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# Goniometric measurement of light sources using an integrating sphere

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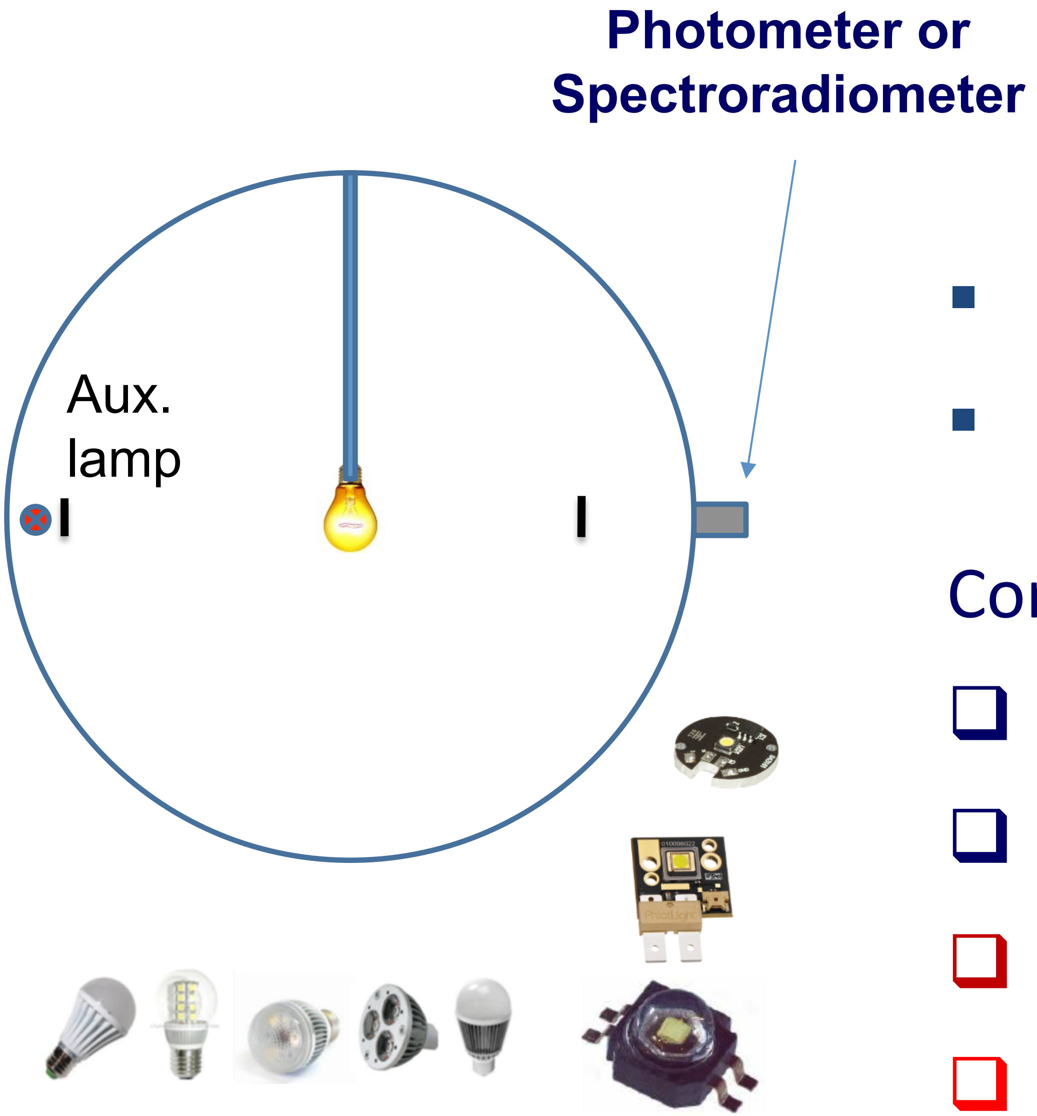
# Outline

1. Motivation
2. The new integrating sphere - fisheye camera method
3. Experiment
4. Summary

# An integrating sphere system



- Fast measurement
- but obtain total flux only.

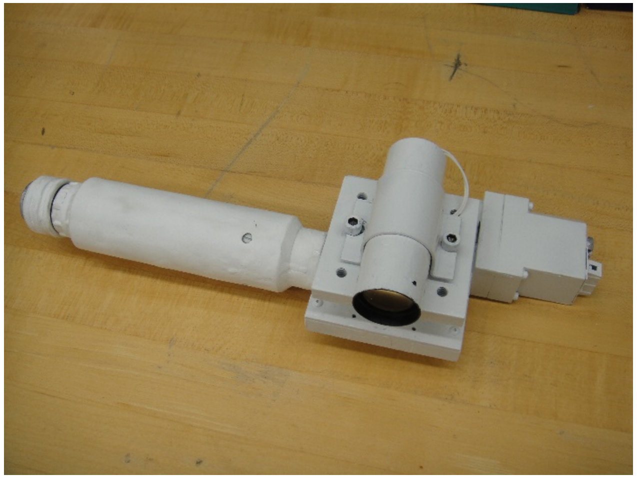
Corrections required

- ☐ Spectral mismatch
- ☐ Stray light
- ☐ Self-absorption
- ☐ Angular mismatch??

# Spatial non-uniformity of Integrating Spheres

- Well-known issue.
- Strict substation, but not always practical.
- Correction, but difficult.
- Practical limit for achievable low uncertainty.
- Efforts has been made …

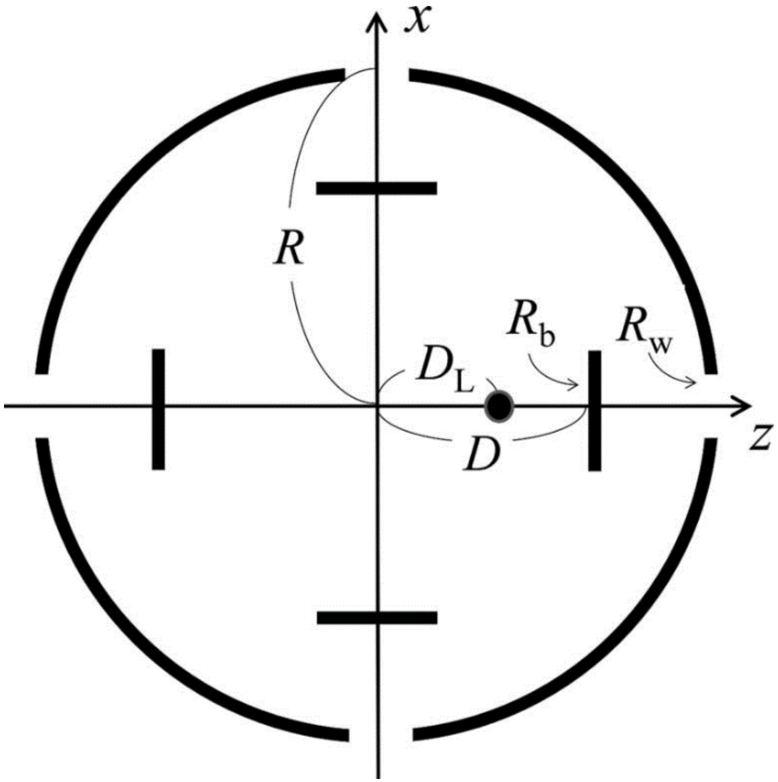
# Effort 1: Mapping sphere using a beam scanner



Ohno Y. and Zong Y.,
“Detector-Based Integrating
Sphere Photometry.” Proc.,
24th Session of the CIE, Vol. 1,
Part 1, 155-160. (1999)

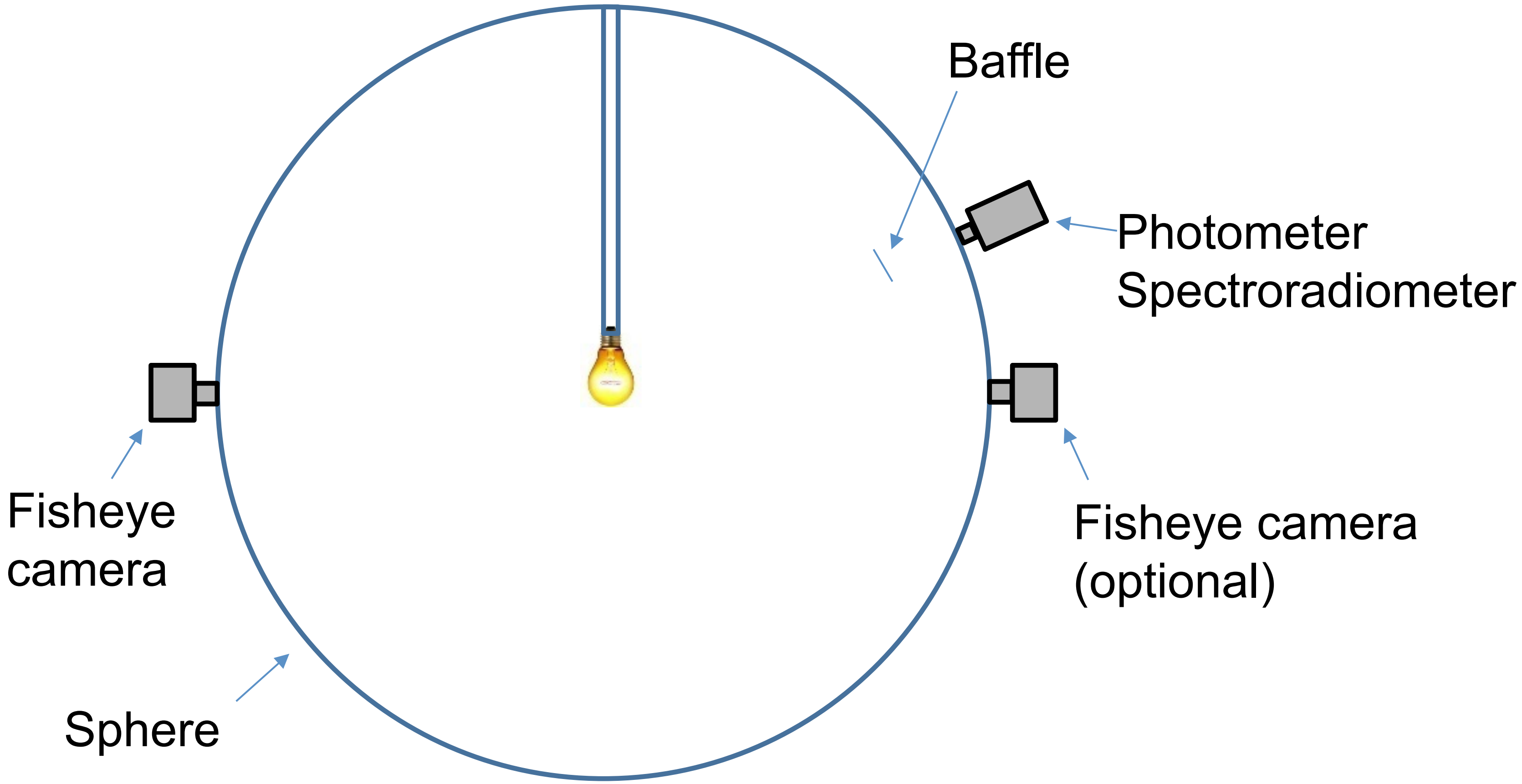
Winter S., Lindermann M., Jordan W.,
Binder U., and Anokhin M.,
“Convenient integrating sphere scanner for
accurate luminous flux measurements.”
Metrologia, 46, S248-S251. (2009)

# Effort 2: Six-port integrating sphere photometer

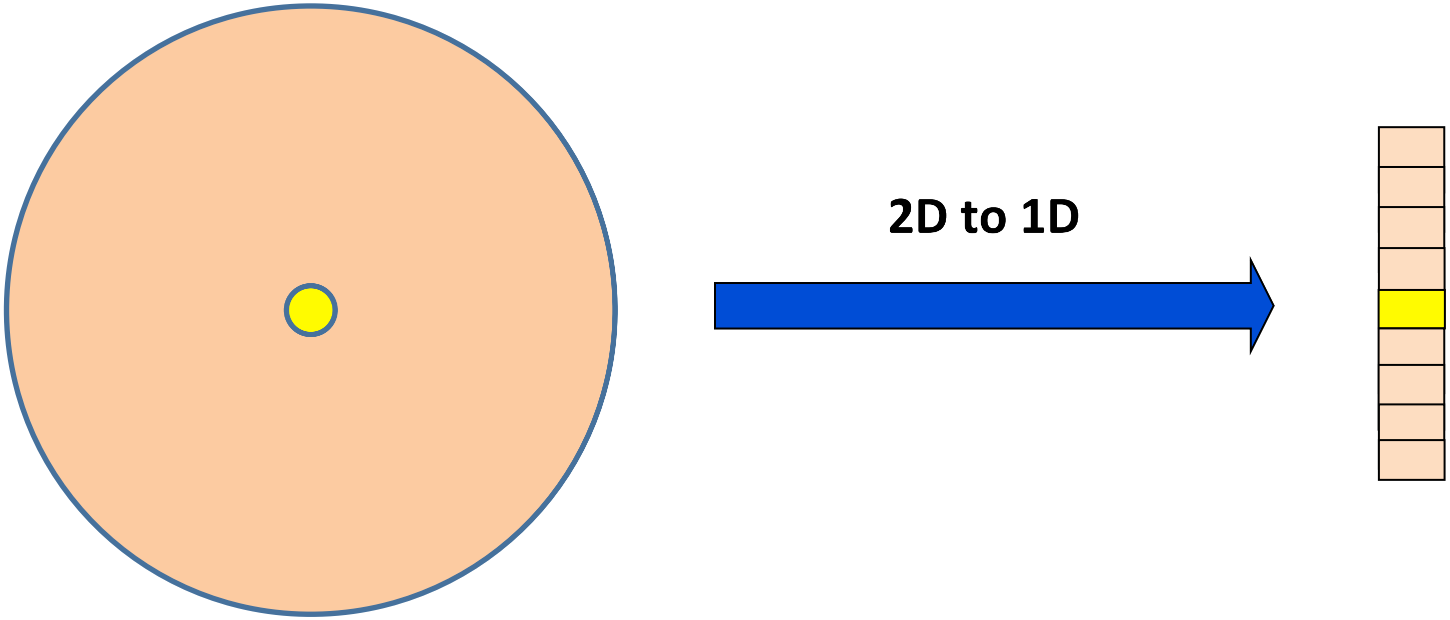


Park S. C., Lee D. H., and Park S. N., “Six-port integrating sphere photometer with uniform spatial response.” Applied Optics, 45, No. 6, 1111-1119. (2011)

# The new integrating sphere–fisheye camera method



# Point Spread Function (PSF) of the system



**2D PSF**

**1D column vector PSF**

**2-D problem to 1D problem!**

# Calculation of Point Spread Function (PSF)

$$L_J = \Phi_J \rho_J \frac{n}{4\pi^2 r^2} + \Phi_J \rho_J^2 \frac{\rho}{4\pi^2 r^2 (1-\rho)}$$

$$L_i = \Phi_J \rho_J \frac{\rho_i}{4\pi^2 r^2 (1-\rho)}$$

$$h_{i,J} = \begin{cases} 1 & i=J \\ \frac{\rho_i}{(1-\rho)n+\rho_J \rho} & i=1, 2, \ldots, J-1, J+1, \ldots n \end{cases}$$

$L_J$ is the luminance at the “hot” element, J;

$L_i$ is the luminance at any other element, *i*;

$\Phi_J$ is the total flux from the spot light illuminating the element, J, directly;

$\rho_J$ is the diffuse reflectance of coating at element, J;

$\rho_i$ is the diffuse reflectance of coating at element, *i*;

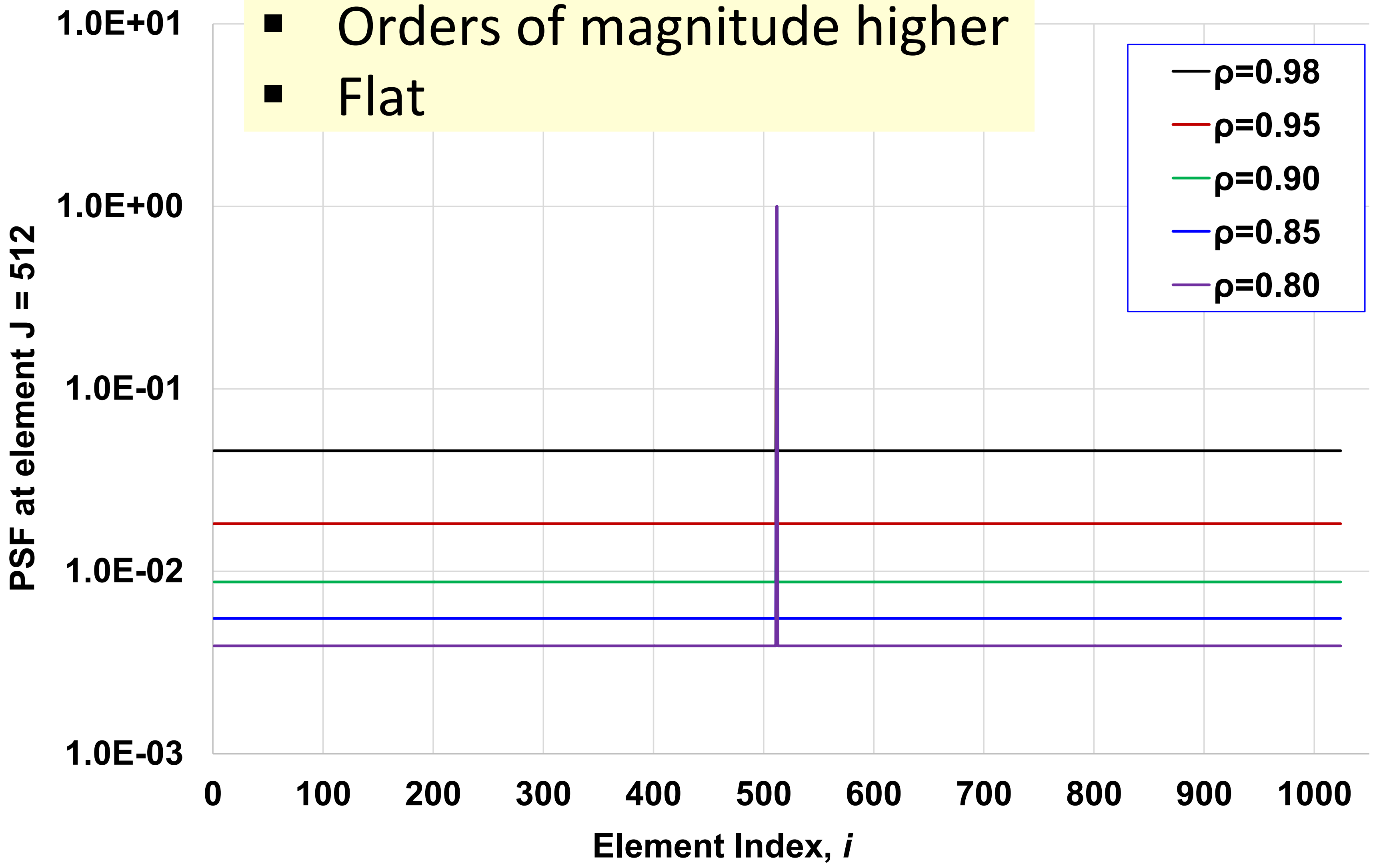
$\rho$ is the effective diffuse reflectance of the sphere determined by the averaged coating reflectance, total port areas, self-absorption of the light source;

$r$ is the radius of the sphere;

$n$ is the total number of surface elements.

# Characteristic of PSFs

- Orders of magnitude higher
- Flat



# Building PSF matrix, H

[■1&ℎ1,2&ℎ1,3&ℎ1,4&ℎ1,5&ℎ1,6&ℎ1,7&ℎ1,8&ℎ1,9&⋯&ℎ1,1022&ℎ1,1023&ℎ1,1024@ℎ2

# Obtaining the relative luminance distribution

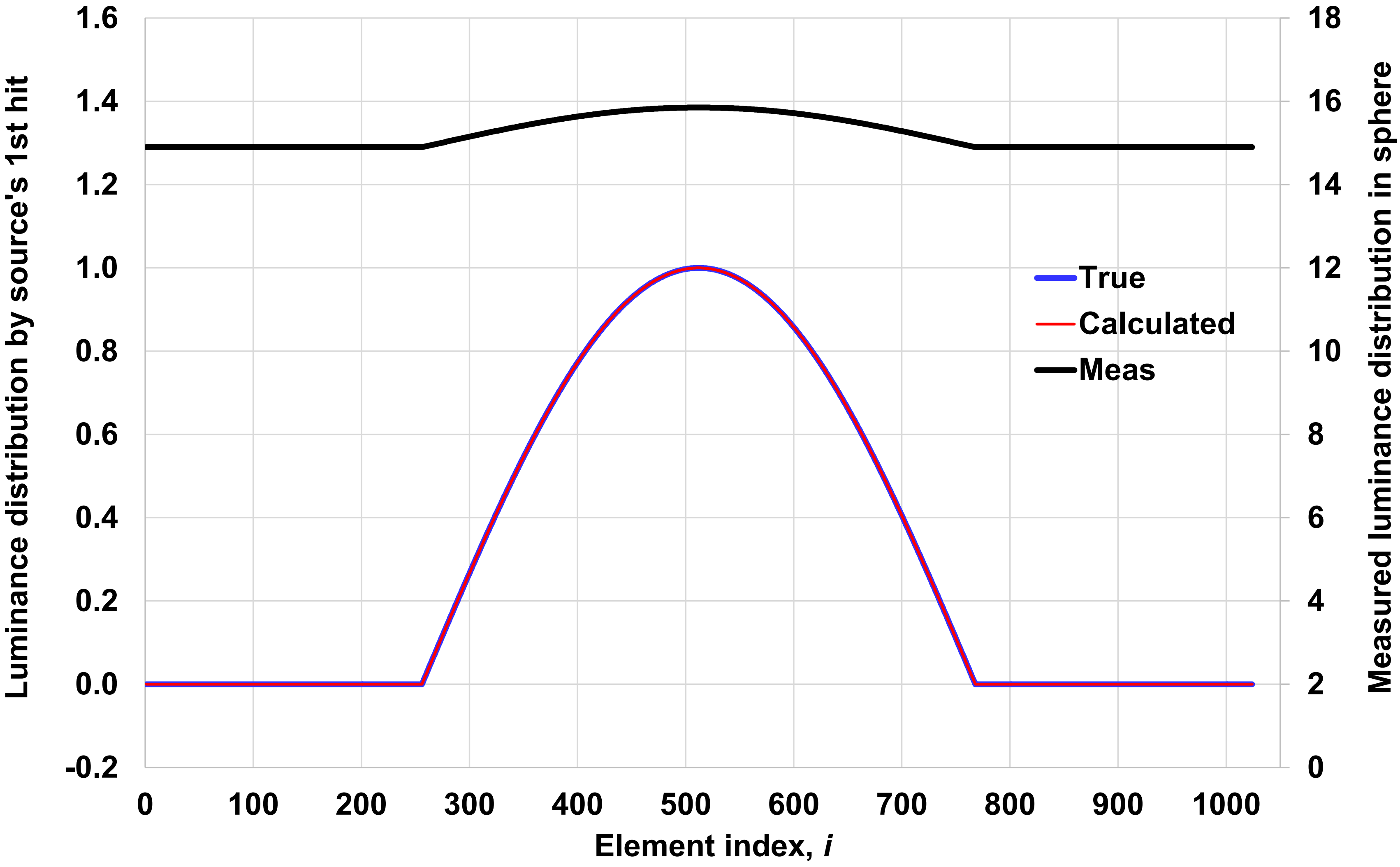
$$L_{I,\,meas} = \sum_{j=1}^{n} h_{\mathrm{I},\,j} \times L_j$$

$h_{\mathrm{I},\,j}$ is element, *j*, at row, I, of the PSF matrix;

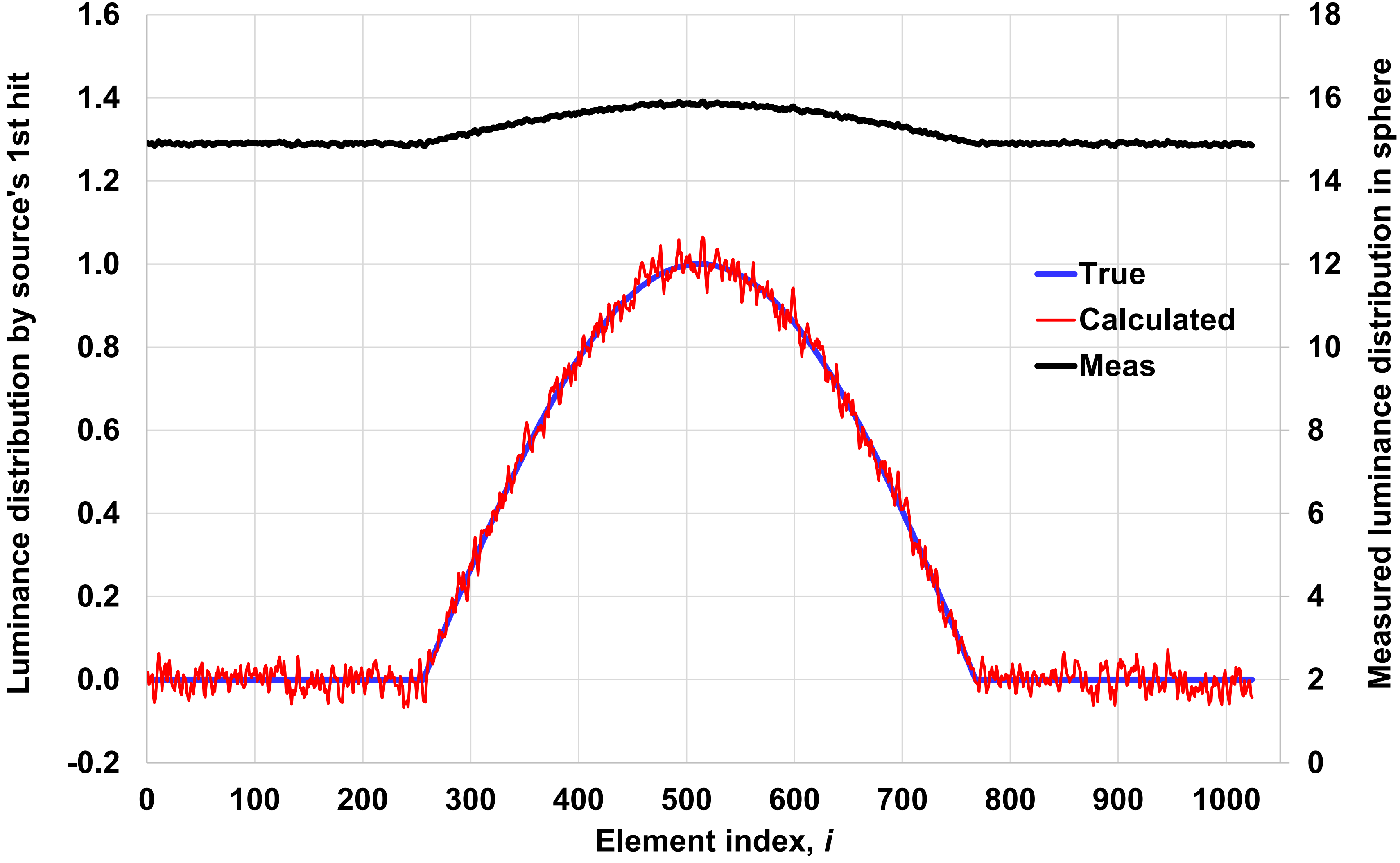
$L_j$ is the luminance at element, *j*, resulting from the luminous flux of the light source within the solid angle covered by the area of the element, *j*.

$L_{\boldsymbol{meas}} = H\,L$ → $\mathrm{L} = H^{-1}\; L_{\boldsymbol{meas}}$

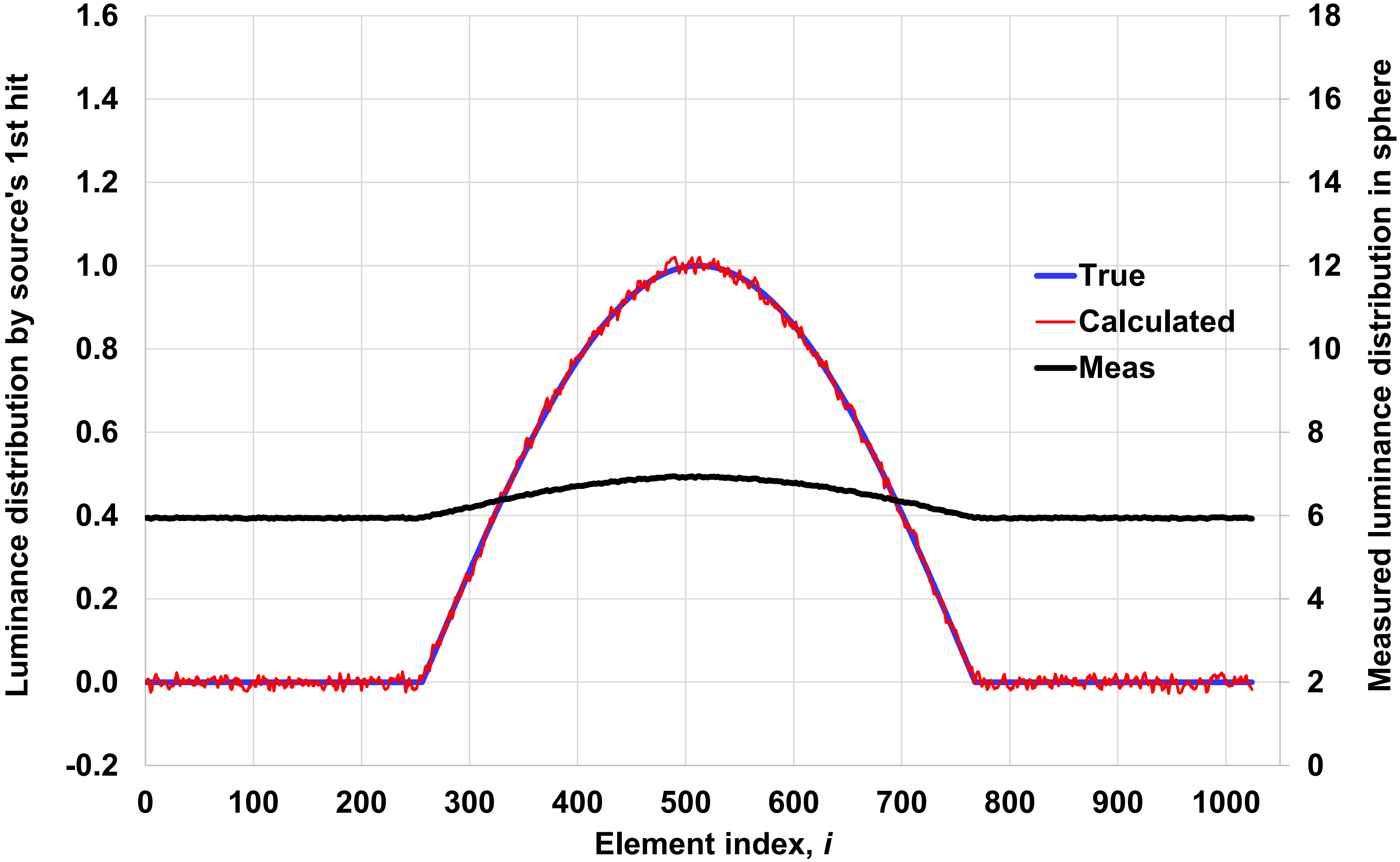
# Derived luminance distribution (*n*=1024) ρ = 0.98, no added noise



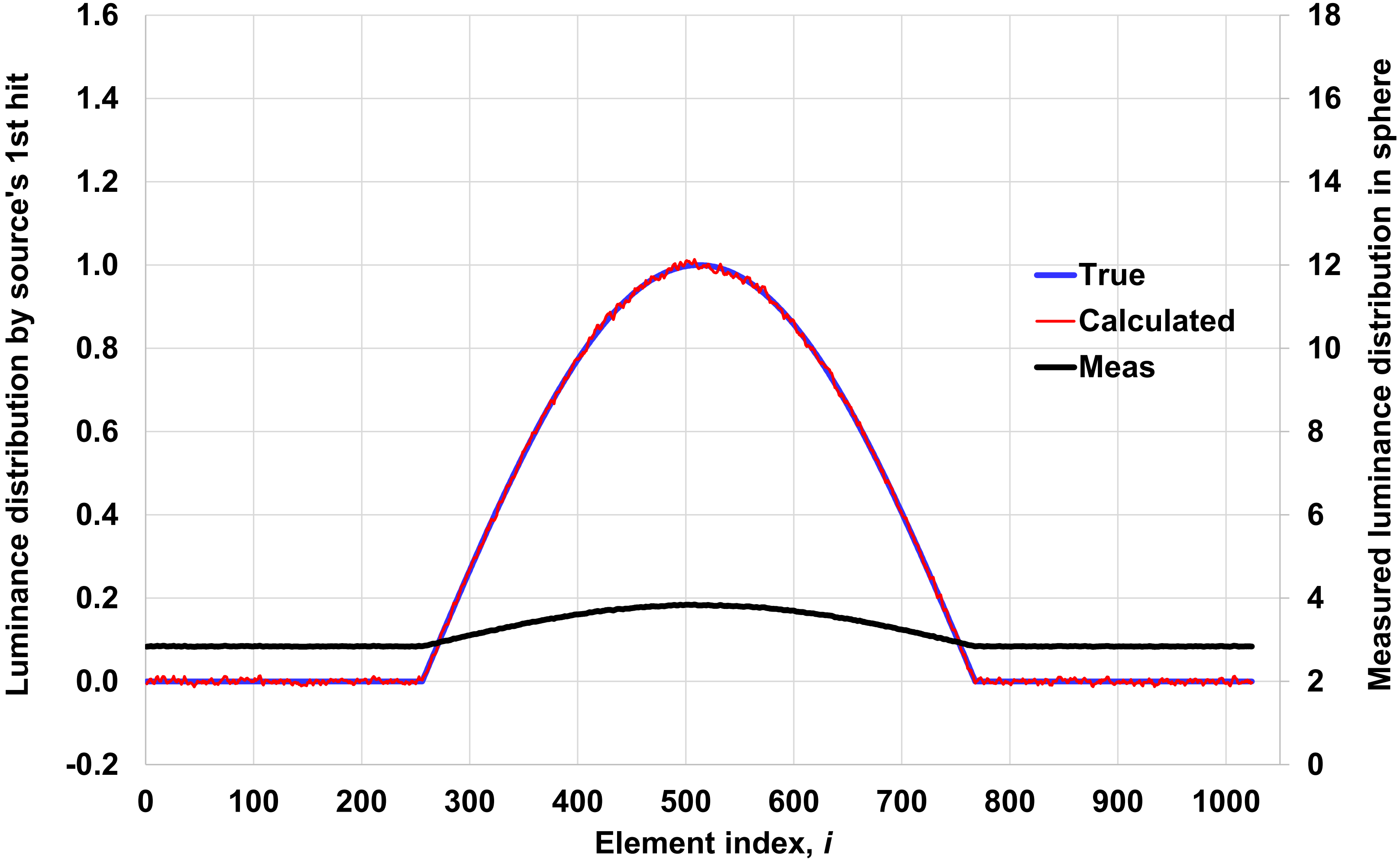
# Derived luminance distribution (*n*=1024)
# $\rho$ = 0.98, 1 % added noise



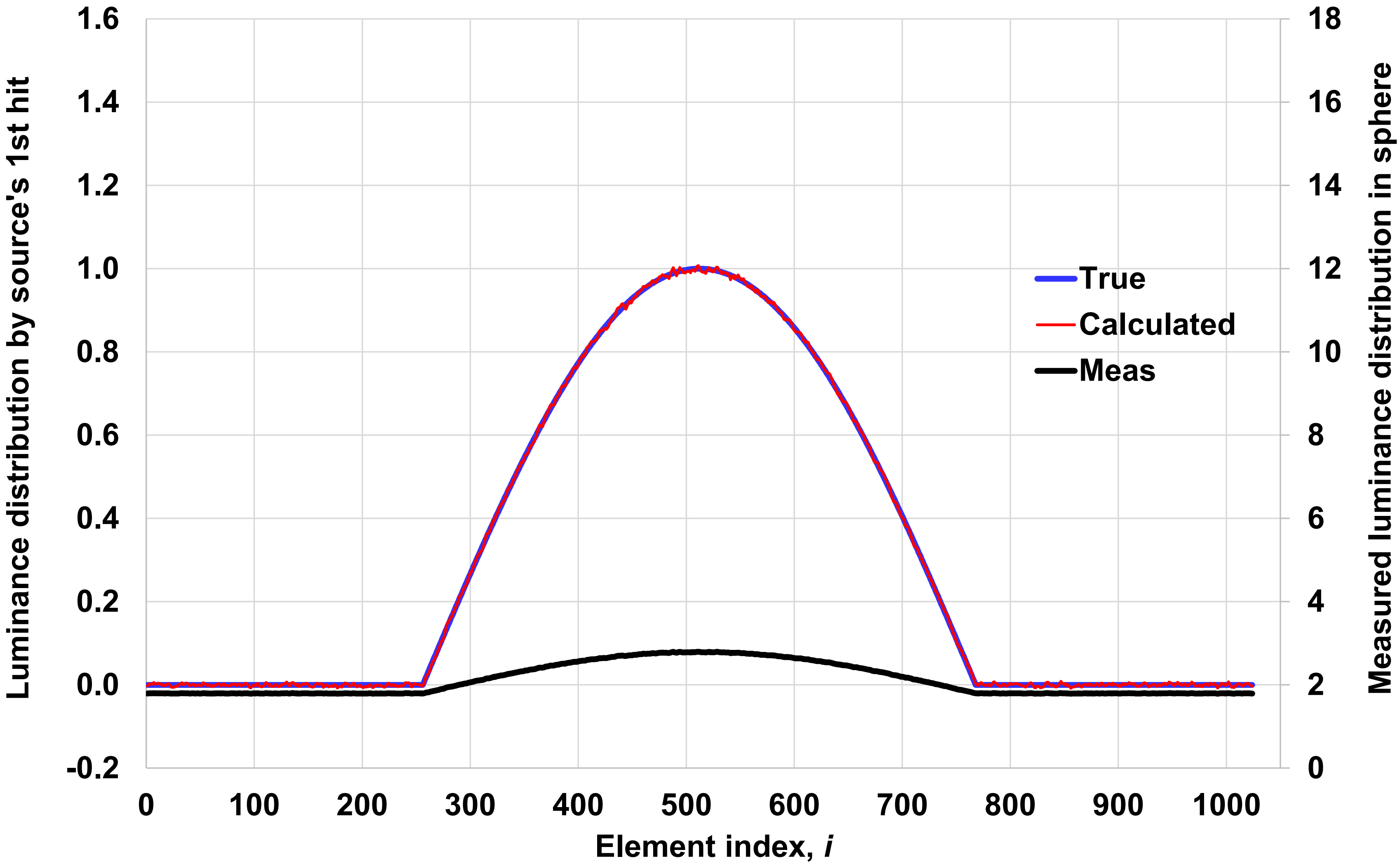
# Derived luminance distribution (*n*=1024)
# $\rho$ = 0.95, 1 % added noise



# Derived luminance distribution (*n*=1024) $\rho$ = 0.90, 1 % added noise

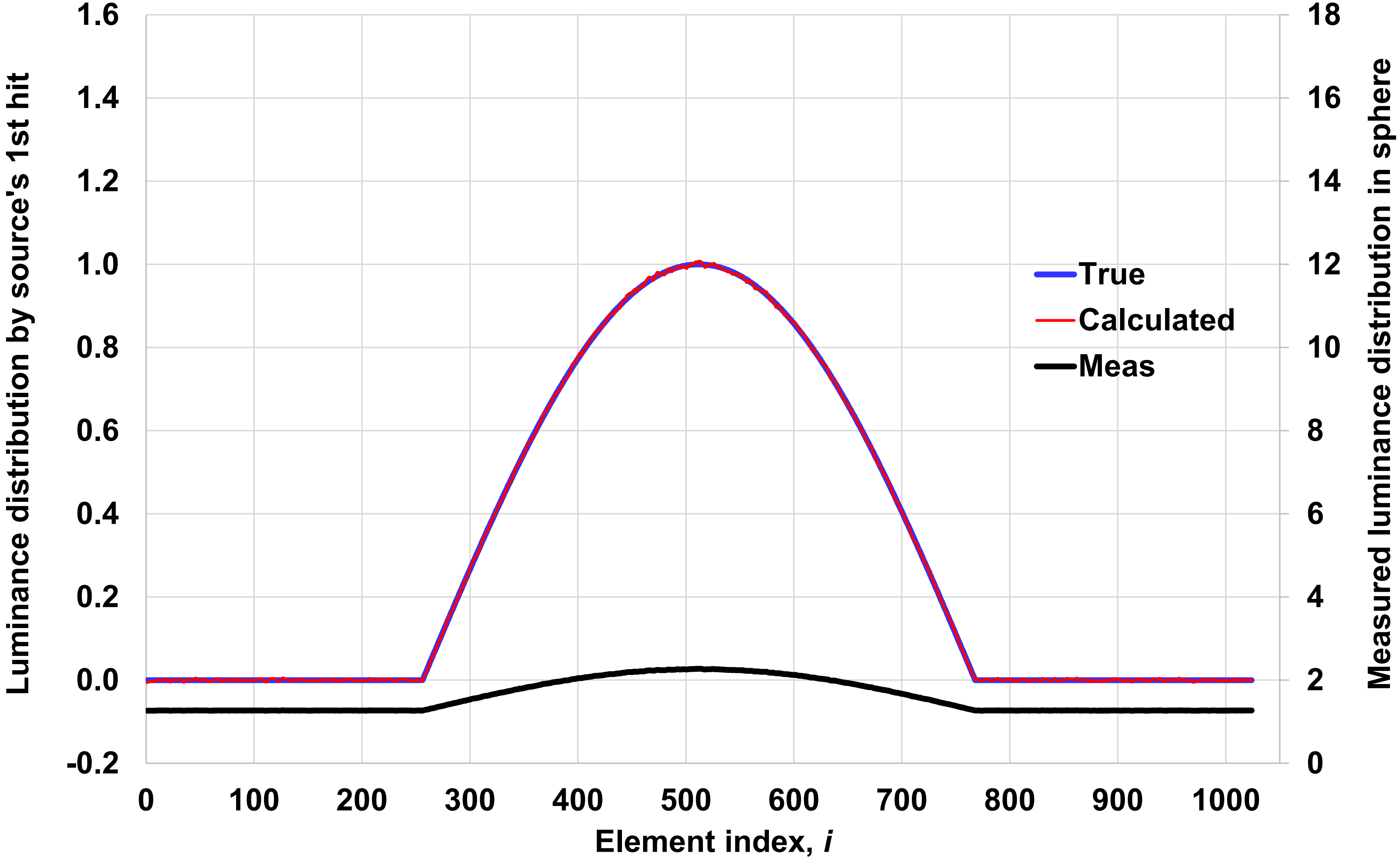


# Derived luminance distribution (n=1024)
# $\rho$ = 0.85, 1 % added noise



# Derived luminance distribution (*n*=1024)

# ρ = 0.80, 1 % added noise



# Correction of angular mismatch error

$$C_{\tau} = \sum_{i=1}^{n} L_{\mathrm{v,\,rel},\,i}(\mathrm{test}) \Big/ \sum_{i=1}^{n} L_{\mathrm{v,\,rel},\,i}(\mathrm{test})\,\rho_{i} \Big/ \sum_{i=1}^{n} L_{\mathrm{v,\,rel},\,i}(\mathrm{standard}) \Big/ \sum_{i=1}^{n} L_{\mathrm{v,\,rel},\,i}(\mathrm{standard})\,\rho_{i}$$

CIE 198:2011, "Determination of Measurement Uncertainties in Photometry." (2011)

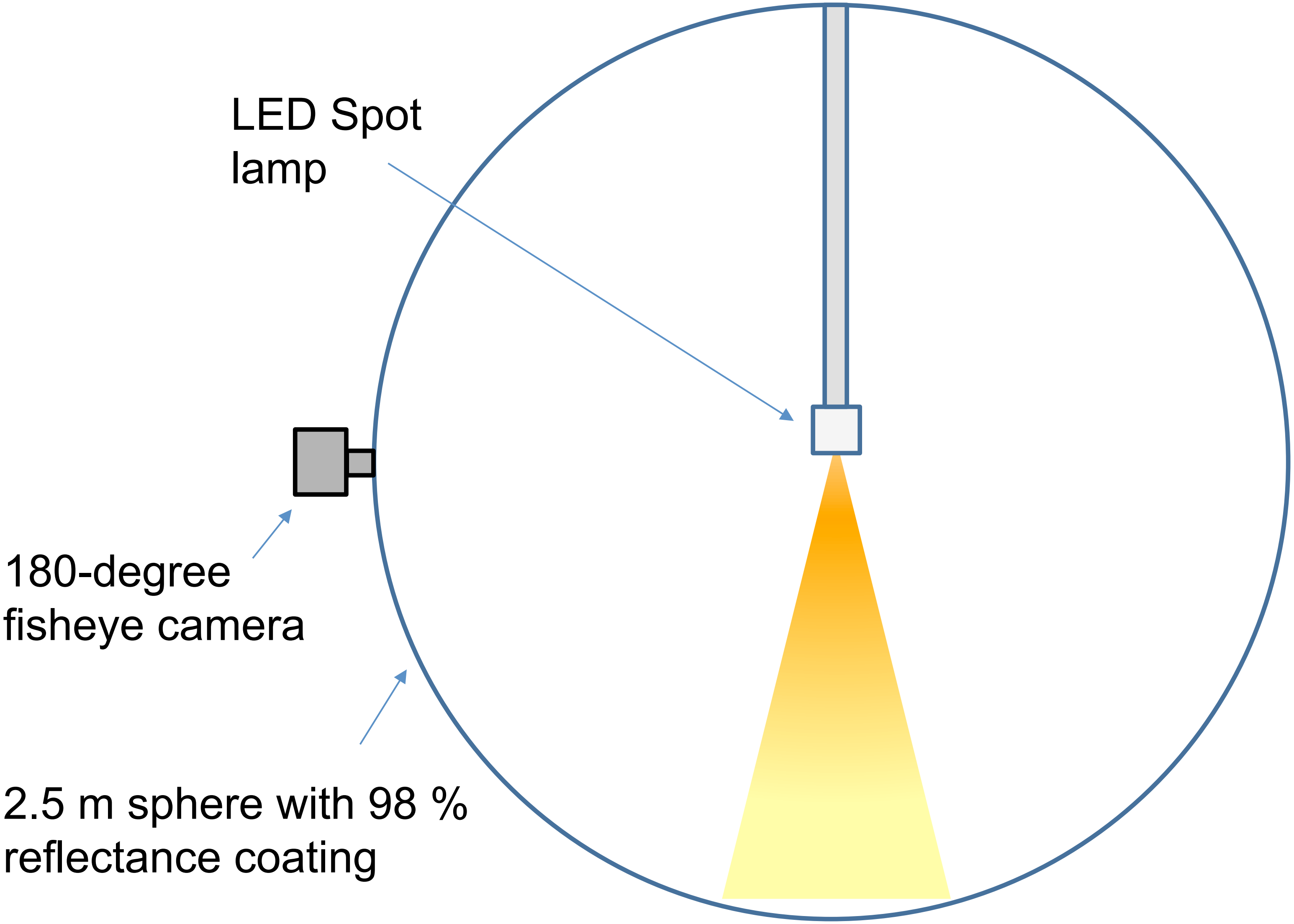
# Derivation of absolute luminous intensity

$$I_{\mathbf{v},\,\mathbf{rel}} = \pi r^{2}\,(\boldsymbol{\rho}\, L)$$

$$I_{\mathbf{v}} = k\, I_{\mathbf{v},\,\mathbf{rel}}$$

$$k = \frac{\Phi_{v}\, n}{4\pi \sum_{i=1}^{n} I_{\mathrm{v},\,\mathrm{rel},\,i}}$$

# Schematic of the experimental setup

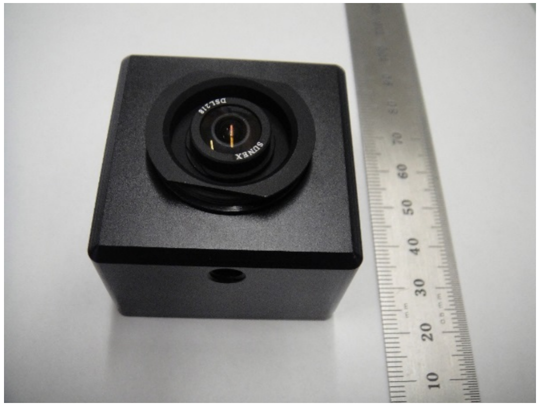


LED Spot lamp

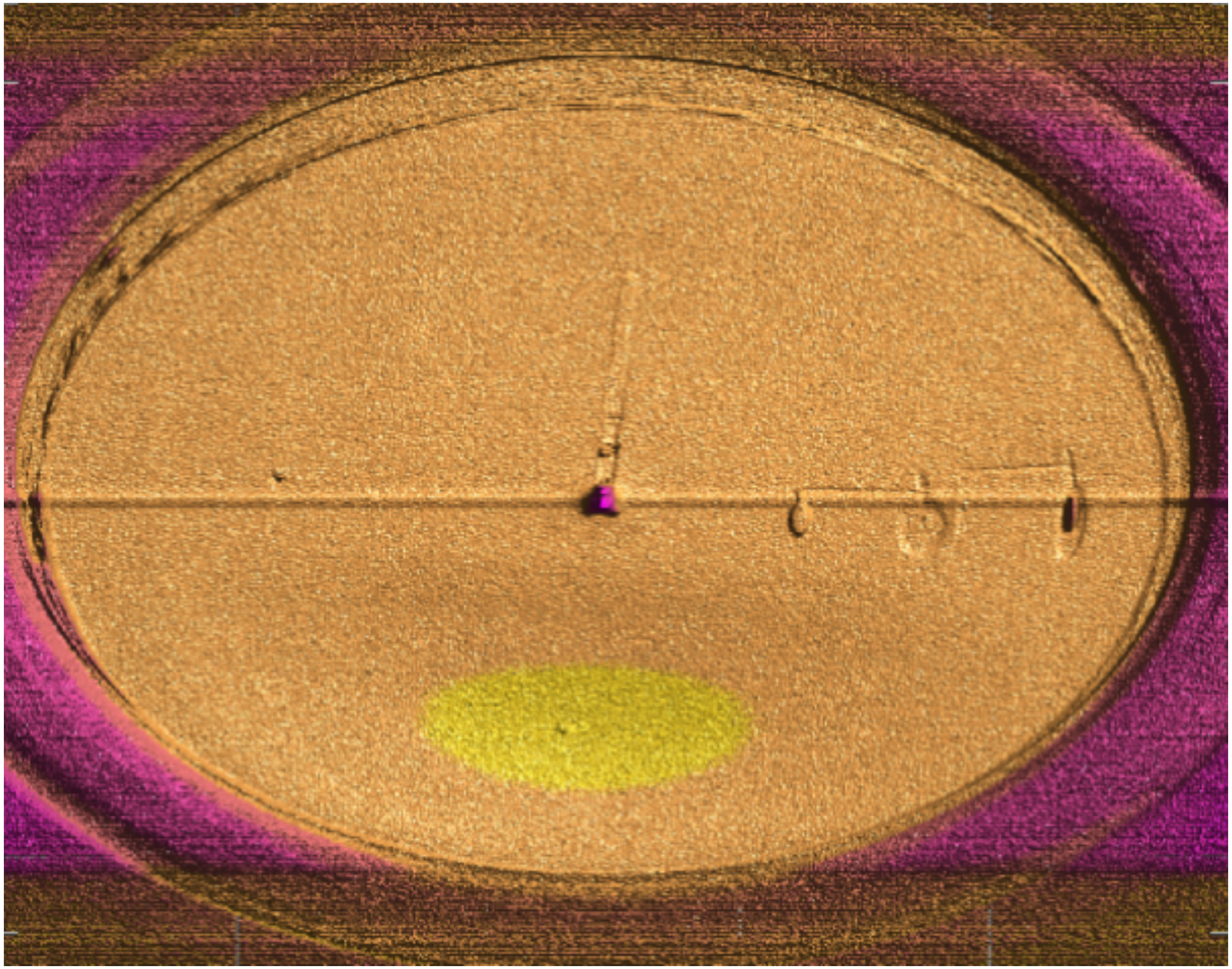
180-degree fisheye camera

2.5 m sphere with 98 % reflectance coating

# The fisheye camera



# Measured radiance distribution in the sphere wall



# Summary

- The new method can be implemented in existing sphere systems.
- The measured angular luminance distribution can be used for real-time correction of the error from the spatial non-uniformity of the integrating sphere.
- The best reflectance of the coating should be **re-considered now**. A lower coating reflectance not only makes sphere more stable but also enables the sphere to measure accurate luminance distribution; making it a true gonio-integrating sphere.
- Further validations are in progress.

# Acknowledgements

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# Thank you