Integrating Sphere Photometers Designed for Solid State Lighting Measurement

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NEWRAD
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Outline

- Motivation
- Problems to be solved
  - Self-screening effect for a large area light source
  - Spatial mismatch error for a directive light source
- Method of numerical experiment
- Results for self-screening correction
- Results for spatial mismatch-free design
- Summary

Motivation

- Total luminous flux
  - measurand for luminous efficacy (lm/W)
  - key quantity for energy efficiency
- Solid state lighting (SSL) products
  - spatially directive sources
  - flat surface-emitting sources
- Integrating sphere (IS) photometer vs. Gonio-photometer
  - cost effective
  - fast measurement
  - reference standard required
  - specific errors to be corrected

Questions

1. Can we use an IS photometer for measuring a large-area surface-emitting source? (but please quick and easy…)

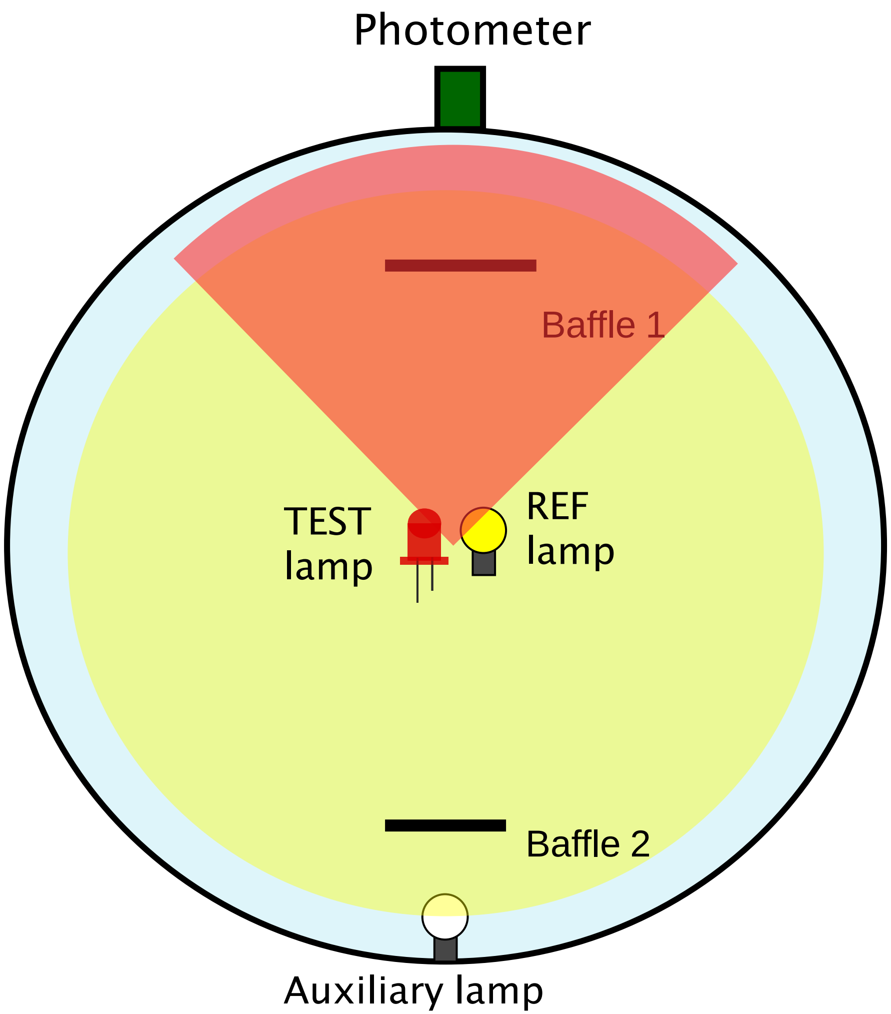
2. Is there no way to remove the “troublesome” procedure of spatial mismatch correction for a highly directive light source?

IS Photometer

$$\Phi_v^T = \frac{y^T}{y^R} \cdot \Phi_v^R \cdot k_{CCF} \cdot k_{SCF} \cdot k_{abs}$$

$$k_{abs} = \frac{y^{RA}}{y^{TA}}$$

- spectral mismatch correction (k_{CCF})
- spatial mismatch correction (k_{SCF})
- self-absorption correction (k_{abs})



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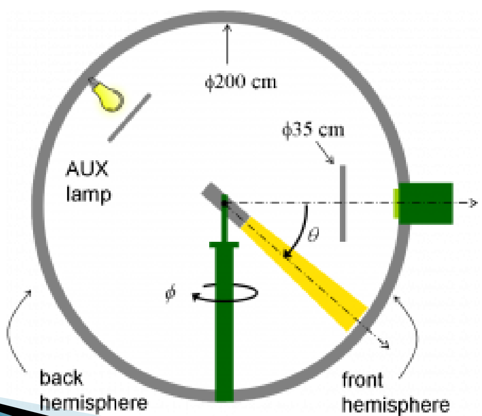
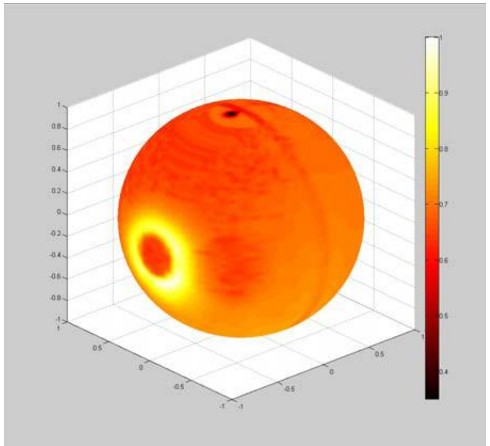
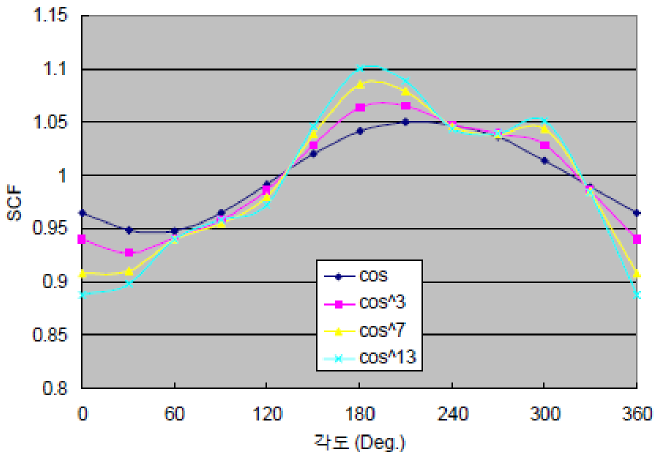
Spatial Mismatch Error

- Accurate correction possible <u>only if</u> the following information available:
  - spatial response distribution function (SRDF) of the IS photometer
  - angular distribution of the test source







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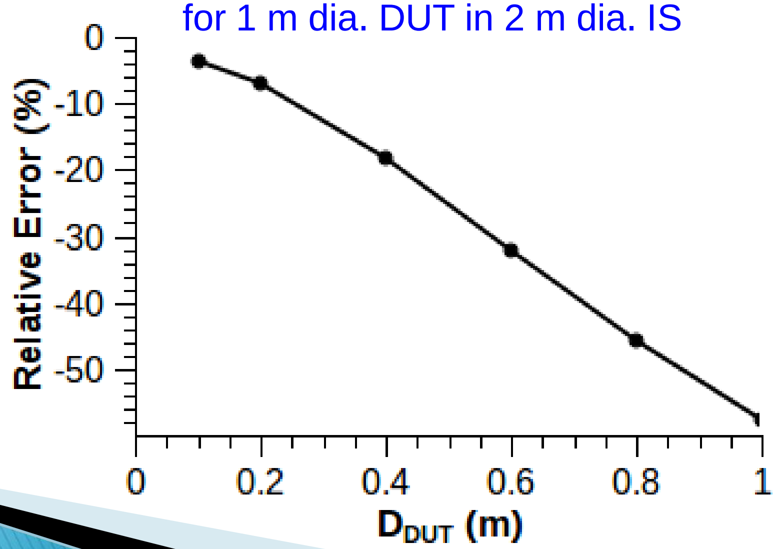
Self-Screening Effect

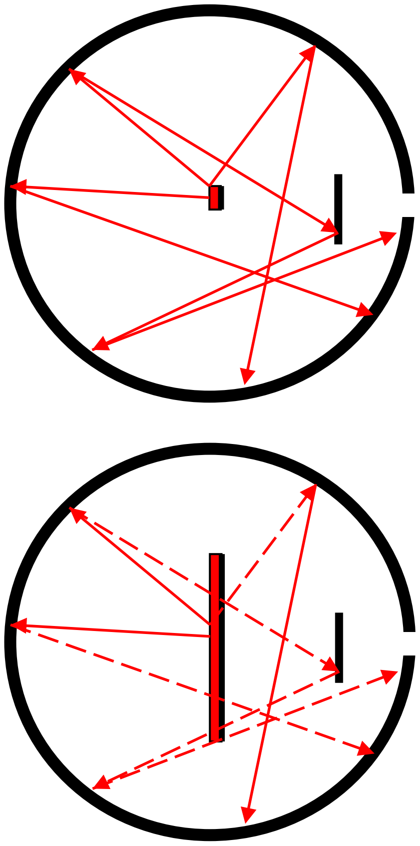
- Additional error for a large-area (surface-emitting) source
- Test source acts as a low-reflectance baffle

  → change of radiation transfer pattern

  → change of the IS response

Error in luminous flux > 50 %
for 1 m dia. DUT in 2 m dia. IS

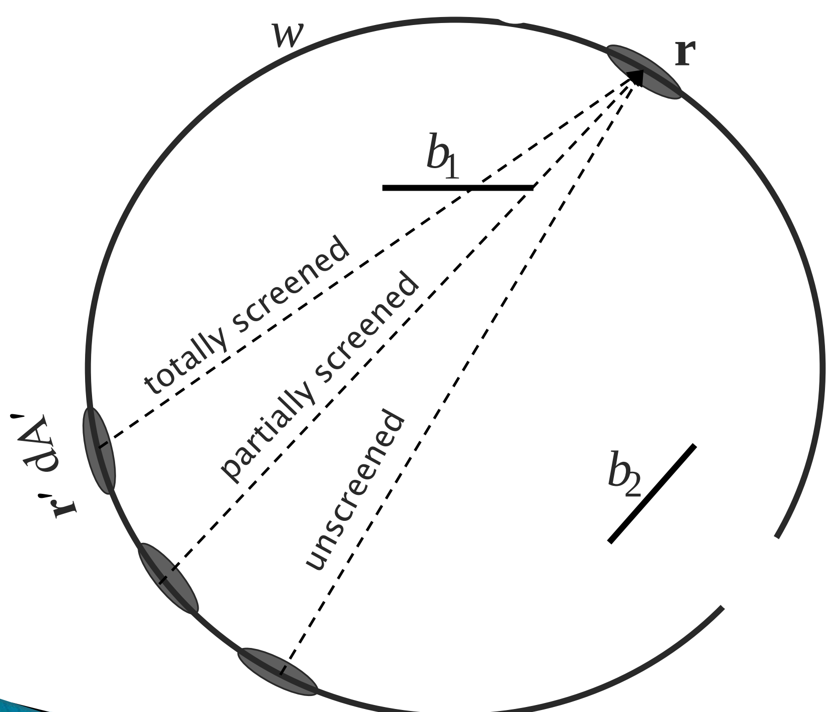




Numerical Experiment

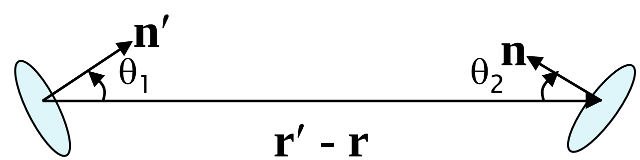
Radiative Transfer Equation

$$E_i(\mathbf{r}) = \frac{1}{\pi} \iint_{w,b1,b2} \rho(\mathbf{r}') E_{i-1}(\mathbf{r}') S(\mathbf{r},\mathbf{r}') T(\mathbf{r},\mathbf{r}') dA', \quad E(\mathbf{r}) = \sum_{i=0}^{\infty} E_i(\mathbf{r}).$$



- $\mathbf{r}, \mathbf{r}' \in w, b_1, b_2$
- Screening function, $S(\mathbf{r}, \mathbf{r}')$
  - fully screened, $S(\mathbf{r}, \mathbf{r}') = 0$
  - fully unscreened, $S(\mathbf{r}, \mathbf{r}') = 1$
  - partially screened, $0 < S(\mathbf{r}, \mathbf{r}') < 1$
- Transfer function, $T(\mathbf{r}, \mathbf{r}')$

$$T(\mathbf{r},\mathbf{r}') = \frac{|\mathbf{n}' \cdot (\mathbf{r}' - \mathbf{r})||\mathbf{n} \cdot (\mathbf{r}' - \mathbf{r})|}{|\mathbf{r}' - \mathbf{r}|^4} = \frac{\cos\theta_1 \cos\theta_2}{|\mathbf{r}' - \mathbf{r}|^2}$$



Y. Ohno, Applied Optics 33, 2637 (1994)

Numerical Experiment

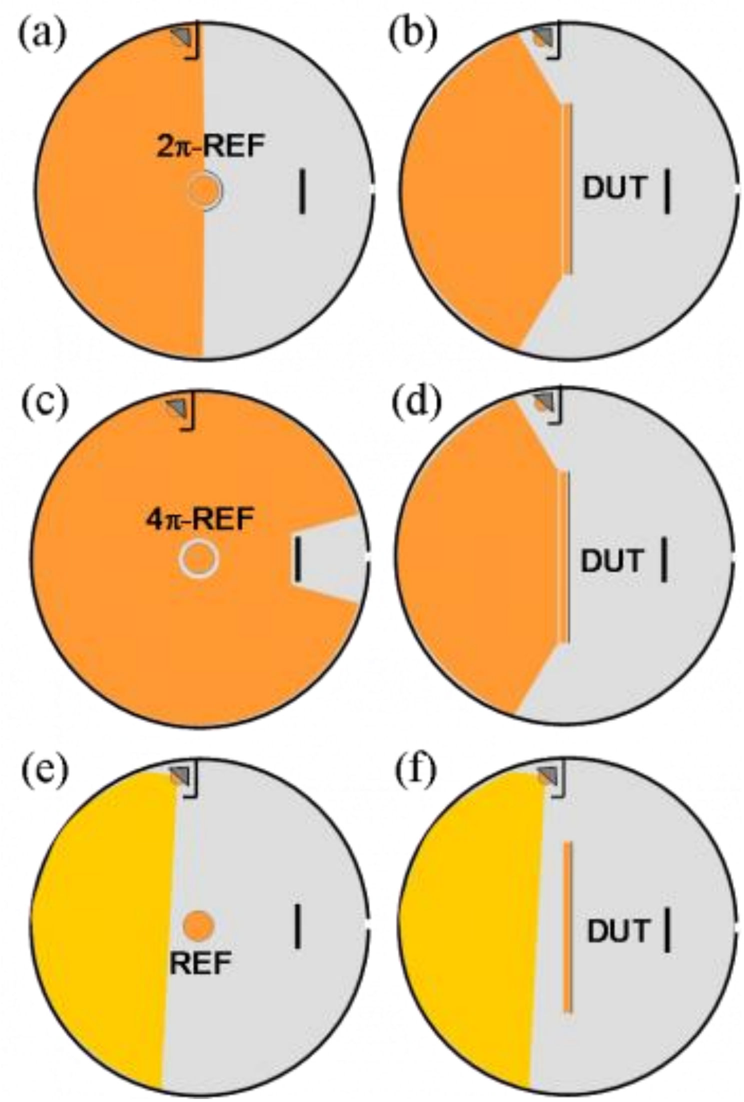
- Commercial ray-tracing simulator (LightTools™)
  - based on Monte-Carlo Method
  - applicable to non-Lambertian surface.
  - no limits on internal structures. e.g. baffles, openings
- Direct Integration by iteration method (home-made)
  - vectorized codes in MATLAB™
  - equal-area mesh generation: up to 5000 elements
  - partial screening effect handling by taking additional sub-meshes
  - procedures:
    1. mesh generation (5000 elements, 1 s for a AMD64 PC)
    2. screening and transfer function calculation (5000 elements, 3 min.)
    3. iteration (5000 elements, 30 s) to get $E(\mathbf{r})$
    4. if necessary, repetition of step 3 for other calculation points $\mathbf{r}$

Results for Self-Screening Correction

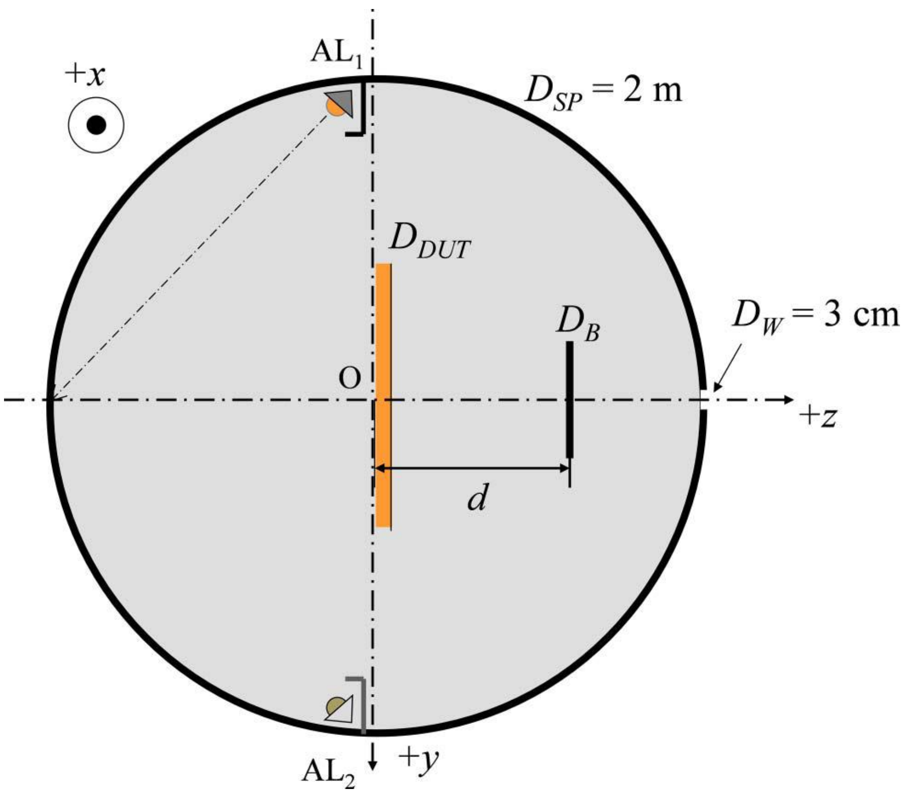
S. Park et al., Applied Optics 49, 3831 (2010)

Idea

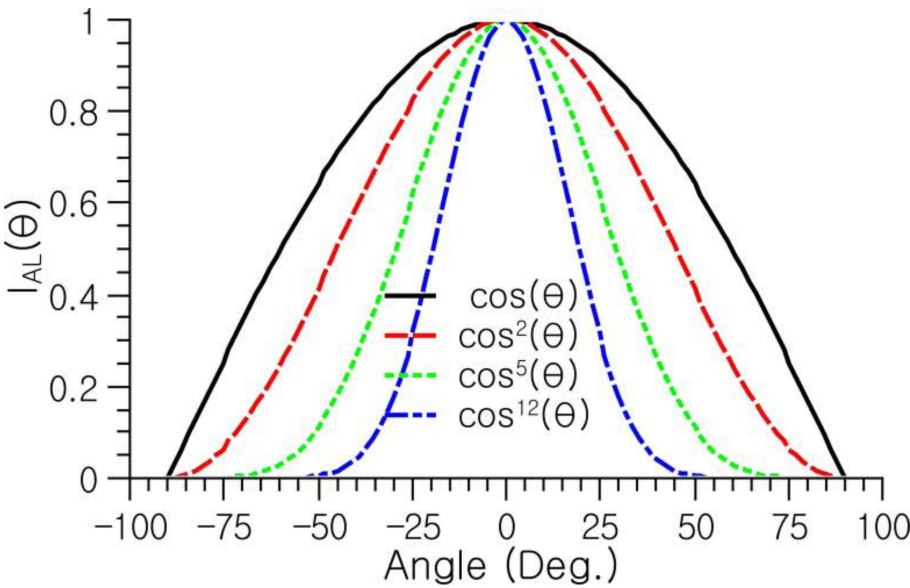
- Main Idea: match the spatial distribution of <u>auxiliary lamp </u>to that of the test lamp
  - usually 2π half-sphere illumination for surface-emitting sources
  - easy to realize
  - no influence on other conditions
- Self-absorption correction automatically corrects the self-screening effect
  - proved by numerical experiment



Simulation Design

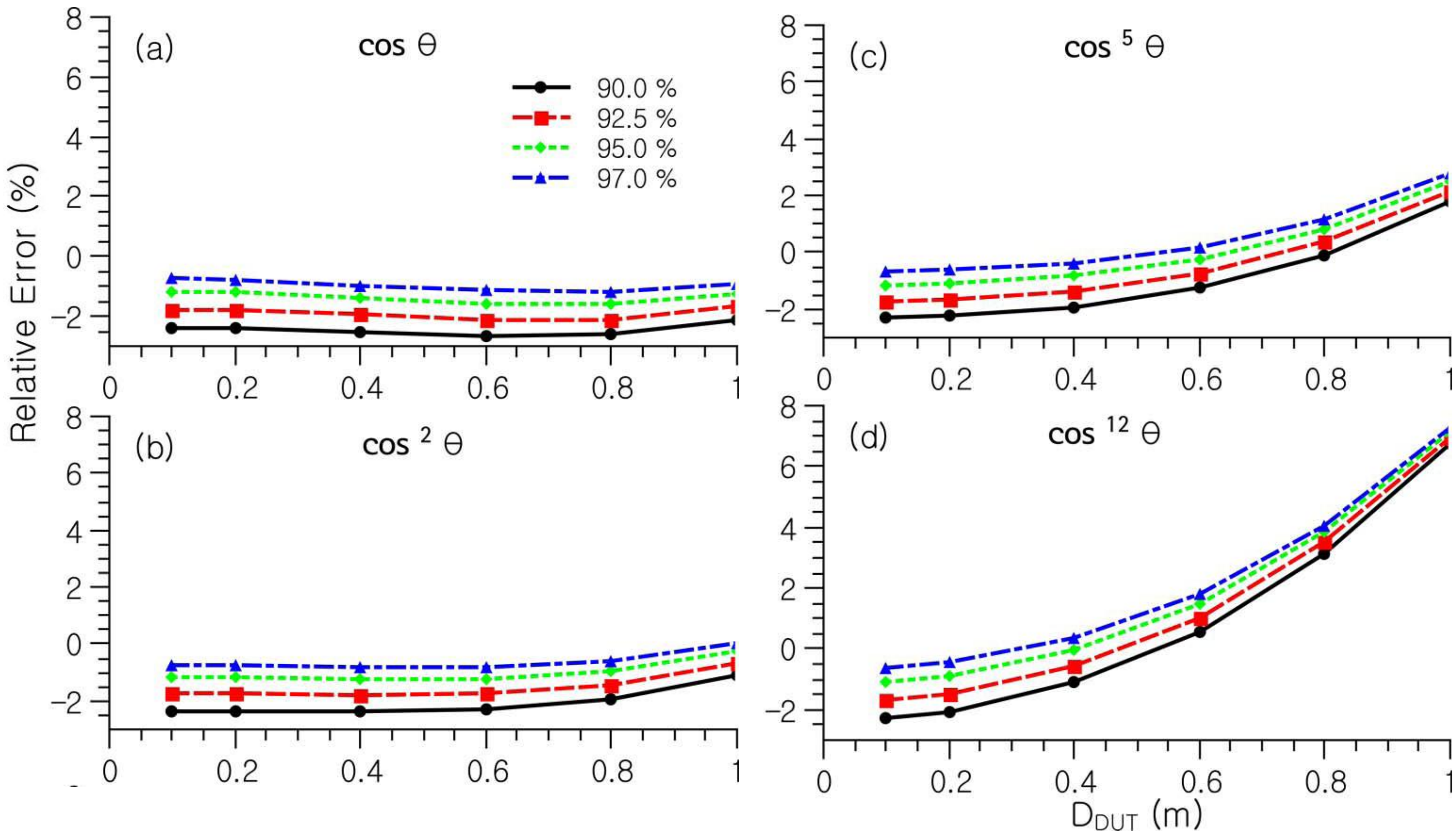


Dimension of IS under experiment



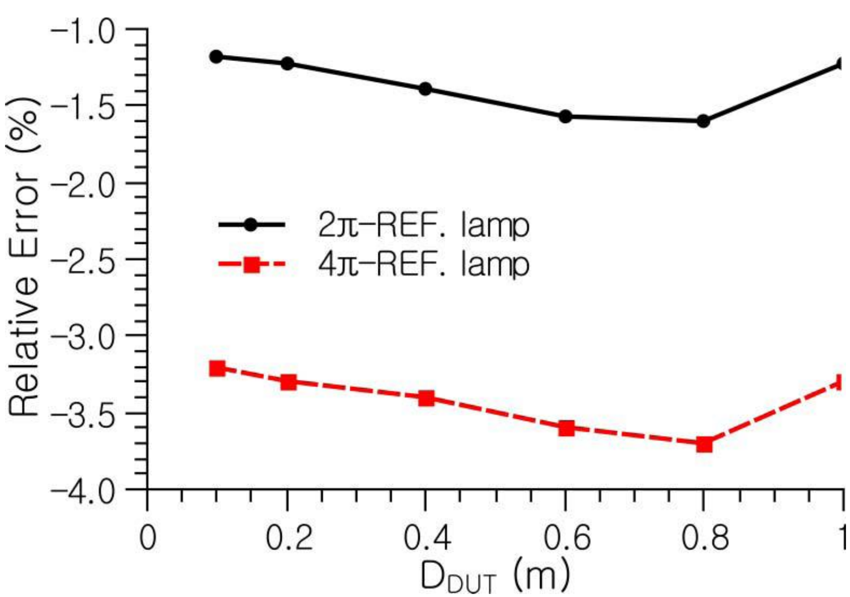
Angular distribution of auxiliary lamp

Self-Screening Correction Results

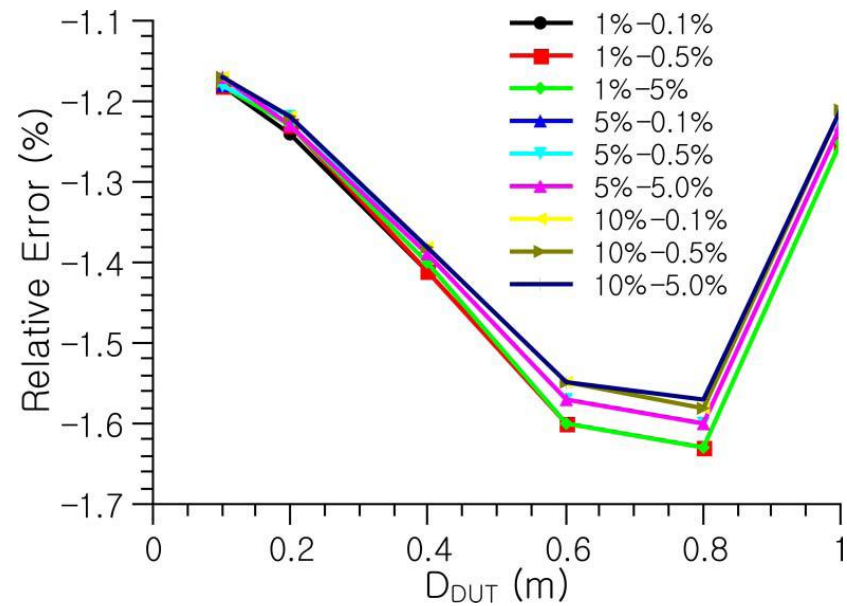


Relative residual error of total luminous flux as a function of the diameter of a SLS-DUT for the case that the self-screening correction is applied using one auxiliary lamp with the angular distribution of (a) cos θ, (b) $\cos^2\theta$, (c) $\cos^5\theta$, and (d) $\cos^{12}\theta$.

Self-Screening Correction Results

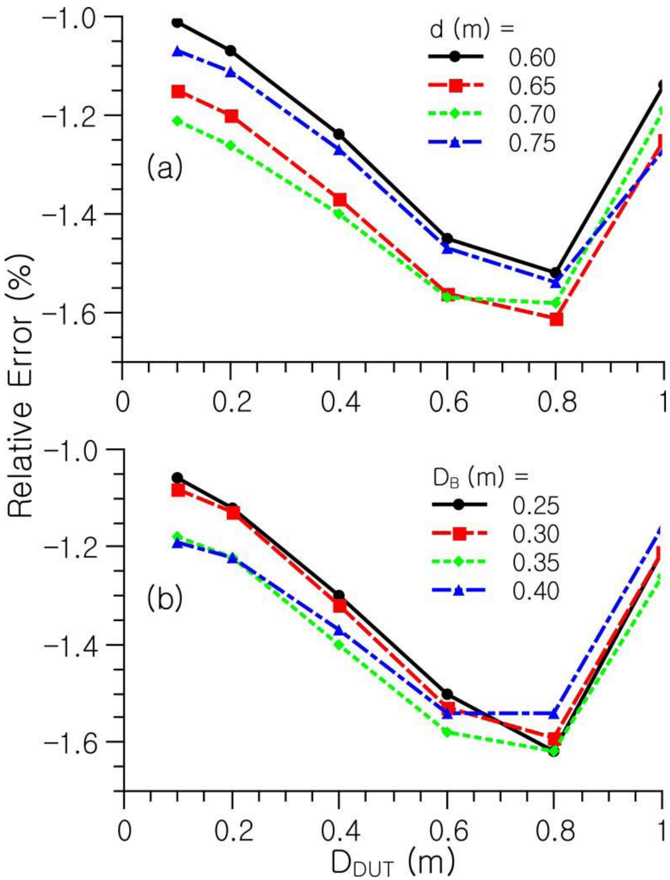


Comparison of the relative residual errors after self-screening correction between the case using a 2π REF (black circles) and the case using a 4π REF (red squares)



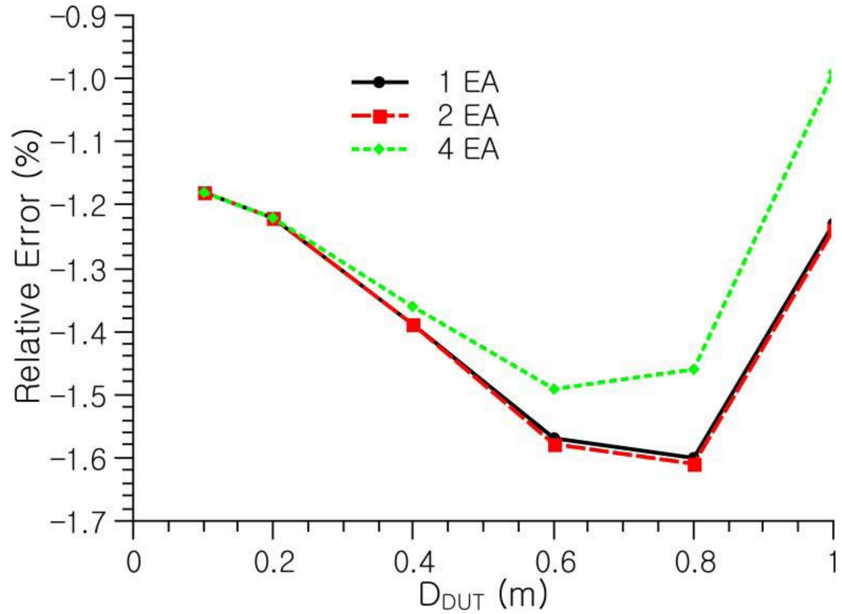
Error as a function of the diameter of a SLS-DUT after the self-screening correction using one cos θ auxiliary lamp for different values of the reflectance of the front/rear surface of the SLS-DUT.

Self-Screening Correction Results



Error for different values of (a) distance d of the baffle from the SLS-DUT, and (b) diameter D_B of the baffle.

Error due to self-screening corrected to < 2 %



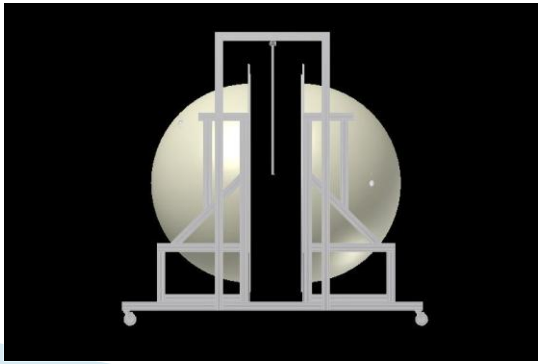
Error for using one, two, and four auxiliary lamp(s) with the cos θ distribution.

Proof Experiment (on-going)

Test source consisting of 17 white LEDs (40 mA) in series mounted on a 1 m x 1 m frame. The sum of TLF was approximately 125 lm.

Test source mounted inside the 2 m IS photometer.

Screening of the test source to investigate the self-screening effect of a surface-emitting source.



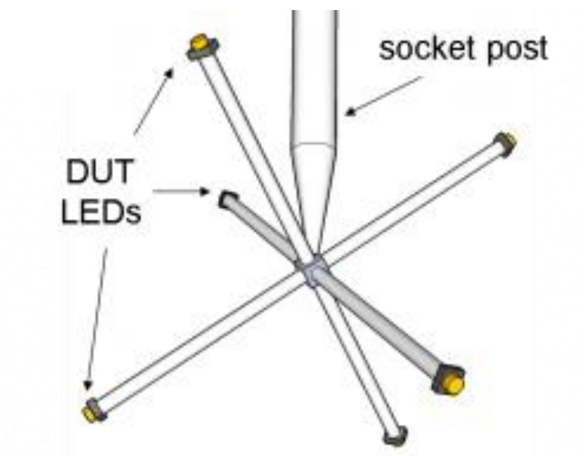
(New Ø 2 m IS photometer to be installed in Oct 2011)

Results for Spatial Mismatch-free Design

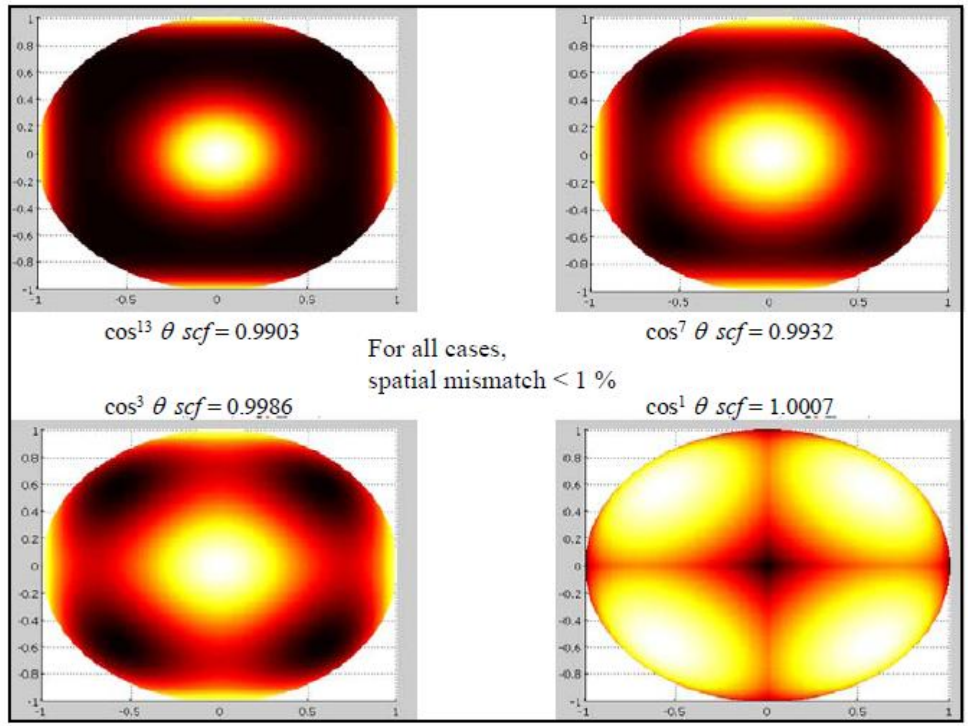
S. Park et al., Applied Optics 50, 2220 (2011)

Multiple Lamp Socket

- Idea #1: mount multiple test sources to make a uniform distribution of test lamp → Multi-LED socket



Spatial mismatch error reduced to < 1 %

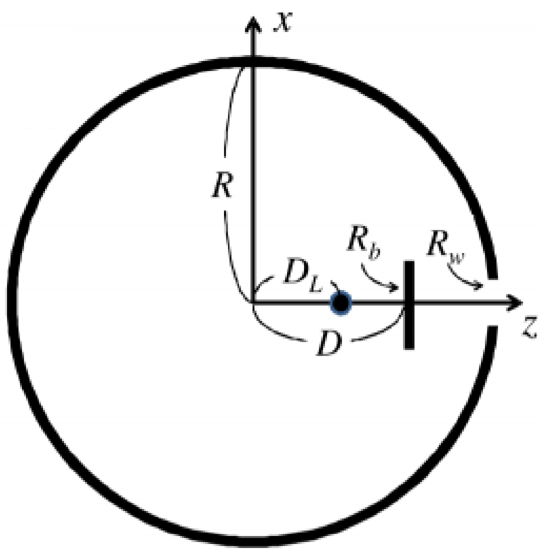


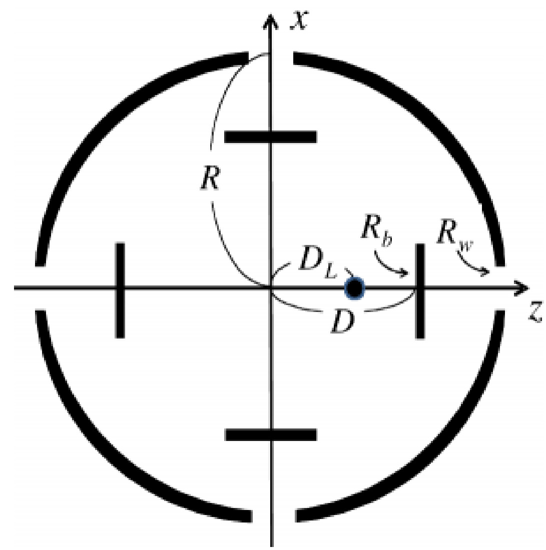
Irradiance distribution and SCF for different angular patterns of test LEDs

S. Park et al., CIE session 2011

Multi-port Design

- Idea #2: install mutiple detectors to make a uniform response of the IS photometer → a universal solution!

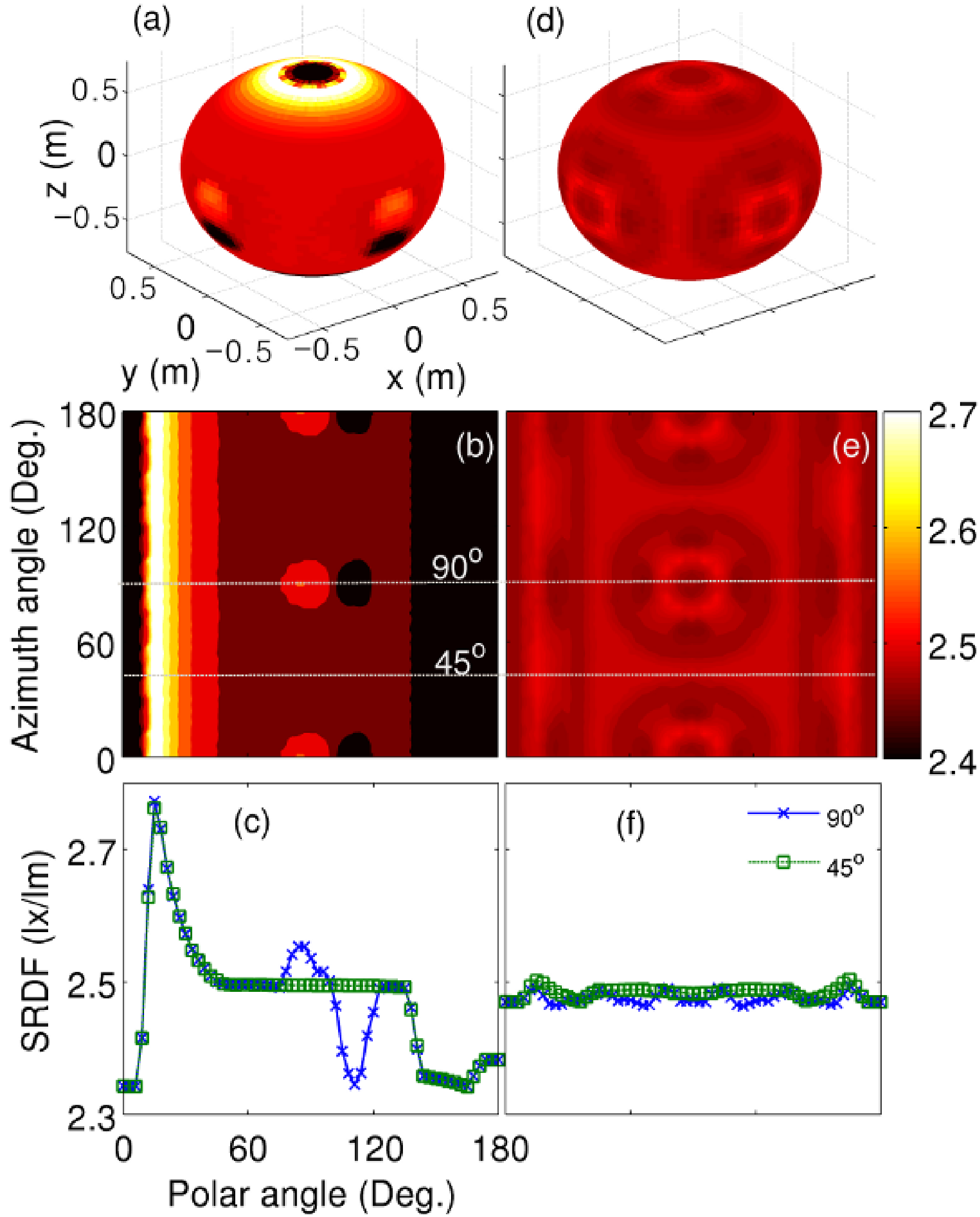




$$K_{1p}(\theta,\phi)=\frac{E_w}{\Phi_{beam}(\theta,\phi)}$$

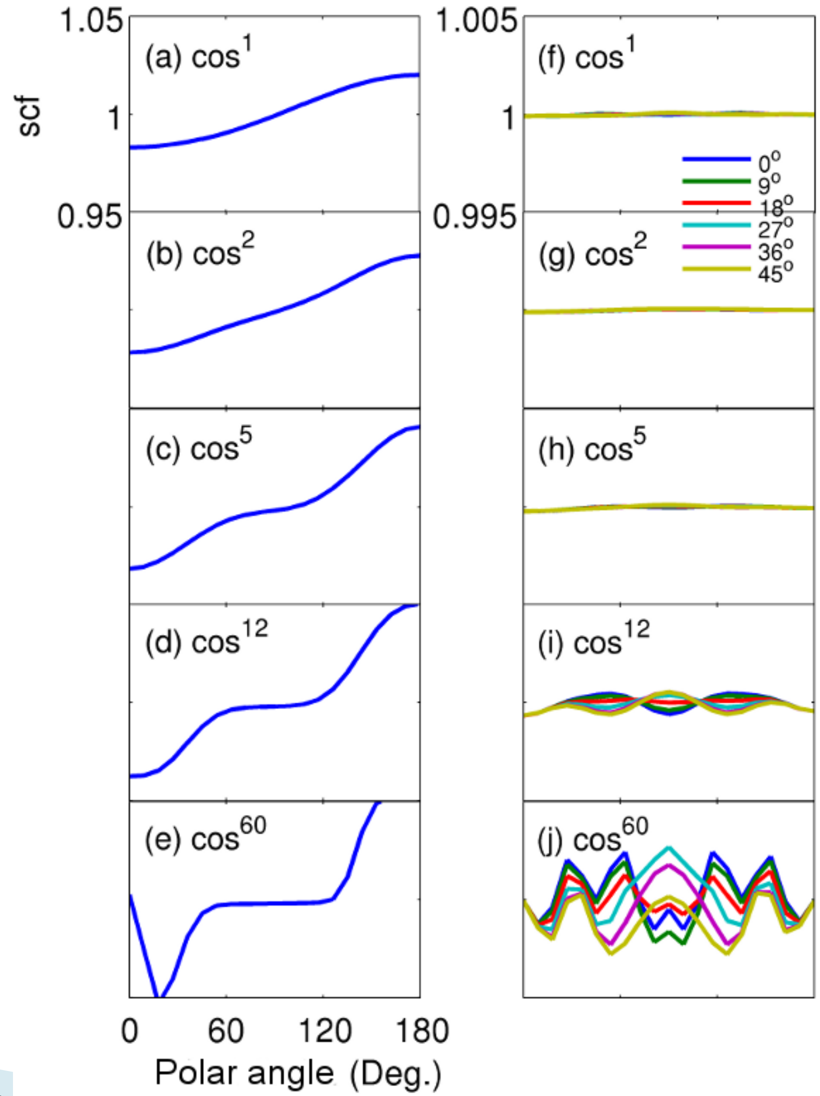
$$K_{6p}(\theta,\phi)=\frac{1}{6}\sum_{i=1}^{6}K_{6p,i}(\theta,\phi)\equiv\frac{1}{6}\sum_{i=1}^{6}\frac{E_{w,i}}{\Phi_{beam}(\theta,\phi)}$$

$$K_{6p}(\theta,\phi)\approx\frac{1}{6}\left\{K_{1p}[+z](\theta,\phi)+K_{1p}[-z](\theta,\phi)+K_{1p}[+x](\theta,\phi)+K_{1p}[-x](\theta,\phi)+K_{1p}[+y](\theta,\phi)+K_{1p}[-y](\theta,\phi)\right\}$$



Single-port vs. 6-port SRDF calculated by numerical simulation with ρ = 95 %, R = 0.75 m, R_b = (1/4) x R, R_w = 0.025 m, D = (2/3) x R, and D_L = 0.

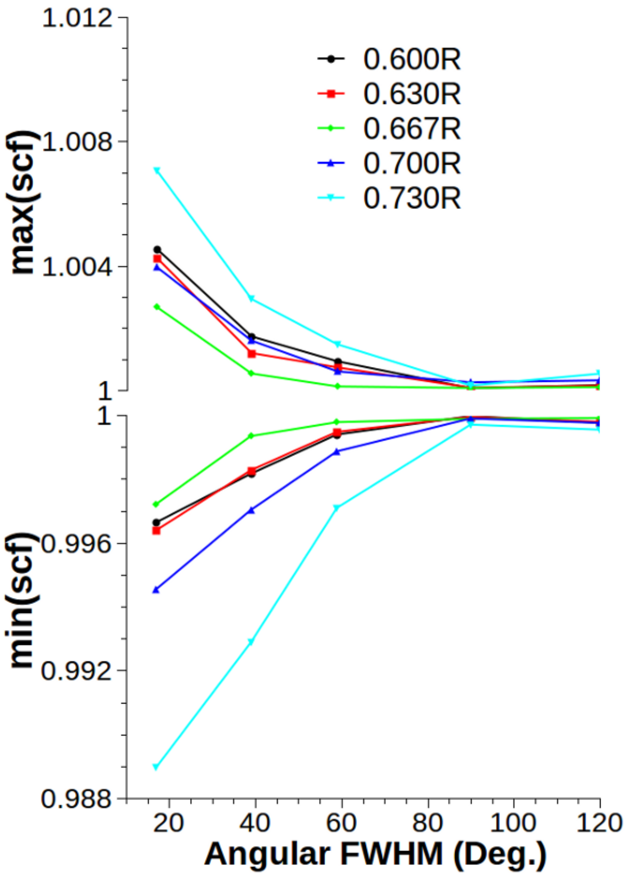
Spatial Correction Factor



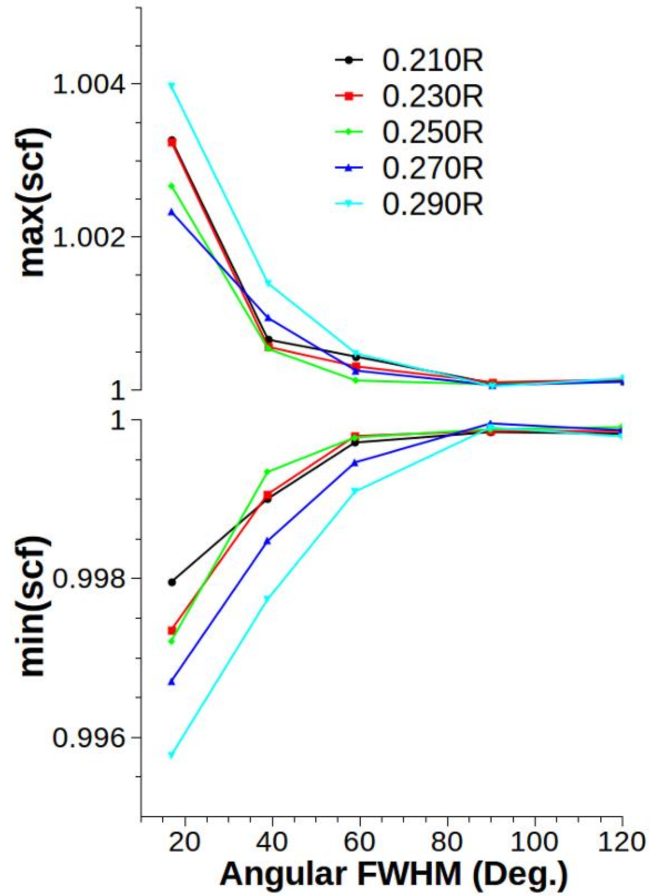
Spatial mismatch error reduced to < 0.5 %

Single-port vs. 6-port SCF for different angular distributions of a test source.

Parameter Dependence

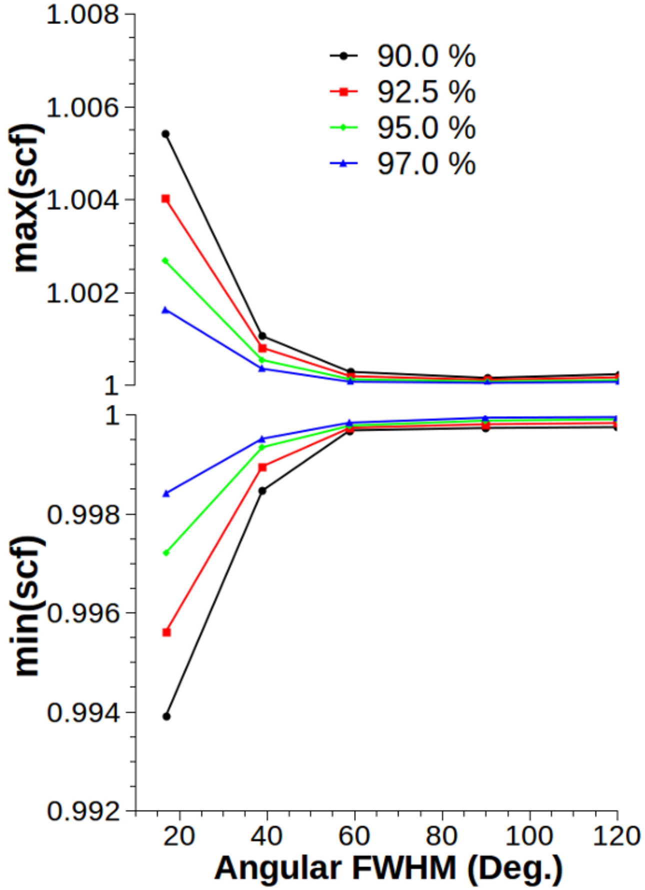


SCF dependence on baffle position *D*
(*R* is the radius of the sphere.)

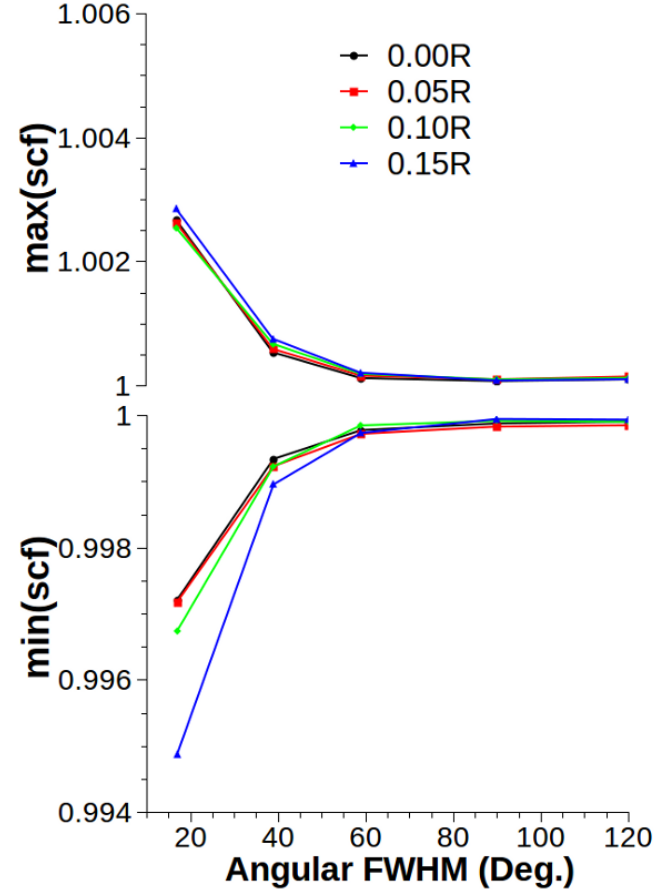


SCF dependence on baffle radius R_b
(*R* is the radius of the sphere.)

Parameter Dependence

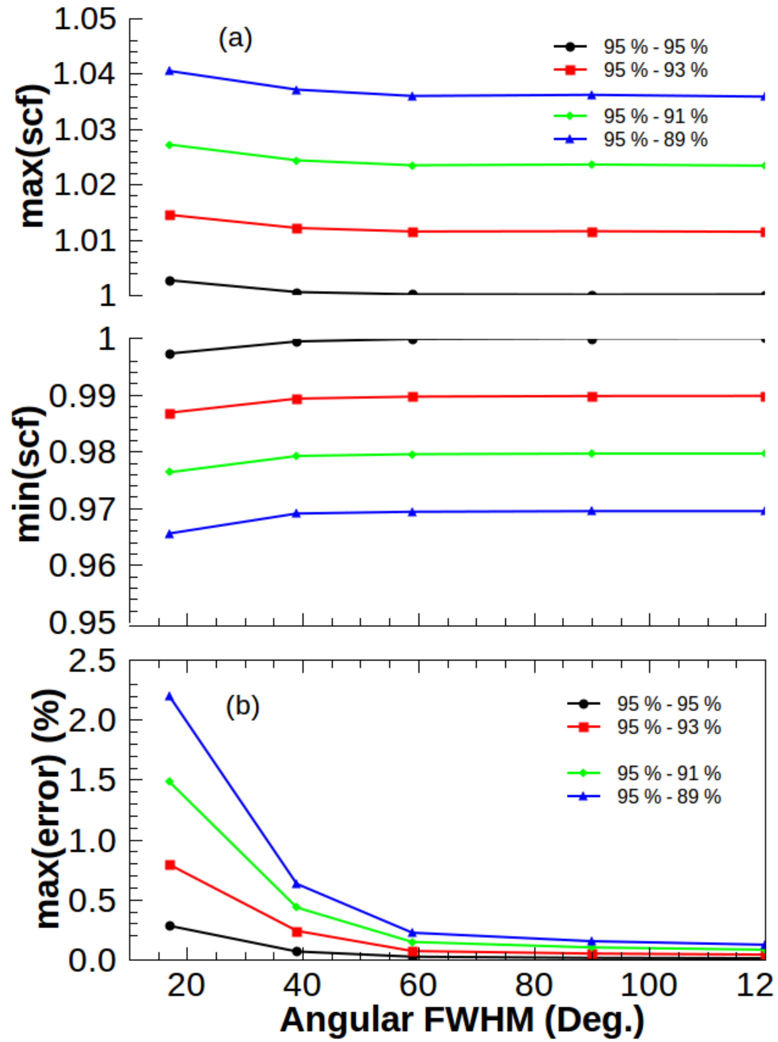


SCF dependence on wall reflectance ρ



SCF dependence on test lamp position D_L. (R is the radius of the sphere.)

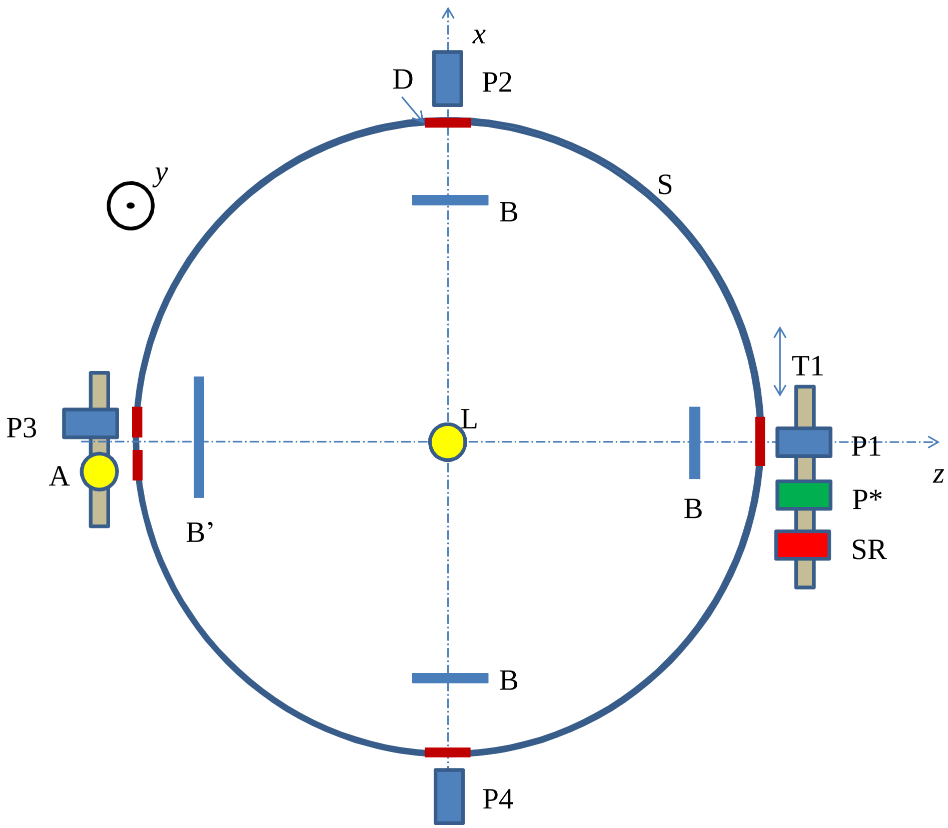
Effect of Contamination

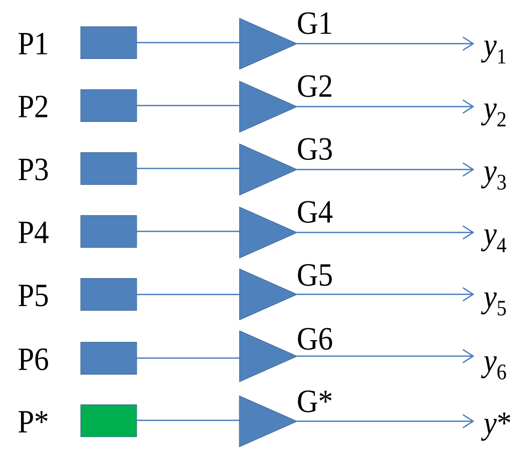


SCF error due to ρ difference between upper and lower hemisphere.

SCF error after correction based on approximation: $K(\theta,\phi) \propto \rho_{1st}(\theta,\phi)$

Realization Concept

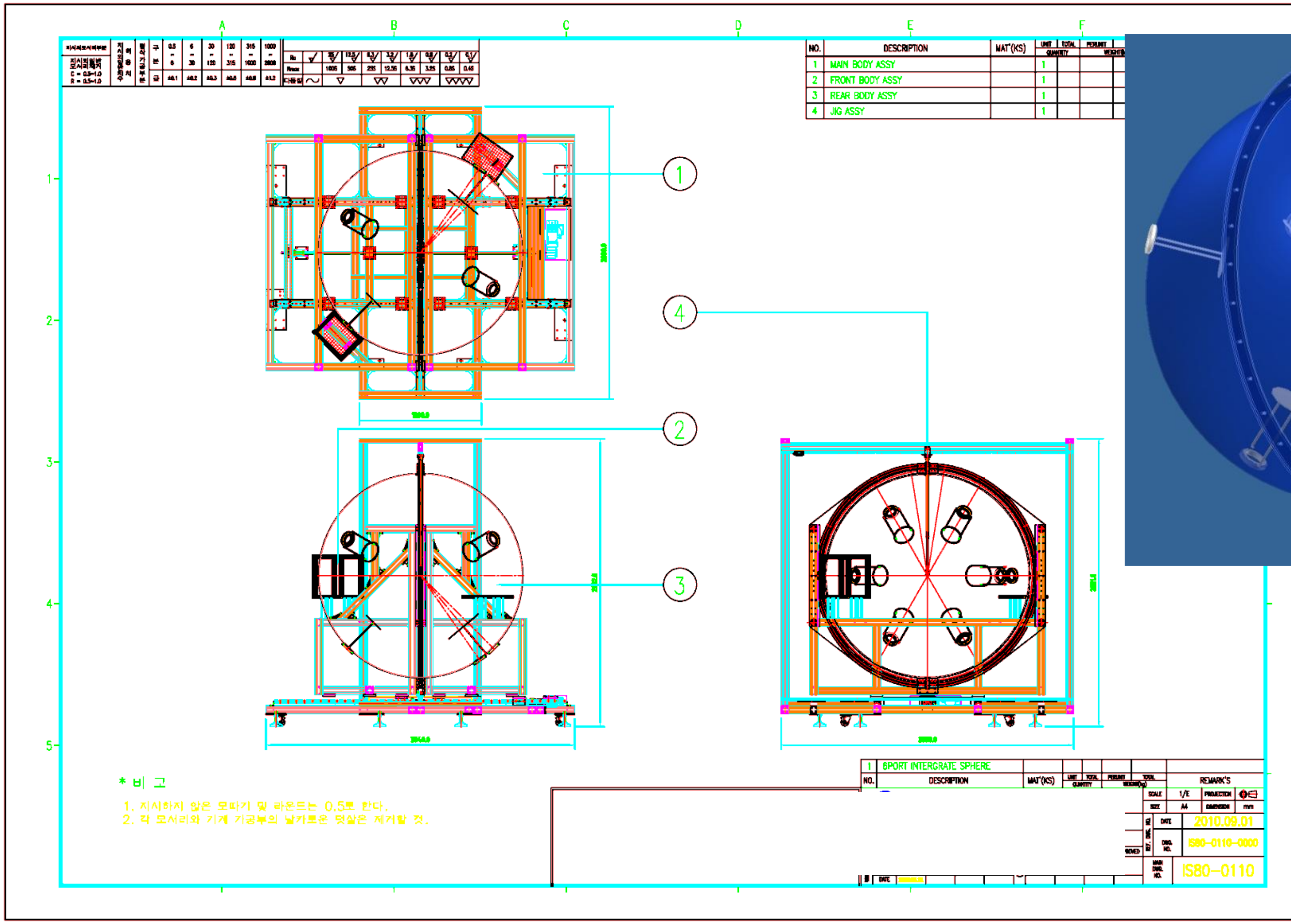


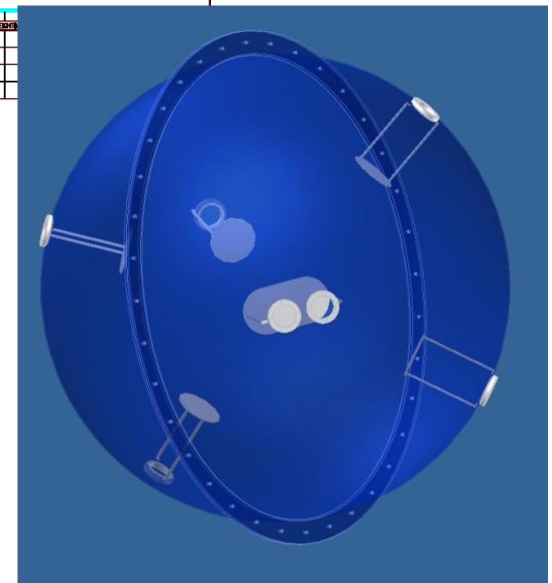


$$\Phi_T = k_{CCF} \cdot k_{abs} \cdot \frac{\frac{1}{6}\sum_{i=1}^{6} y_{Ti}}{y_{T1}} \cdot \underbrace{\frac{y_{R1}}{\frac{1}{6}\sum_{i=1}^{6} y_{Ri}}}_{\equiv 1} \cdot \frac{y_T^*}{y_R^*} \Phi_R$$

- *G* adjusted for $y_1 = y_2 = \ldots = y^*$ for REF lamp
- Only P* used for self-absorption correction

KRISS 6-port IS Photometer





Ø 2 m

(to be installed in Oct 2011)

Summary

- Modification of the auxiliary lamp → correction of self-screening effect for a large-area light source
- Multi-LED socket → spatial mismatch compensated
- Multi-port IS design → spatial mismatch-free measurement of directive light sources
- Validity of the designs tested by numerical experiment based on the radiation transfer equation
- IS photometers have a good chance also for SSL products.