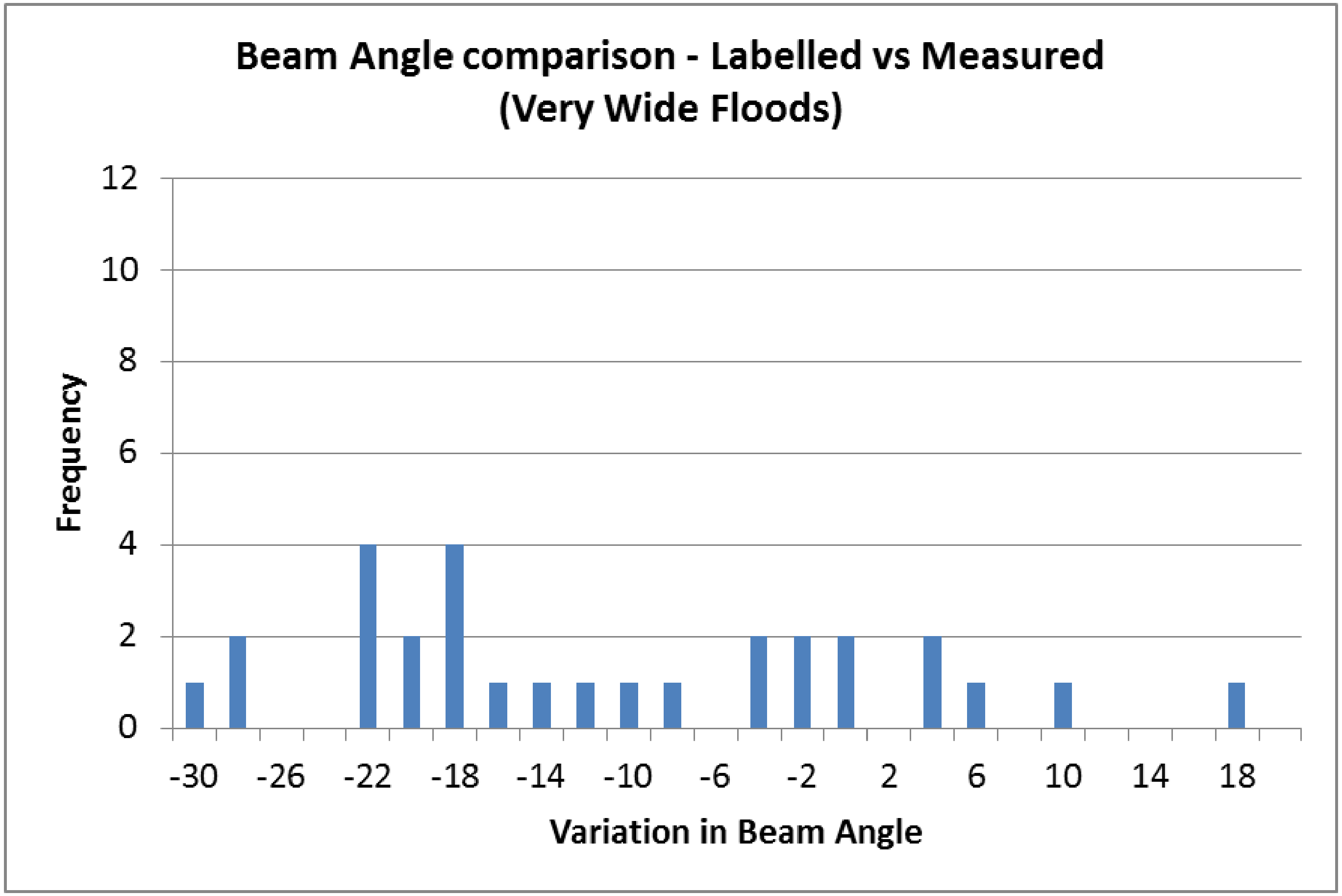
- Need to check (measure on optical bench) before selecting a standard reference lamp with similar beam angle

Declared Beam Angle	Measured Beam Angle	angle difference
60	40	-20
60	38	-22
60	37	-23
60	38	-22
60	42	-18
60	39	-21
60	48	-12
60	45	-15
60	42	-18
60	38	-22
60	41	-19
60	42	-18
60	30	-30
60	31	-29
60	32	-28

Beam angle variations from marketplace



Beam angle variations from marketplace



Recommendations

Possibilities

- Maintain a range of reference lamps with appropriate beam angles/distributions (This may present an issue in terms of maintaining a large range of standard lamps)
- Undertake calibration measurements of various light distribution lamps against the omni-directional standard reference lamp to determine correction factors for future use with test lamps (Future test lamps must be tested in the same orientation as the original calibration test. Remember the SRDF variations!)
- If measuring a significant quantity of lamps of similar light distribution, calibrate one on a goniophotometer system.

Acknowledgement

Results reported are based on:

- Journal publication: Integrating Sphere simulation on spatial non-uniformity errors in luminous flux measurement

  (Journal of the IES, vol 30 no 3, pp 105-115 (2201)

- Lamp test data from Australian Government

Questions ?