Measurement of Directional Lamps in an Integrating Sphere

Steve Coyne

Director, Light Naturally

UNEP Consultant

UNEP

GELC

Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

Introduction & Basic Theory

- Integrating sphere is used to measure total luminous flux of light sources
- Measured is 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 from the light source is directly incident on the detector)

Assumption:

- Lamps have the same spectral distribution. (ie no correction for spectral mismatch. See other presentation)

Formula: ideal sphere with isotropic source

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

- 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

And $$k_0 = \frac{1-\rho}{\rho}.A$$

- k_0 is the ideal sphere responsivity with units: lm/lx

Note: these functions work on the basis of: omni-directional light source; and uniform reflectivity and no obstructions in the sphere.

UNEP GELC Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

The Real World of integrating spheres

Because of practical issues within a real sphere, the ideal sphere responsivity, k_0, cannot be used, due to

- Non-uniform reflectivity
  - coating may not be applied uniformly to all parts of the sphere
  - 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

UNEP

nLtc National Lighting Test Centre China

Real (non-ideal) Sphere: isotropic source

- These non-ideal effects (variations due to obstructions, non-uniform reflectance) can be thought of as the sphere response factor, $f_{s,iso}$ when using an isotropic light source

- Then the real sphere responsivity for an isotropic light source can be expressed as

$$k = k_0 . f_{s,iso}$$

- Obviously $f_{s,iso} = 1$ for an ideal sphere with an isotropic light source

National Lighting Test Centre China

Real (non-ideal) Sphere: non-isotropc source

- A source with a non-uniform luminous intensity distribution in a non-ideal sphere, will again produce a different sphere responsivity value.

- The sphere responsivity value will not be the same for:
  - different light source orientations
  - variations in light source luminous intensity distributions

  due to the non-uniform reflectivity and internal obstructions creating a directionally weighted responsivity within the sphere.

Real (non-ideal) Sphere: non-isotropc source

- Then the real sphere responsivity for a set orientation of a non-isotropic light source can be expressed as

$$k = k_0 . f_{s,Z}$$

- where $f_{s,Z}$ is the sphere response factor for the real sphere for a set orientation and particular luminous intensity distribution of the light source

National Lighting Test Centre China

Real (non-ideal) Sphere responsivity: standard reference lamp

- Can be determined using a reference light source

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

Where

- Φ_{Ref} is the total luminous flux of the standard reference lamp
- $E_{ind,Ref}$ is the indirect illuminance (on the detector) due to the total luminous flux, Φ_{Ref}
- k includes to the combined effects of the "responsivity of an ideal sphere of the same dimensions and reflectance" modified by the "variations due to obstructions, non-uniform reflectance etc" for this intensity distribution and lamp orientation

Measuring total luminous flux of test lamps

- The test lamp MUST have the same relative intensity distribution as the standard reference lamp.
- Remember: 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 which have varying reflectance and obstructions) before reaching the detector

Then

$$\Phi_{test} = k.E_{ind,\,test}$$

Where k has been determined from calibration with the standard reference lamp

What about lamps with different distributions to reference lamp?

So

- Let's consider a sphere which is not perfect inside (eg has obstructions and varying surface reflectance)
- Then the light directed to each part of the surface will have different losses on the path to the detector. Therefore collectively contributing differently to the overall detector response.

$$\Phi_{test} = k_{dependent\ on\ beam\ and\ orientation} \cdot E_{ind,\ test}$$

- Therefore the partial contributions need to be determined.

Measuring partial sphere response

$$\Phi_{test} = k.E_{ind,\,test}$$

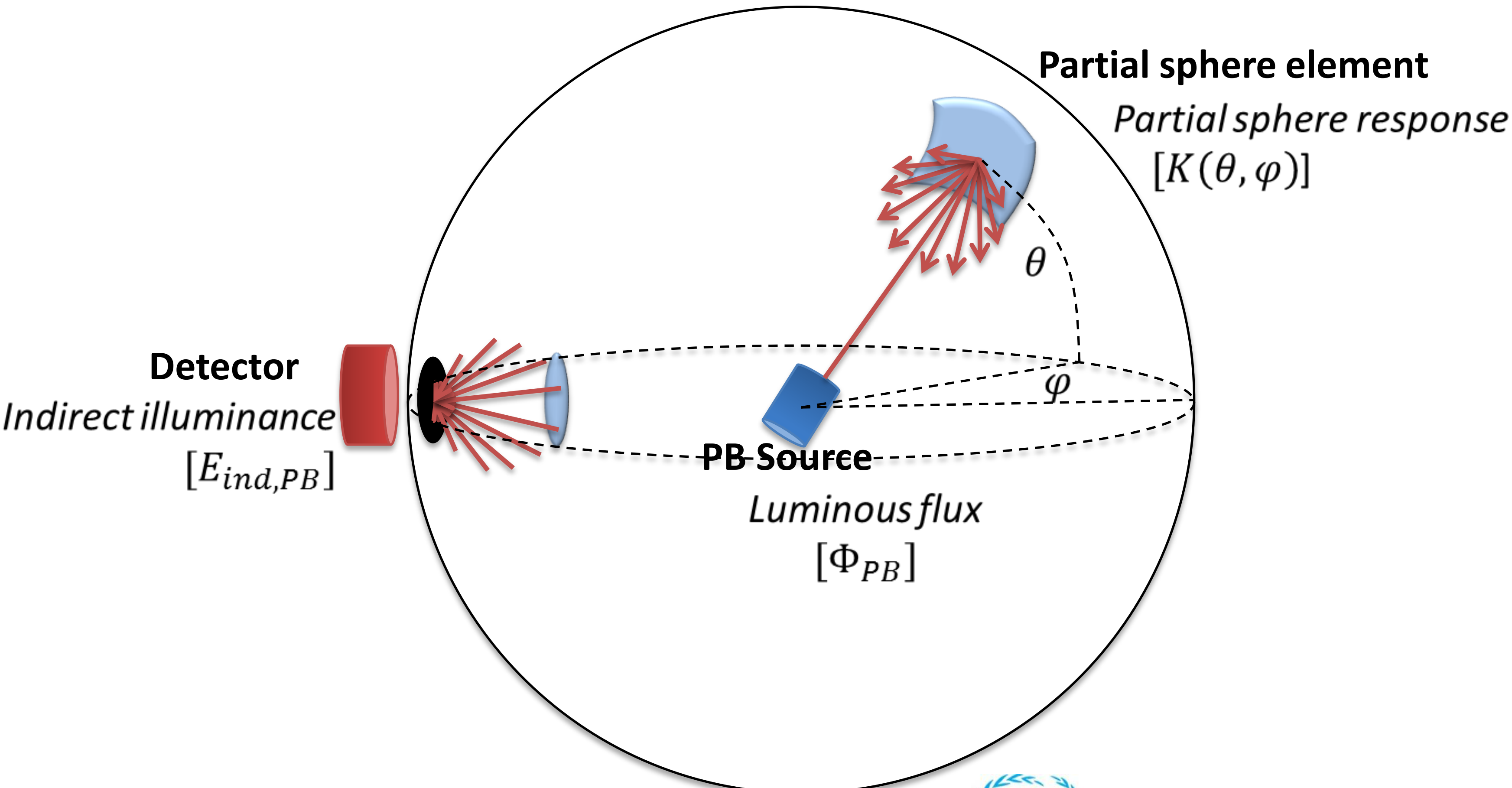
So

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

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

Global Efficient Lighting Centre
UNEP Collaborating Centre for Energy Efficient Lighting

Measuring partial sphere response



National Lighting Test Centre China

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 luminous 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

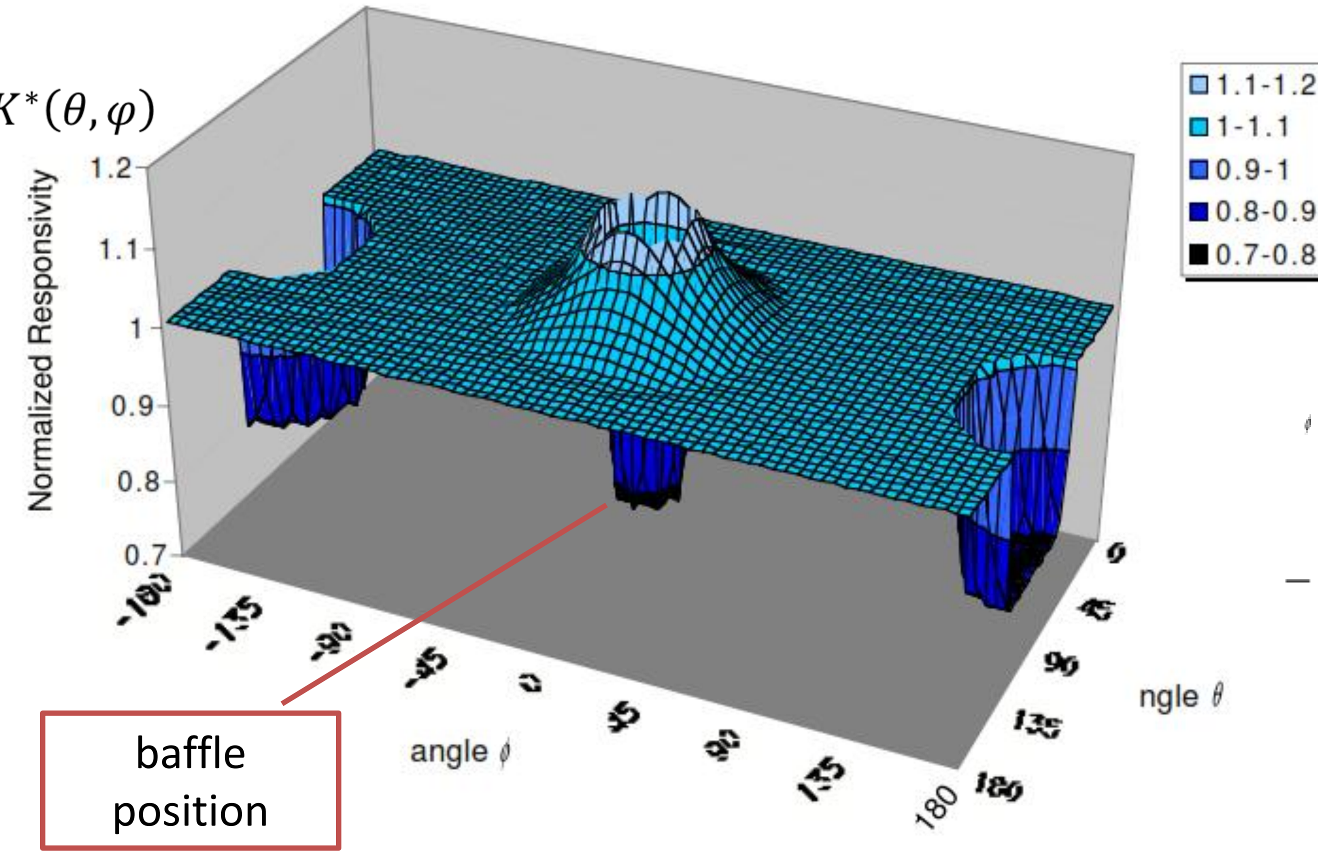
$$K_{ave}(\theta,\varphi) = \frac{\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} K(\theta,\varphi)\, sin\theta\, d\theta\, d\varphi}{4\pi}$$

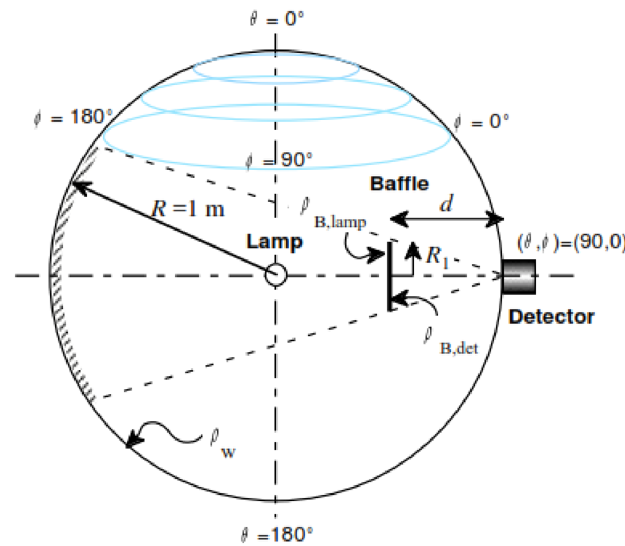
Therefore

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

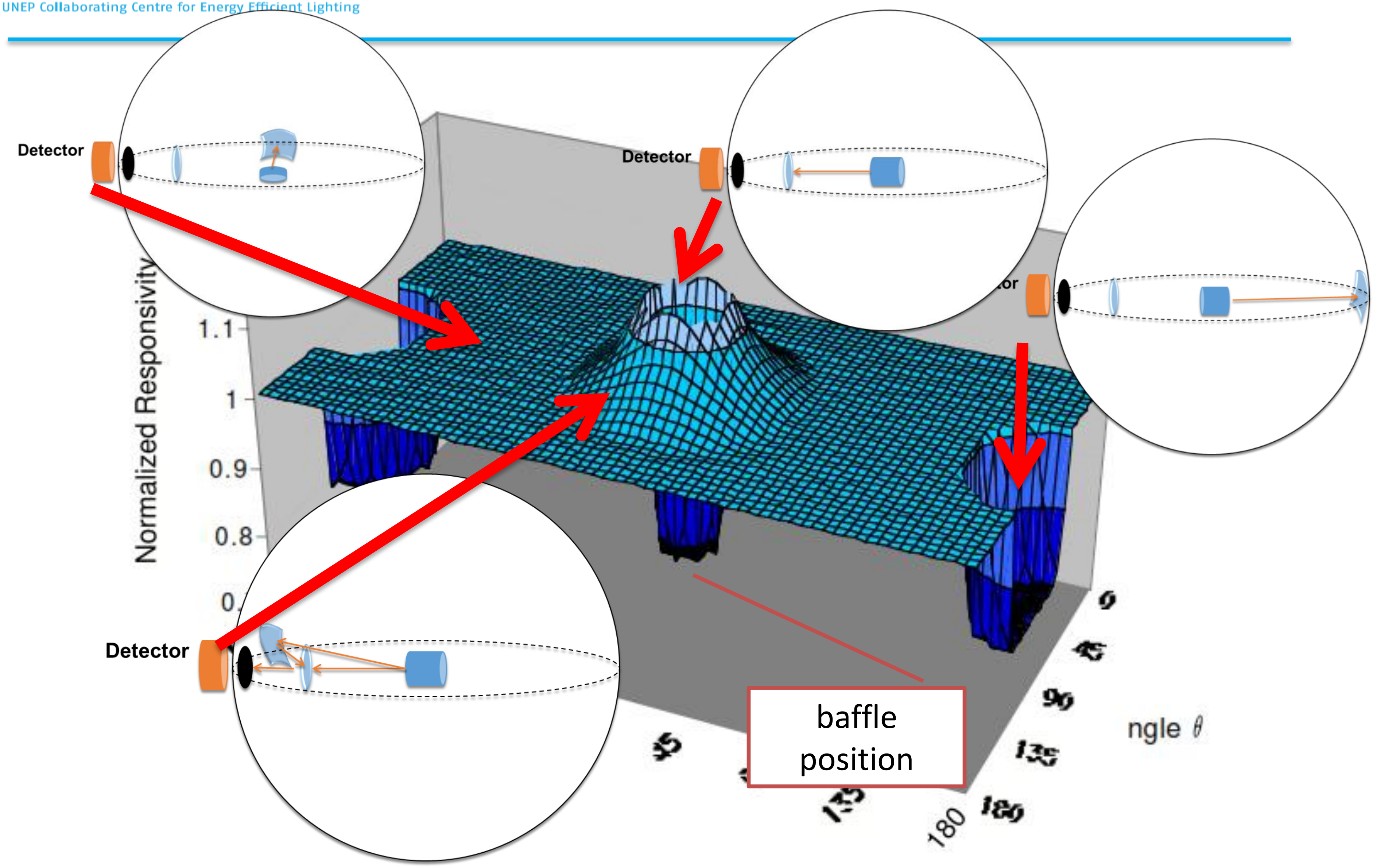
Example of a 3 dimensional SRDF

$\rho = 0.80$



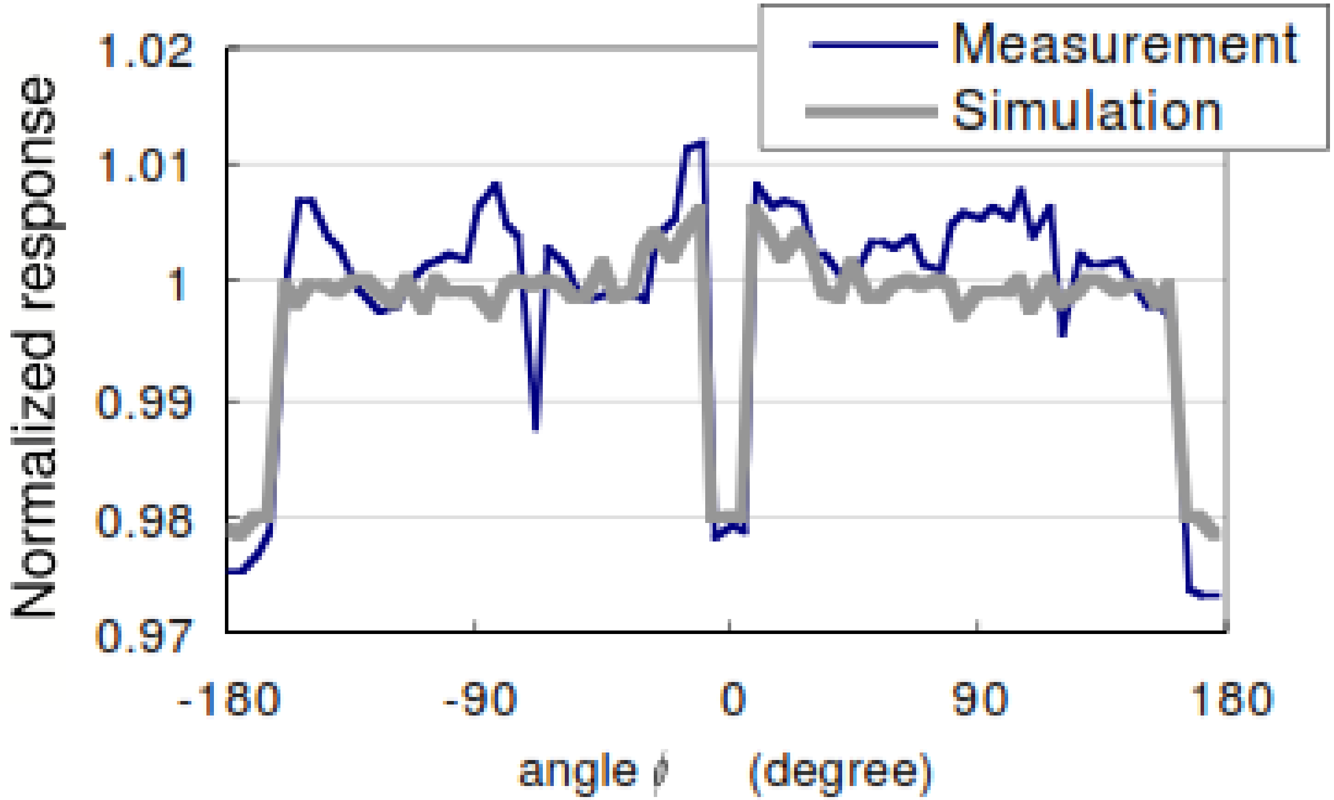


Example of a 3 dimensional SRDF



Example of SRDF – in horizontal plane

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



Global Efficient Lighting Centre
UNEP Collaborating Centre for Energy Efficient Lighting

Calculating the sphere response factor

- The sphere response to an oriented light source is the summing of the product of the relative intensity of the 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:

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

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

National Lighting Test Centre China

The "perfect 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

- No sphere has a normalised partial sphere response factor of 1 in all directions. $K^*(\theta,\varphi) \neq 1$ for all (θ,φ)
- So need to determine:
  - sphere response factor when calibrated with an omnidirectional standard light source, $f_{s,iso}$
  - sphere response factor when measuring the test lamp light in a particular orientation, $f_{s,z}$
- The corrected sphere response factor (for the combined total luminous flux measurement correction for the test lamp is then given by:

$$f_s = \frac{f_{s,iso}}{f_{s,z}}$$

National Lighting Test Centre China

Practical measurements

- Calibration of the sphere with the reference standard lamp

$$\Phi_{ref} = E_{ind}.k$$
$$= E_{ind,ref}.k_0.f_{s,ref}$$

- Using this information to substitute k_0

$$k_0 = \frac{\Phi_{ref}}{E_{ind,ref}\cdot f_{s,ref}}$$

- into test lamp equation

$$\Phi_z = E_{ind,z}.k$$
$$= E_{ind,z}.k_0.f_{s,z}$$
$$= \Phi_{ref} \times \frac{E_{ind,z}}{E_{ind,ref}} \times \frac{f_{s,z}}{f_{s,ref}}$$

Global Efficient Lighting Centre
UNEP Collaborating Centre for Energy Efficient Lighting

Practical measurements

- If luminous intensity distributions of both the reference standard and test lamps (ie beam angles for directional lamps) and their orientation is the same in the sphere then

$$f_{s,z} = f_{s,ref}$$

and

$$\Phi_z = \Phi_{ref} \times \frac{E_{ind,z}}{E_{ind,ref}}$$

National Lighting Test Centre China

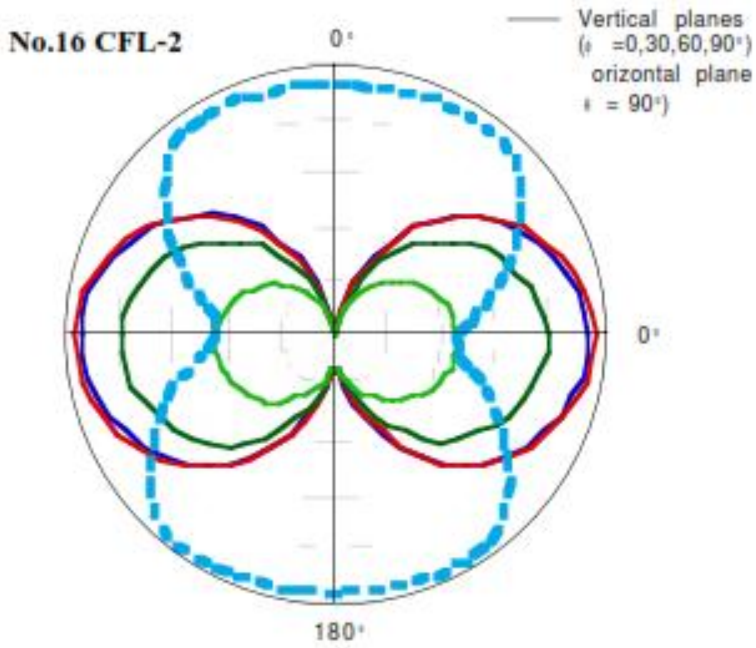
Understanding the errors due to angular distribution of lamp

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

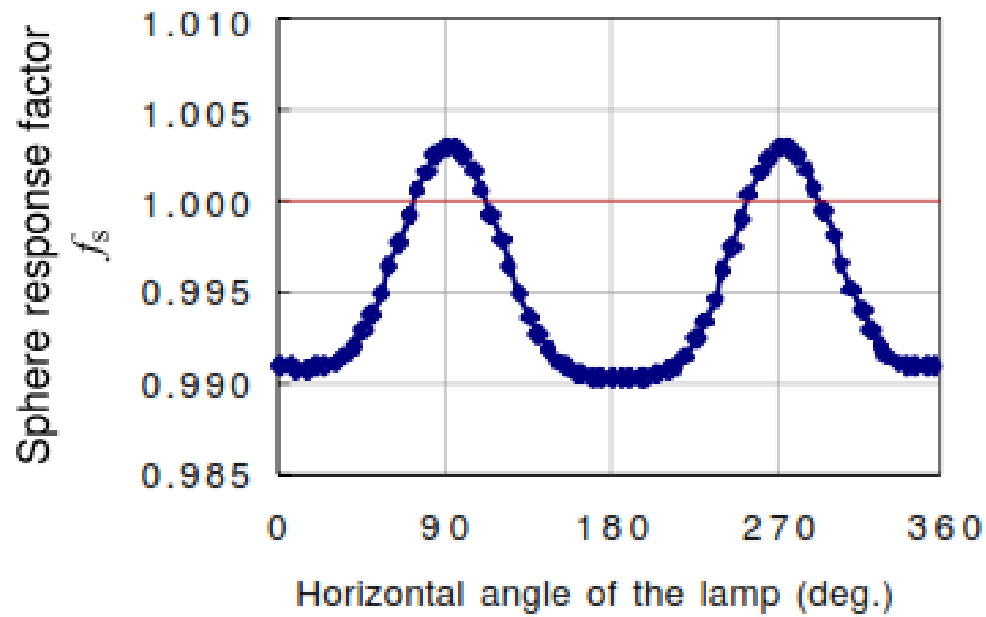
- The magnitude of the error is influenced by a number of parameters.
  - Reflectivity of the internal sphere surface
  - Baffle, size, position, reflectance
  - Detector angular response
  - [Change in light output due to lamp orientation]

Understanding the error due to angular distribution of lamp

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

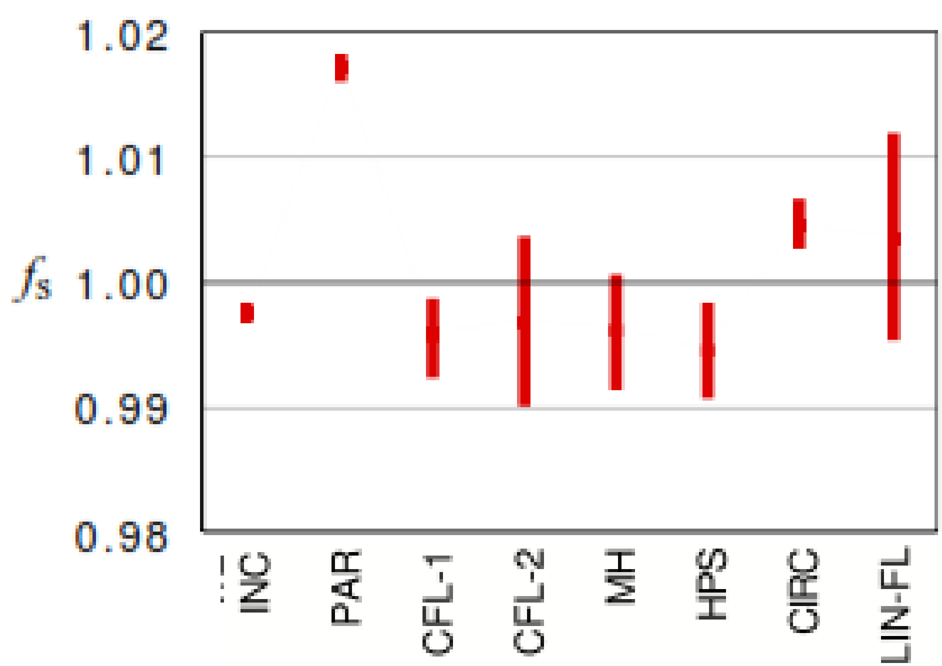


Intensity distribution



Understanding the error due to angular distribution of lamp

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



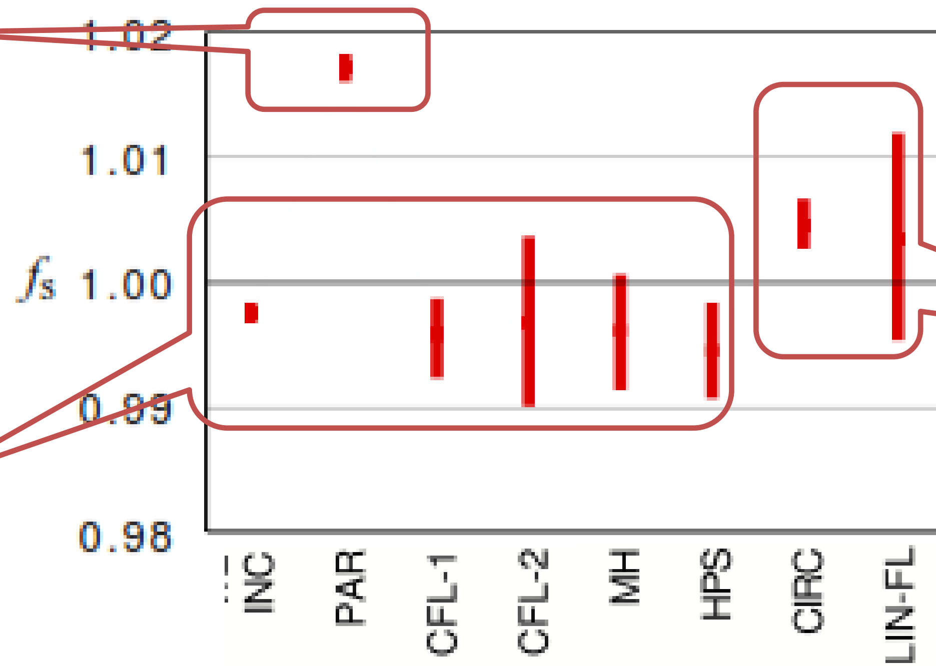
National Lighting Test Centre China

UNEP Collaborating Centre for Energy Efficient Lighting

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

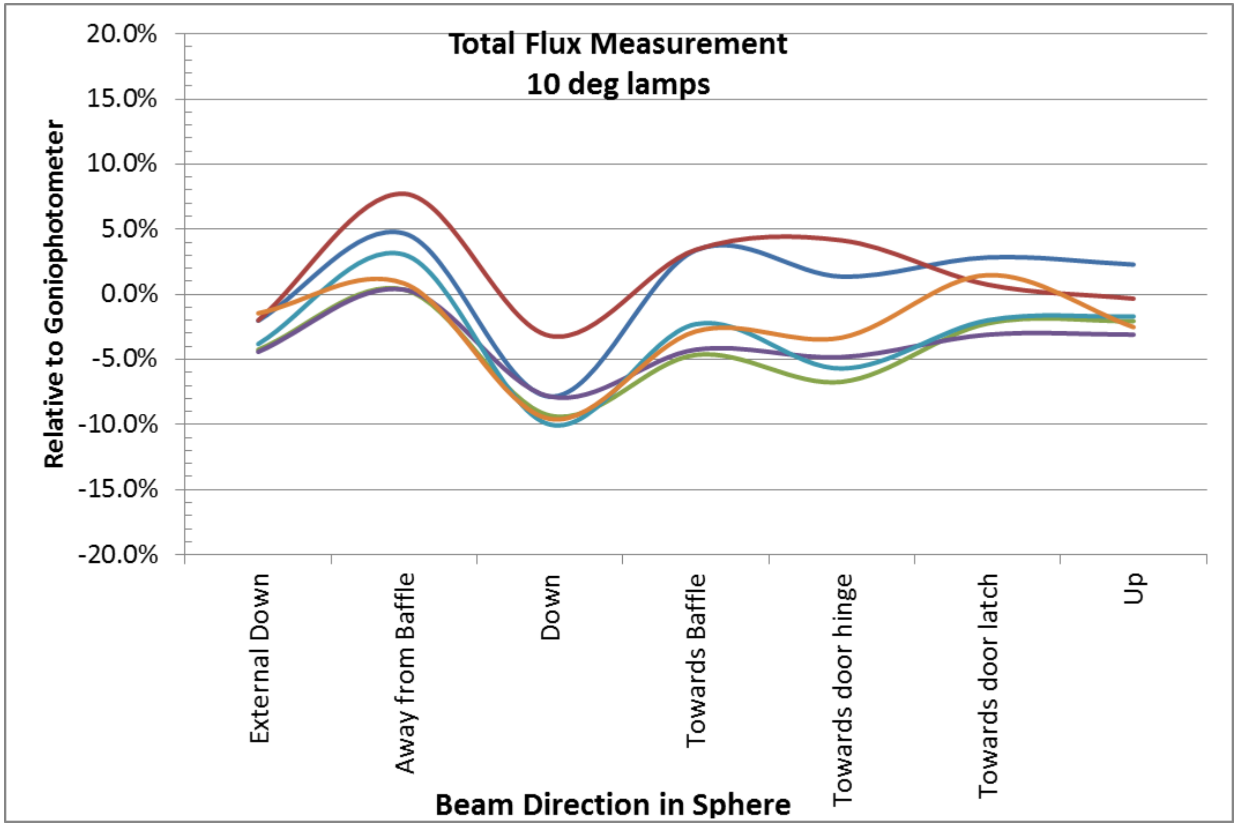
National Lighting Test Centre China

UNEP GELC Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

Understanding the error due to angular distribution of lamp

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



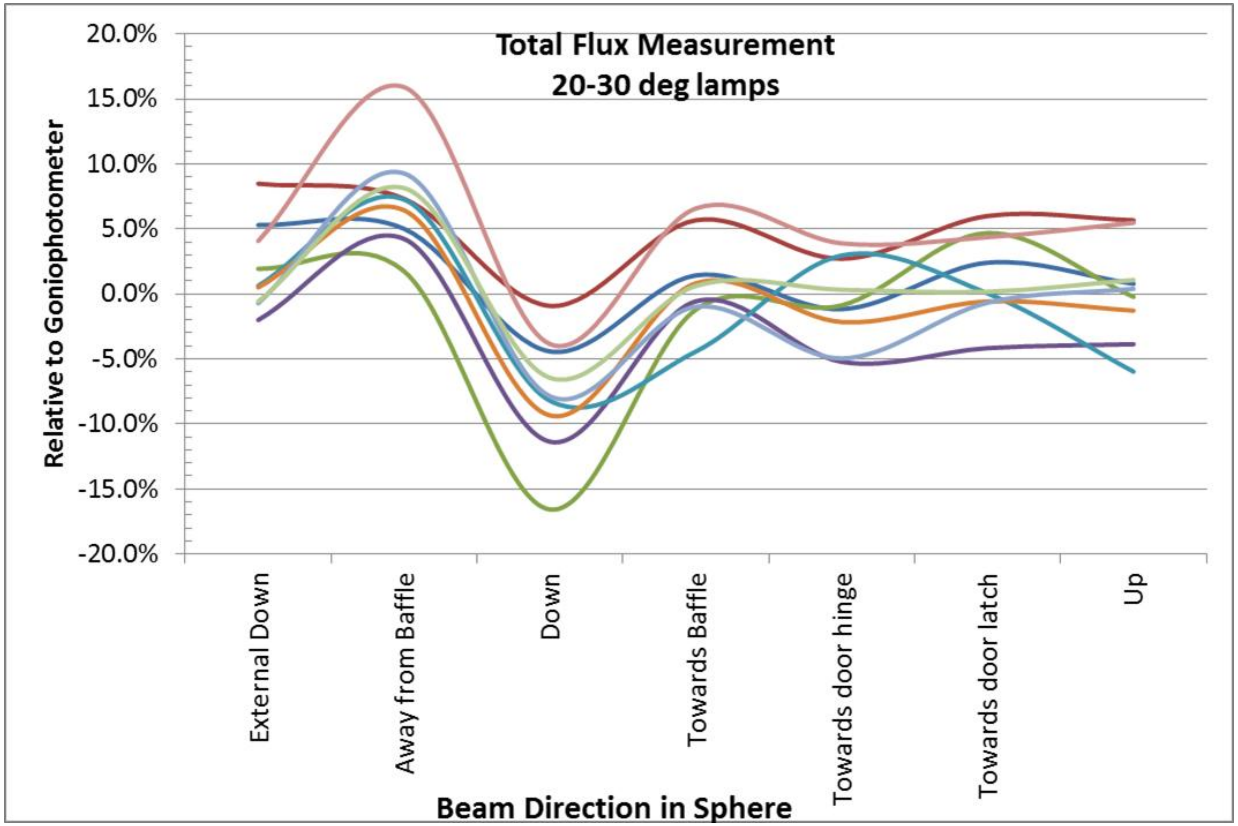
UNEP

nltc National Lighting Test Centre China

Understanding the error due to angular distribution of lamp

UNEP Collaborating Centre for Energy Efficient Lighting

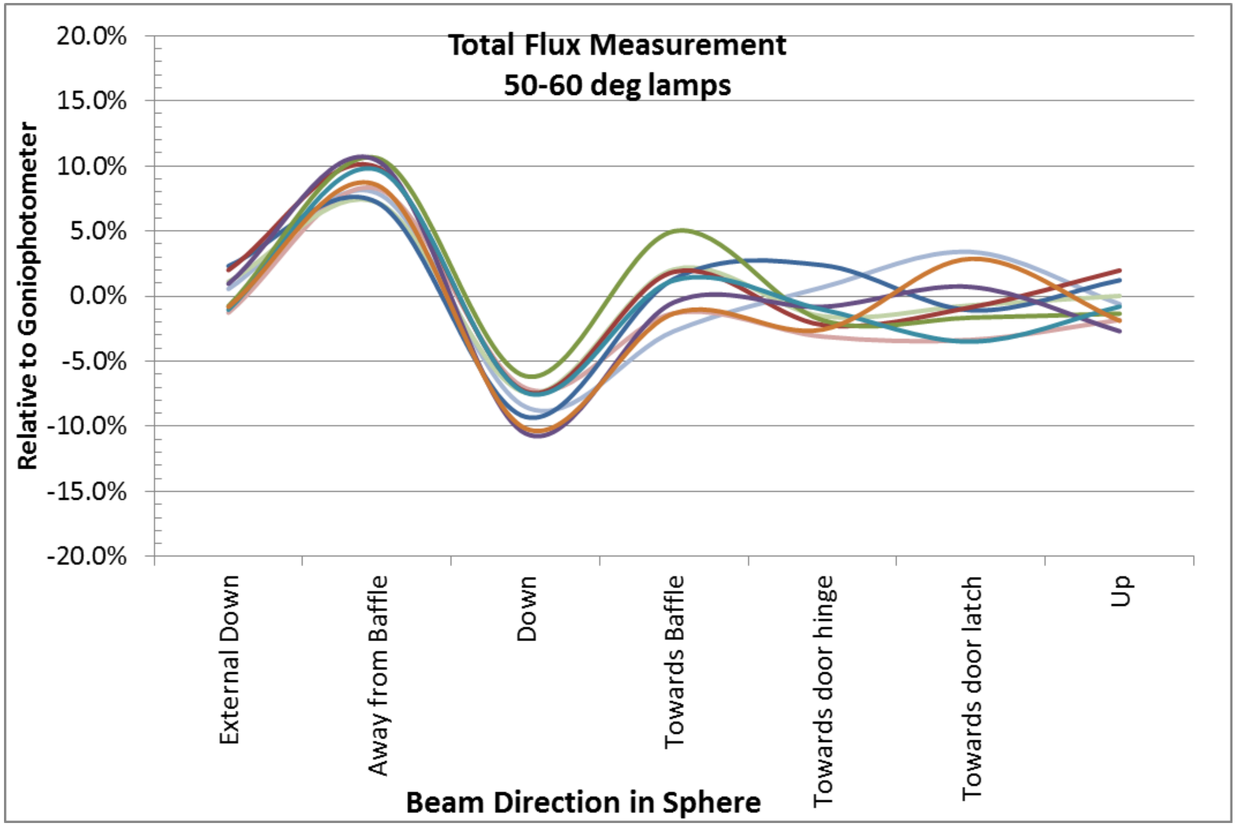
- Actual measurements relative to goniophotometer
- Sphere
  - Dia = 1.5m
  - $\rho = 0.95$



National Lighting Test Centre China

Understanding the error due to angular distribution of lamp

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



UNEP Collaborating Centre for Energy Efficient Lighting

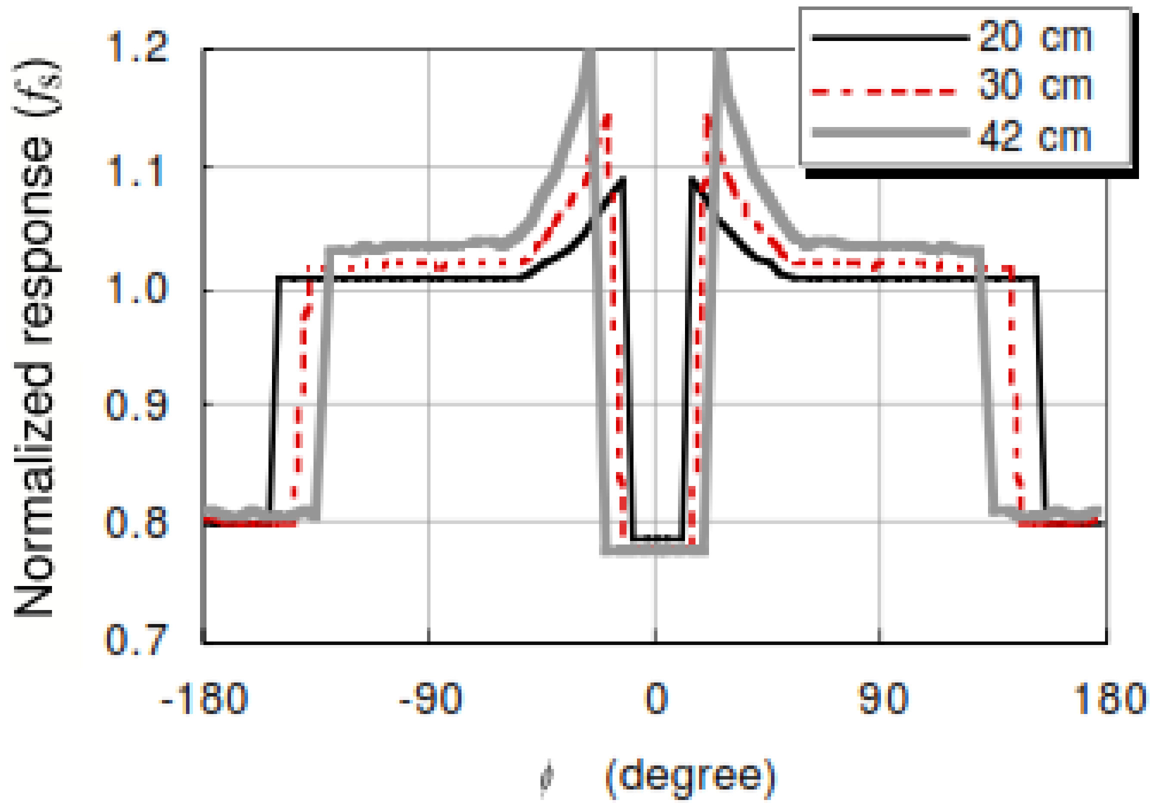
National Lighting Test Centre China

Understanding magnitude of errors: influencing factors

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

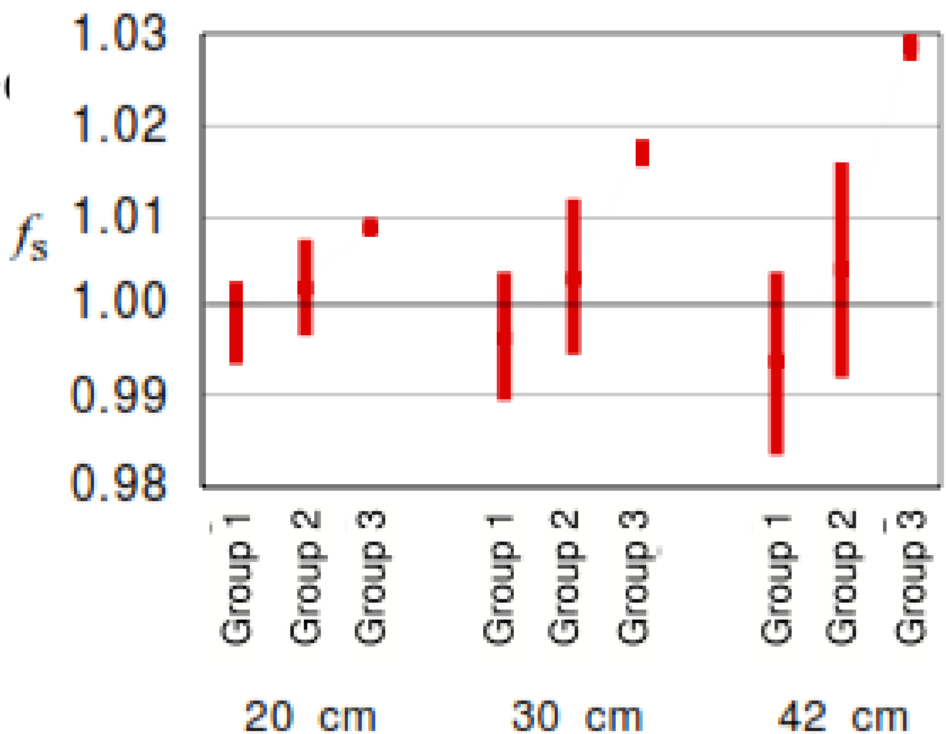
Understanding magnitude of error due to: Baffle Size

- Investigation of simulated SRDF curves for different baffle sizes



Understanding magnitude of error due to: Baffle Size

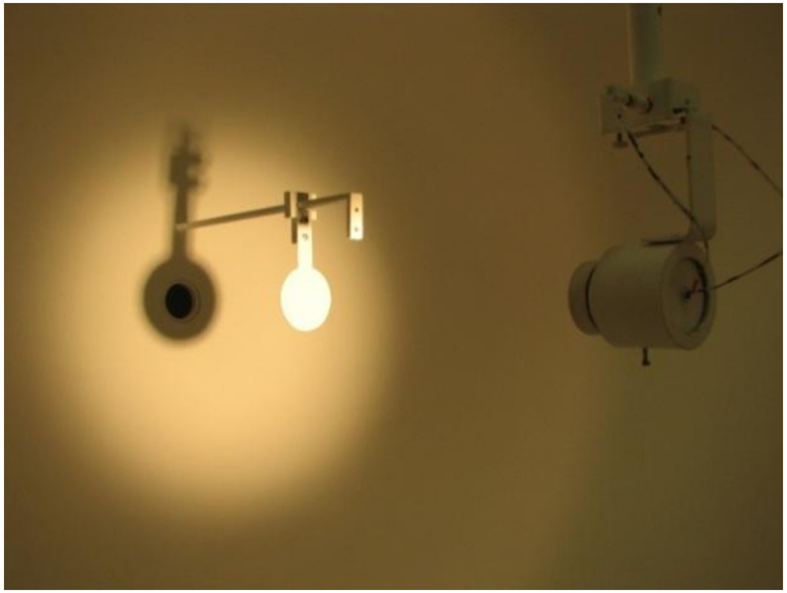
- Indicates that errors in the sphere response factor, f_s increase with increasing baffle size
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly downward



National Lighting Test Centre China

Understanding magnitude of error due to: Baffle Size/Location

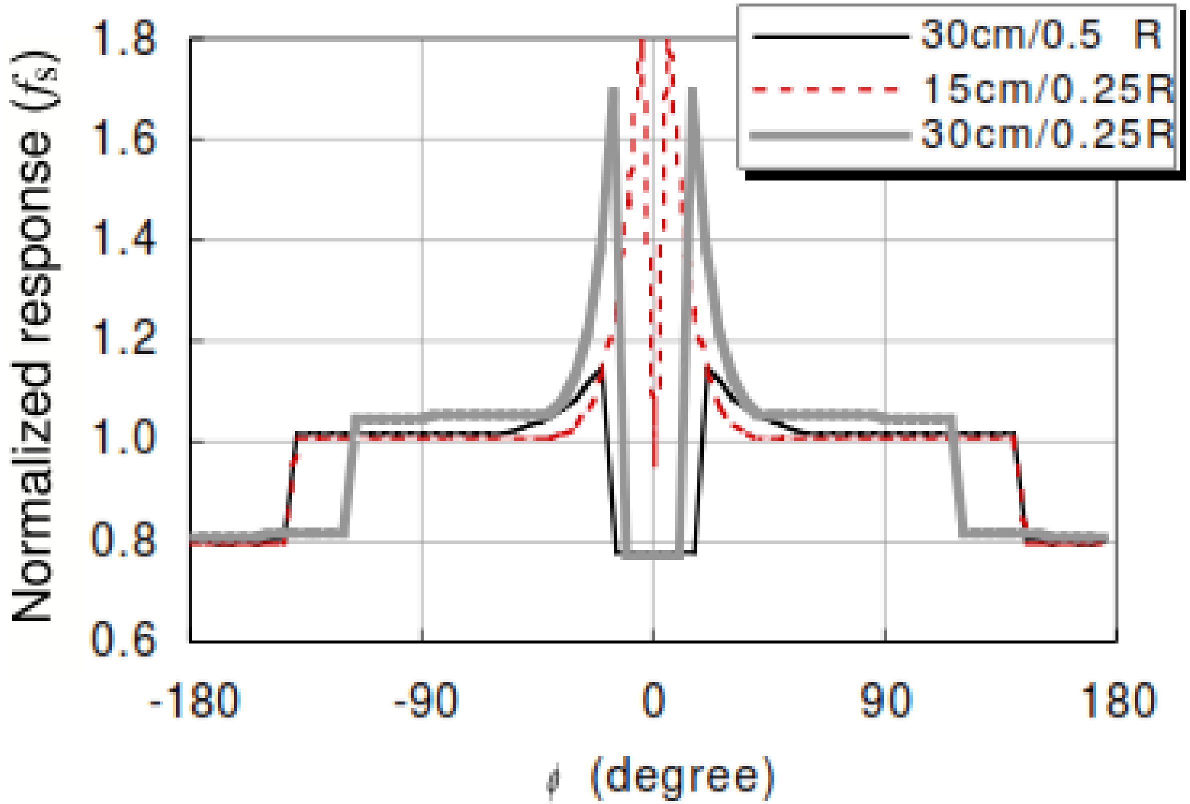
- Different baffle sizes/locations change shadow cone size around detector



National Lighting Test Centre China

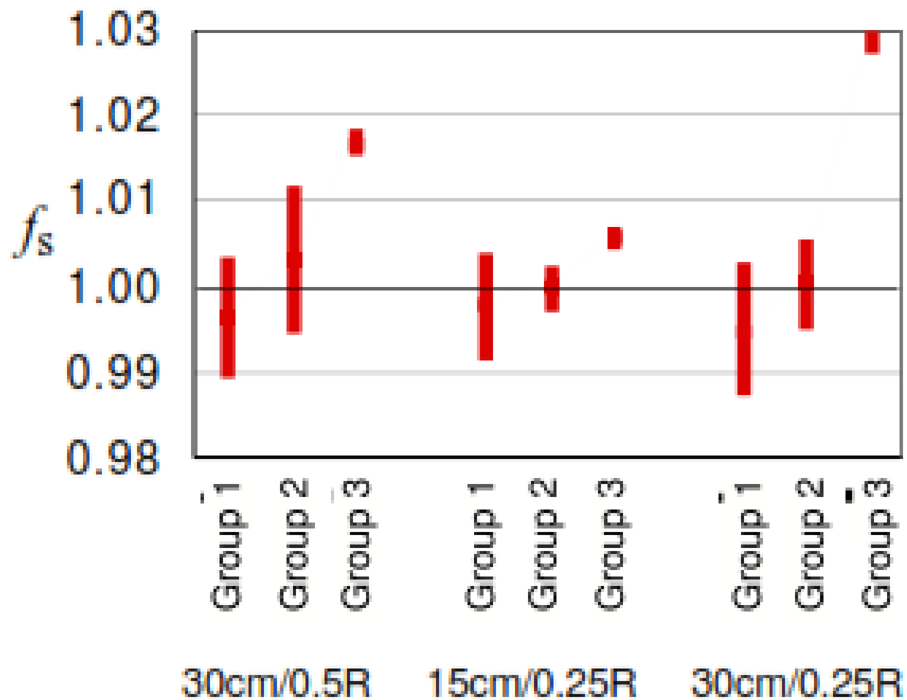
Understanding magnitude of error due to: Baffle Size/Location

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



Understanding magnitude of error due to: Baffle Size/Location

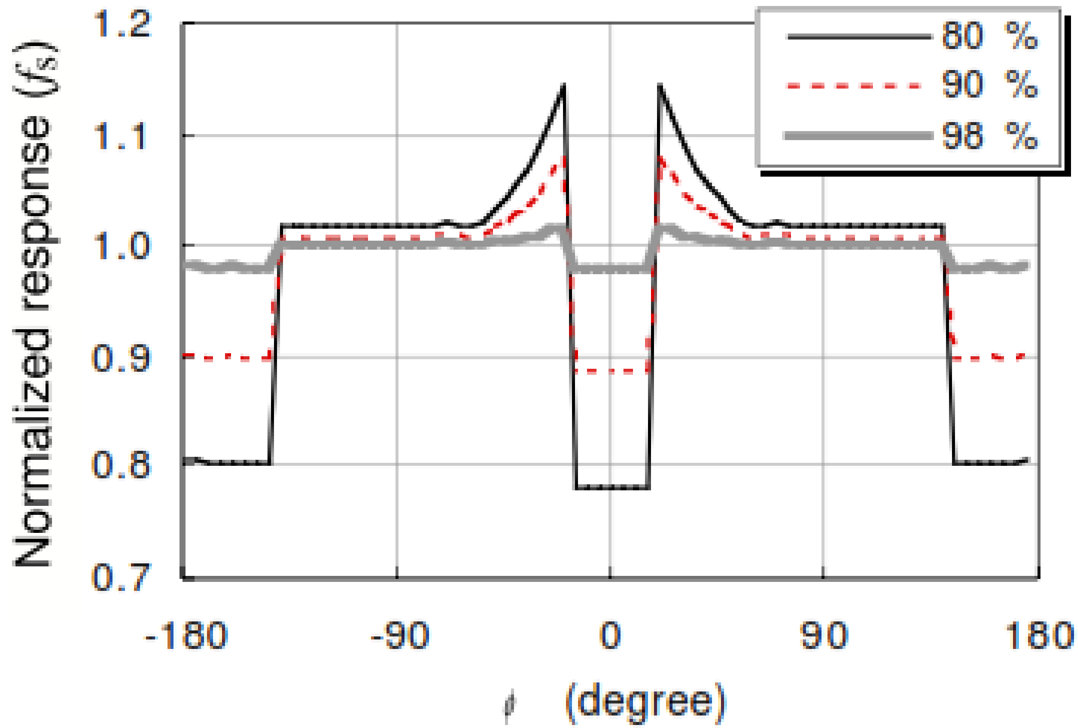
- Indicates that errors in the sphere response factor, f_s increase with 1/3 R to 1/2 R placement of the small baffle from detector
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly downward



National Lighting Test Centre China

Understanding magnitude of error due to: reflectance of sphere wall

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



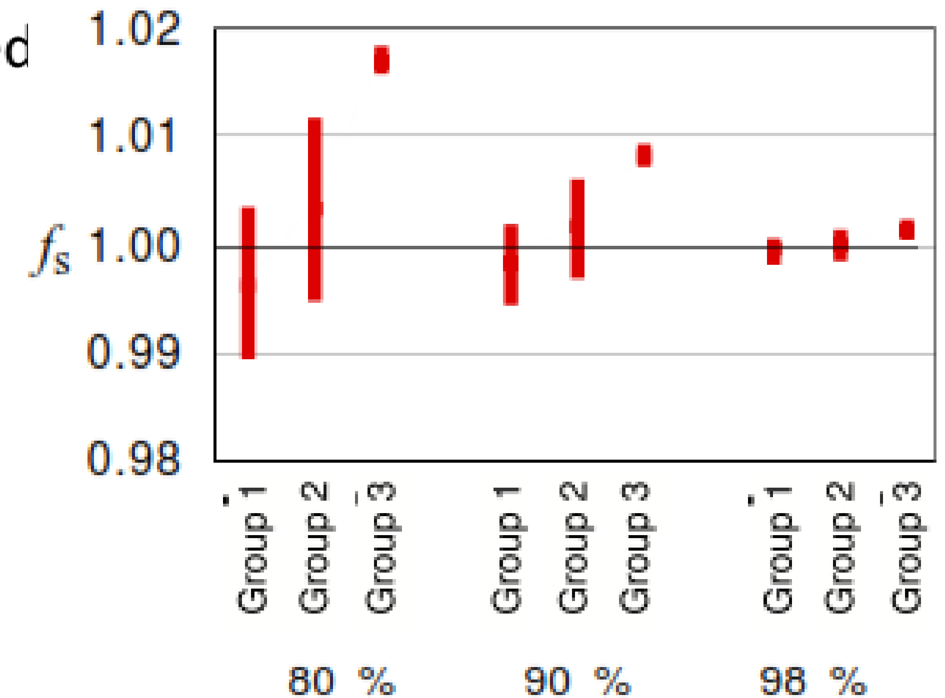
UNEP

National Lighting Test Centre China

UNEP Collaborating Centre for Energy Efficient Lighting

Understanding magnitude of error due to: reflectance of sphere wall

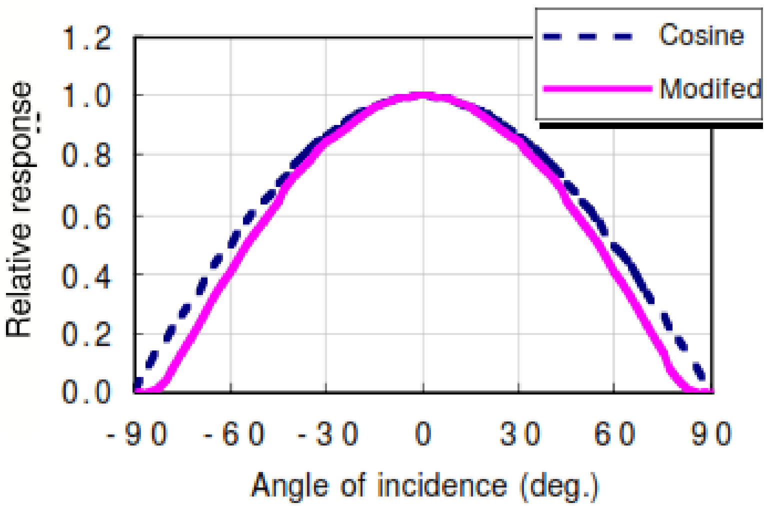
- Indicates that errors in the sphere response factor, f_s decrease with increasing reflectance
- Group 1: horizontally enhanced
- Group 2: vertically enhanced
- Group 3: highly downward

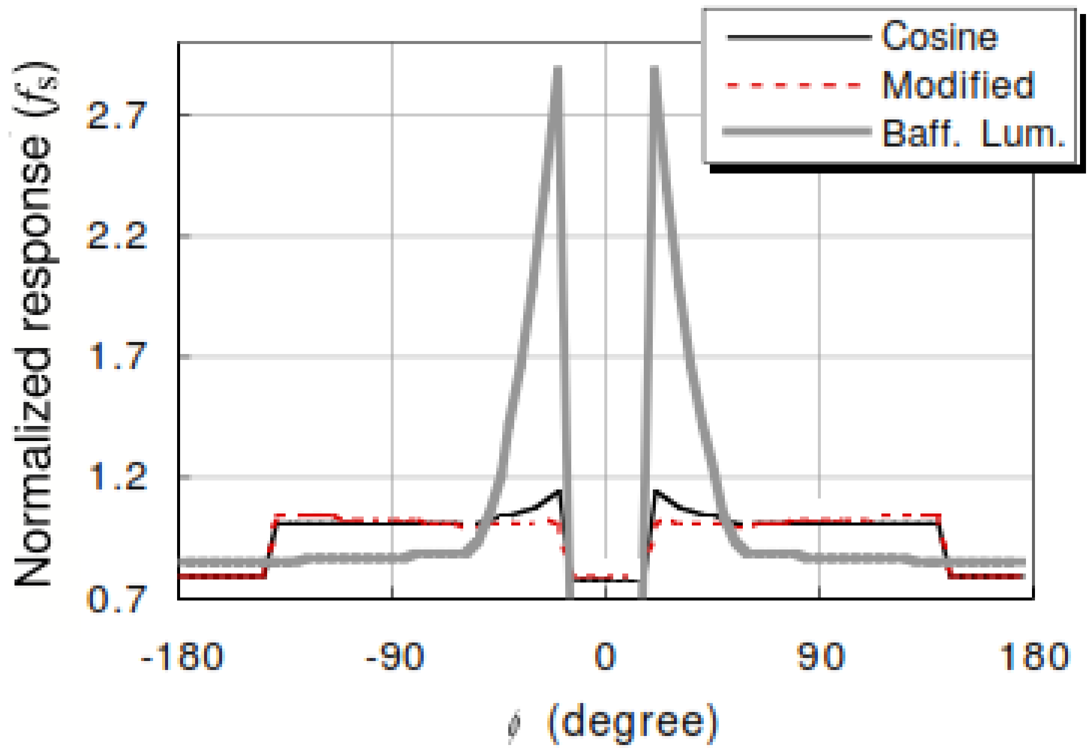


National Lighting Test Centre China

Understanding magnitude of error due to: detector angular response

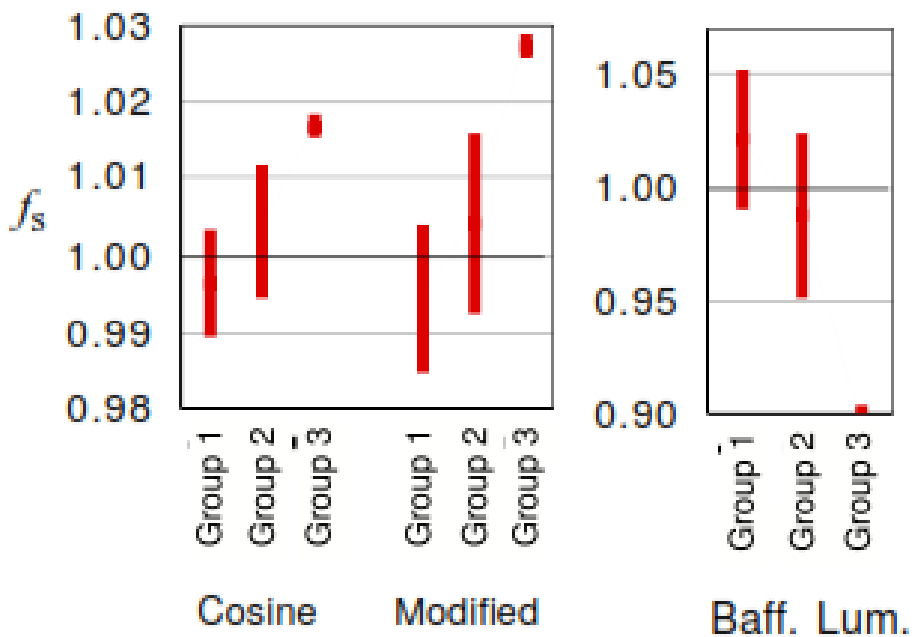
- Investigation of simulated SRDF curves for cosine, modified cosine and baffle FOV response





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 downward



Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

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.

National Lighting Test Centre China

Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

Practical considerations

- Test lamps should only be measured against standard reference lamps with the very similar angular distribution.
- So, 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?

National Lighting Test Centre China

Beam Angle Variations

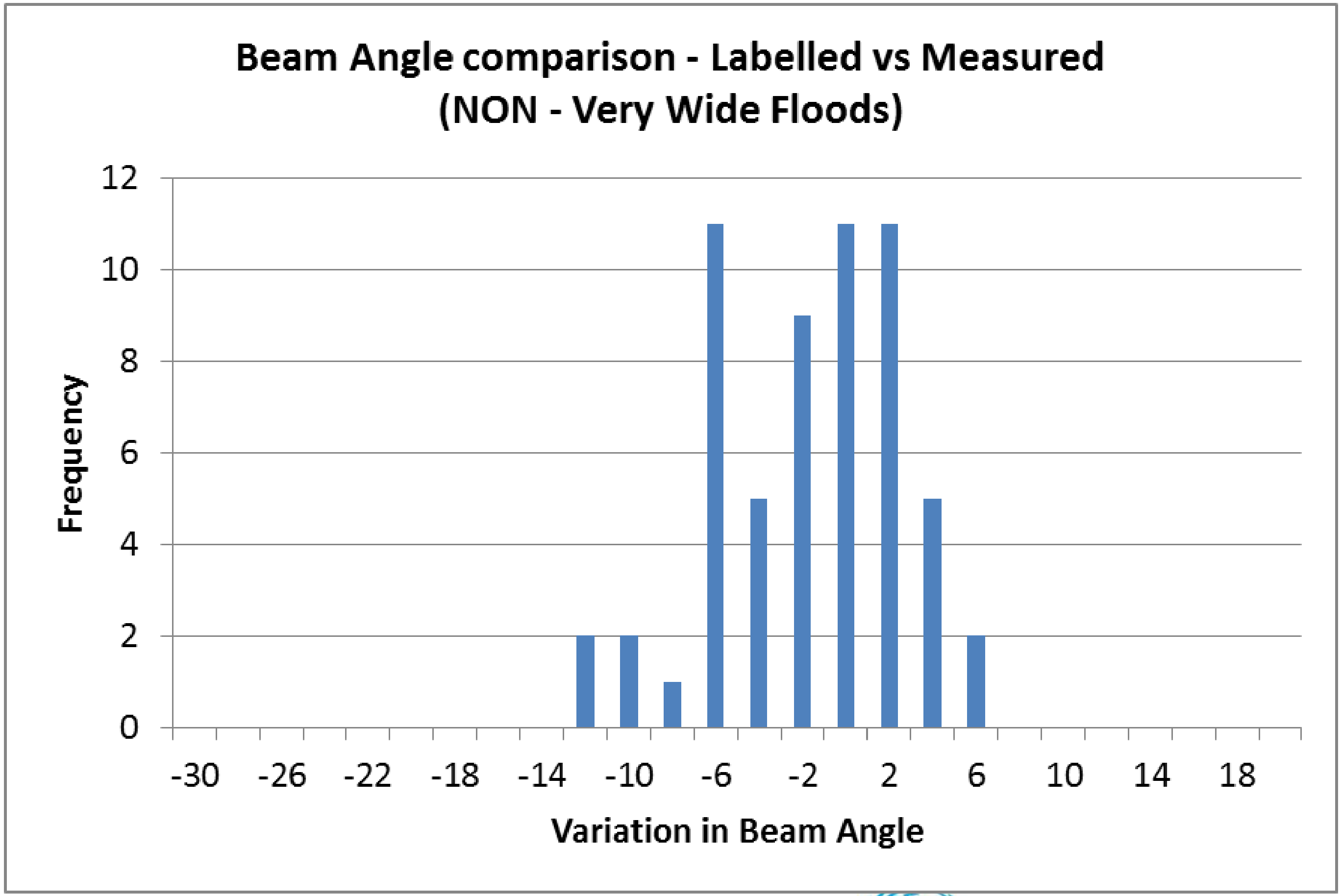
- Cannot assume that the rated beam angle is correct

- 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

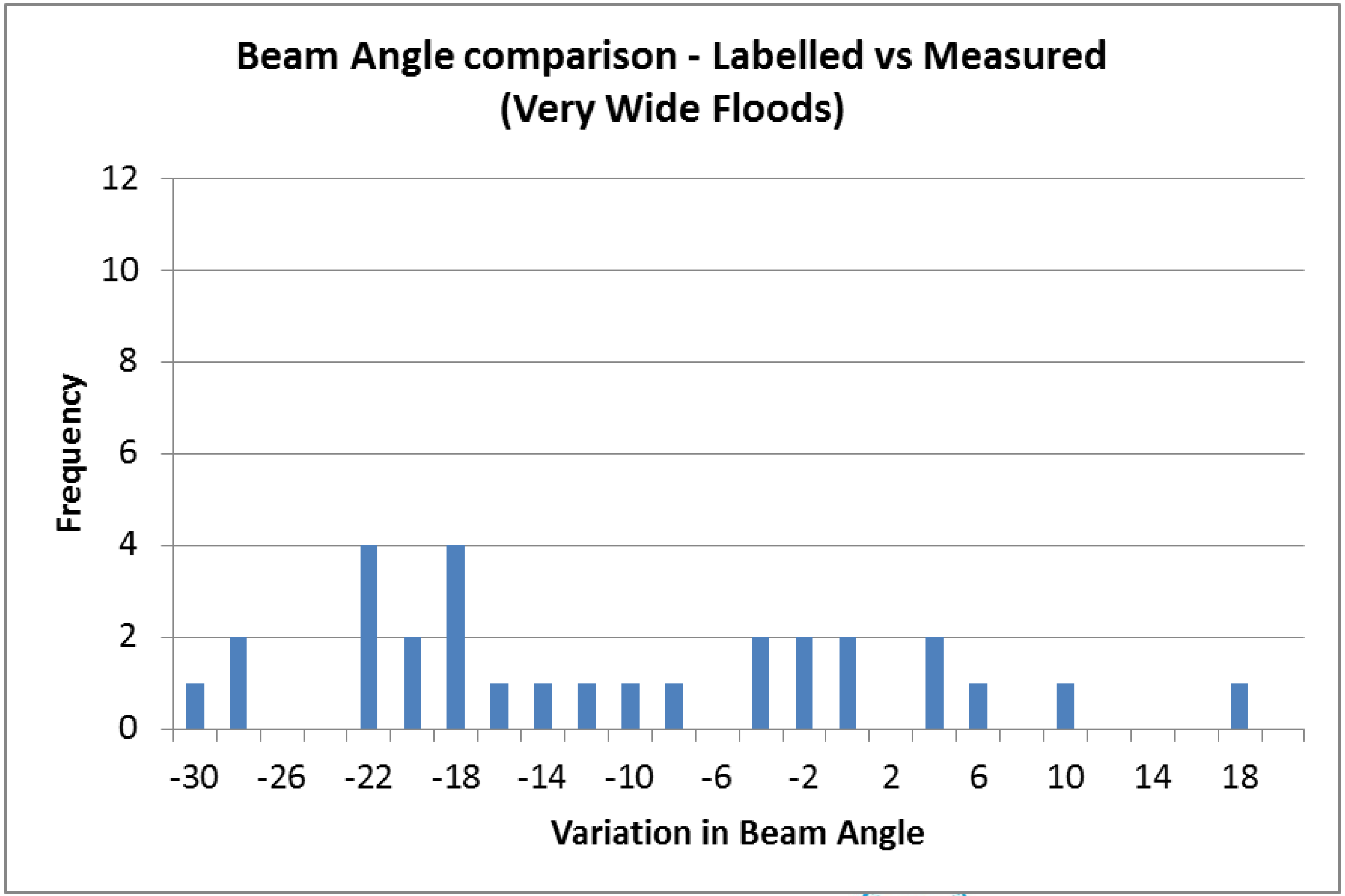
National Lighting Test Centre
China

Beam angle variations from marketplace



National Lighting Test Centre China

Beam angle variations from marketplace



UNEP GELC Global Efficient Lighting Centre

UNEP Collaborating Centre for Energy Efficient Lighting

Recommendations

- 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.

UNEP

nLTC National Lighting Test Centre China

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 ?