Study of Non-Uniformity Corrections in Luminous Flux Measurements of Automotive Headlamps using an Integrating Sphere through Simulations

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Development and Manufacturing of automotive lights since 1976 in Brazil

2 Sites / ~ 500 employees / ~ 2000 products / IATF / ISO 9001 / **ISO 17025 (Photometry)**

Website: www.pradolux.com

Example of products:

Tail lights

Head lights

Markers

Equipment

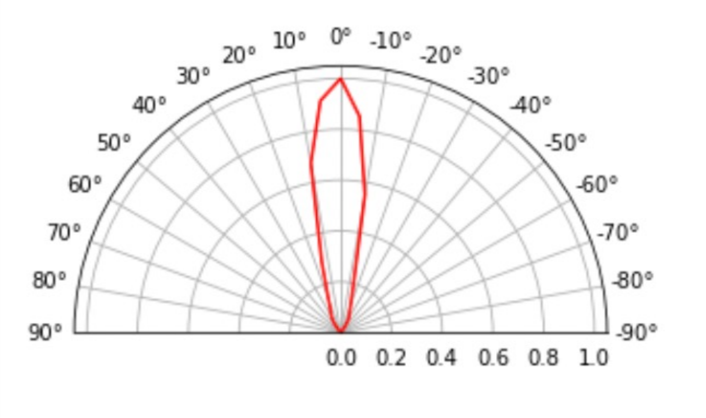
Integrating Sphere, diameter = 1.5 m (*Everfine*)

Spectroradiometer HAAS-2000, 350-1000nm (*Everfine*)

Gonio-photometer type A (automotive) with class A (3%) photometer (*Everfine*)

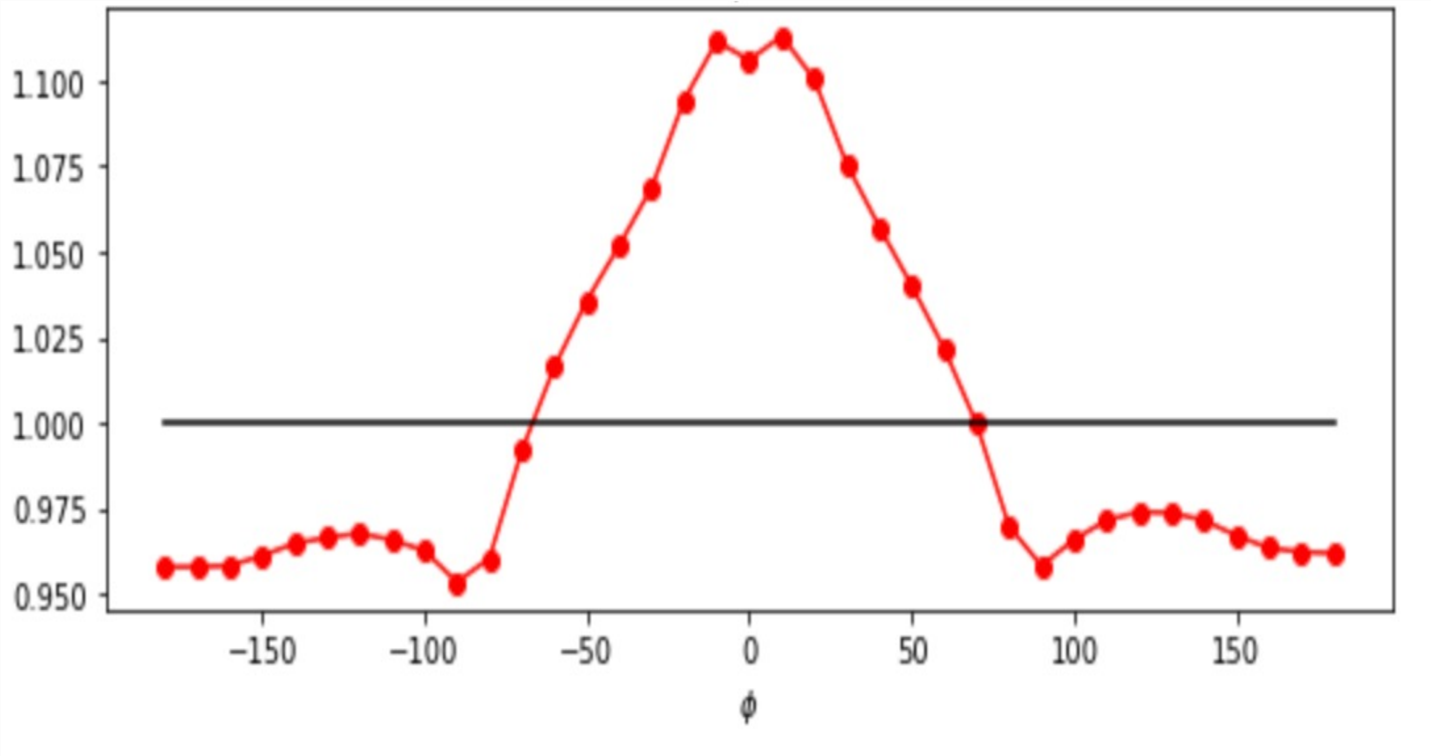
1. The problem of spatial non-uniformity

Example of light - Sample #1



Relative Luminous Flux – Sample #1

Optical axis rotated over 360^o (10^o step measurements)

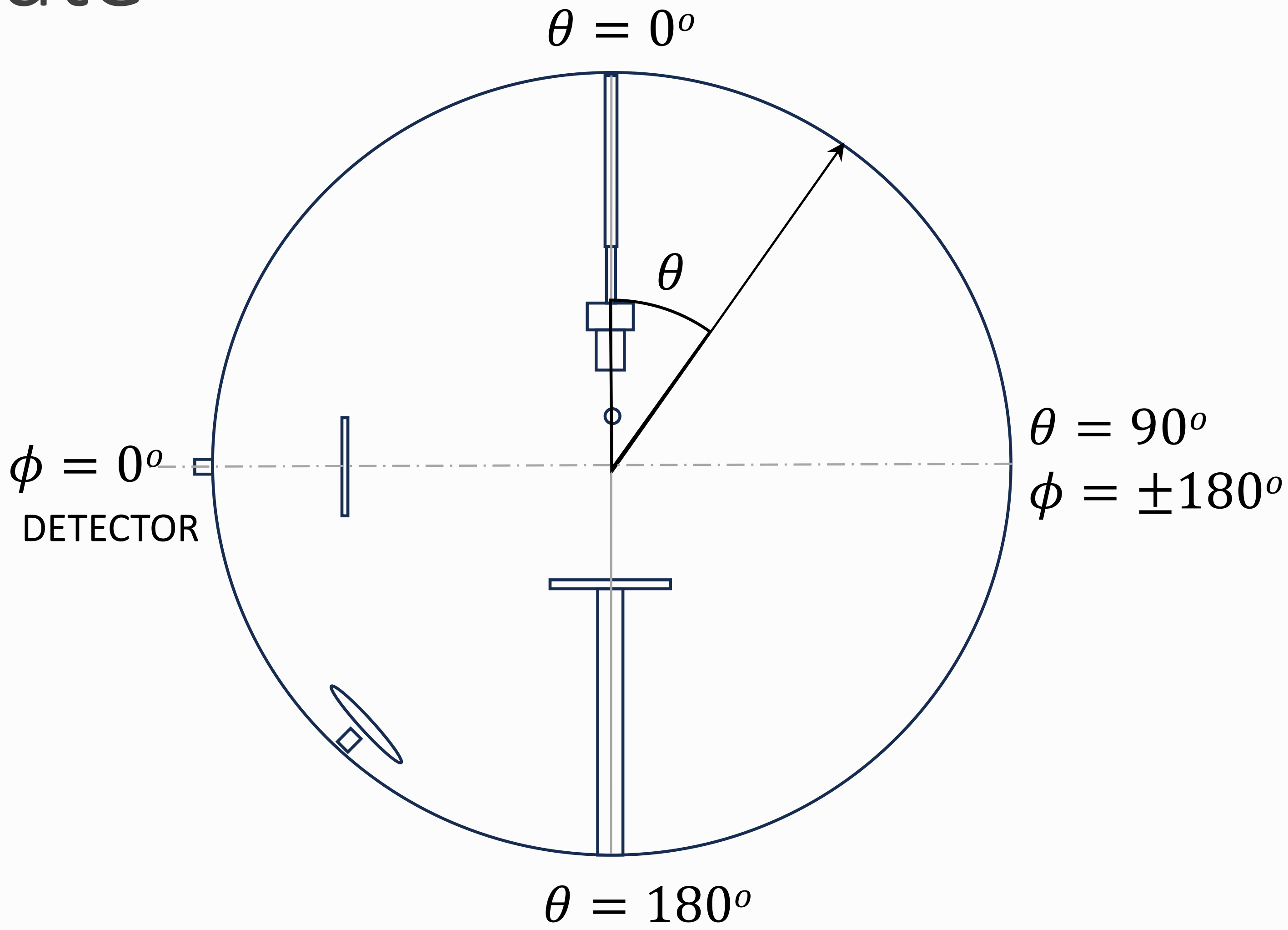


2. Simulations of the SRDF for our device[1]

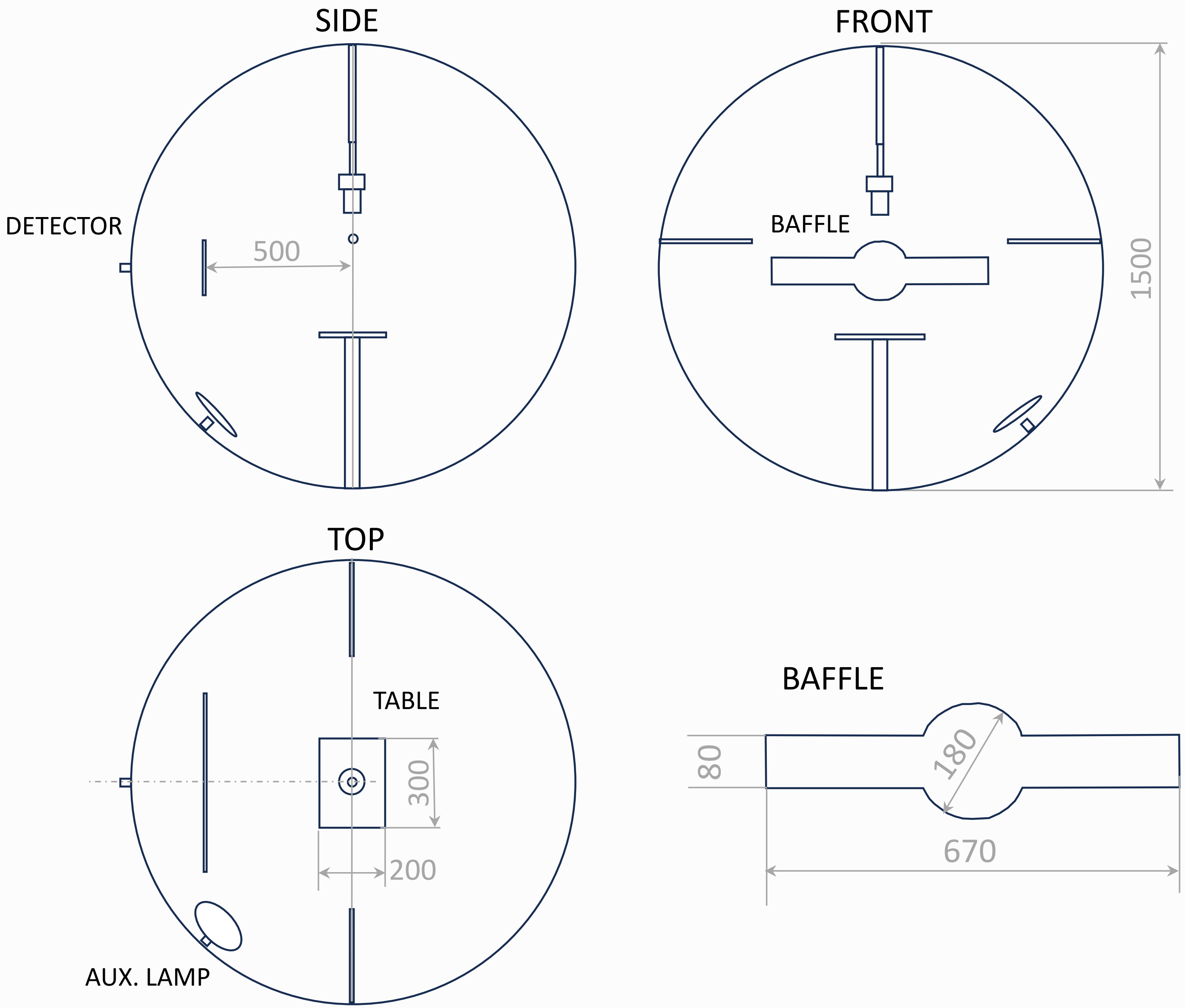
- Build the model of the sphere (baffle, table, holders, detector, aux. lamp, etc.)
- Set all surfaces as Lambertian with a constant reflectivity ρ
- Divide the sphere into 2,592 elements (5^o step on θ and ϕ)
- Each element is illuminated by a lamp and the rays are traced with the reflections to the detector (with 180^o and cosine angular responsivity)
- The detector response is recorded in a function $K = K(\theta, \phi)$
- The SRDF is normalized as

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

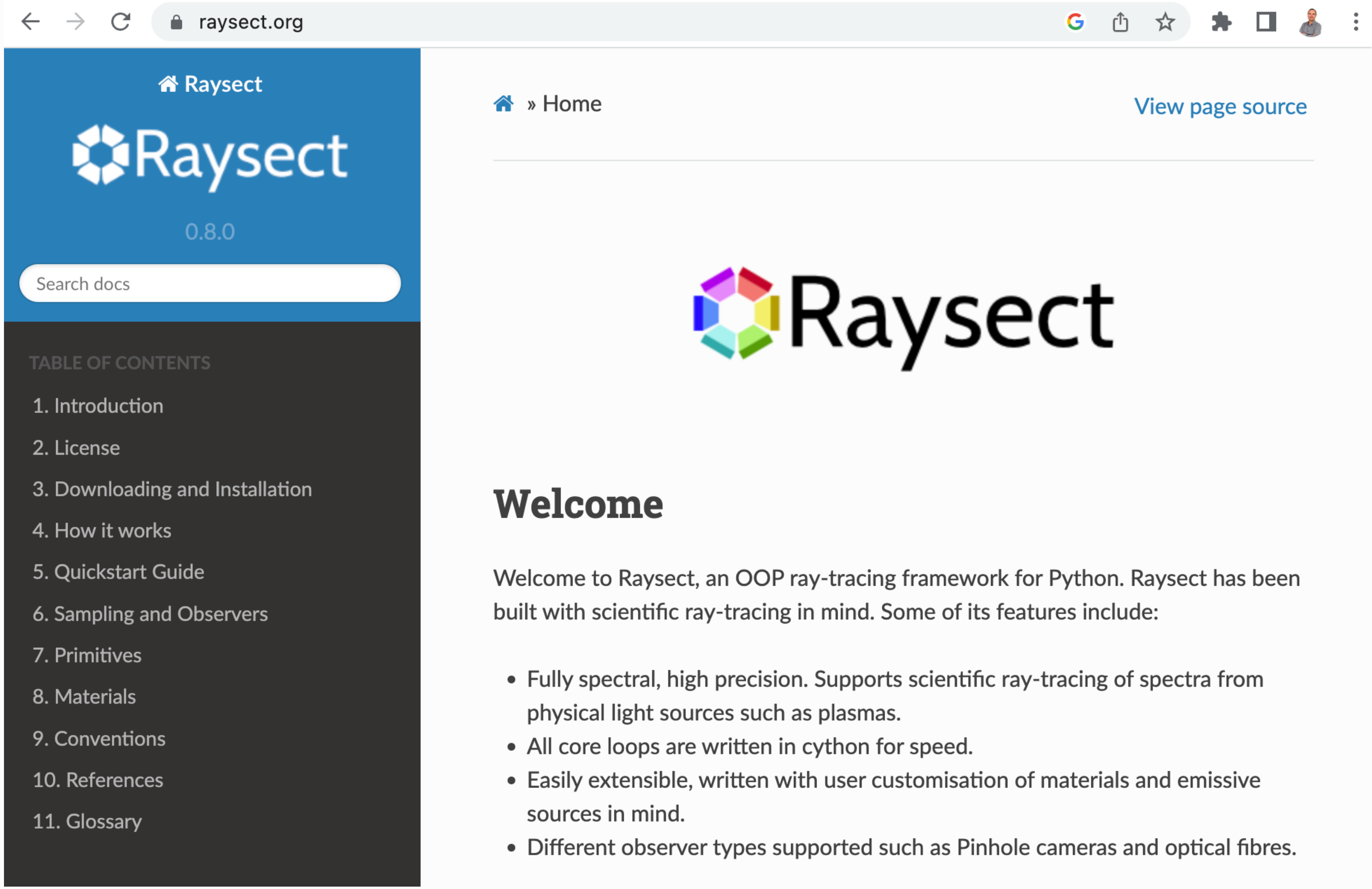
Coordinate system



Modeling the sphere for ray-tracing



Ray-tracing engine – Raysect[2]



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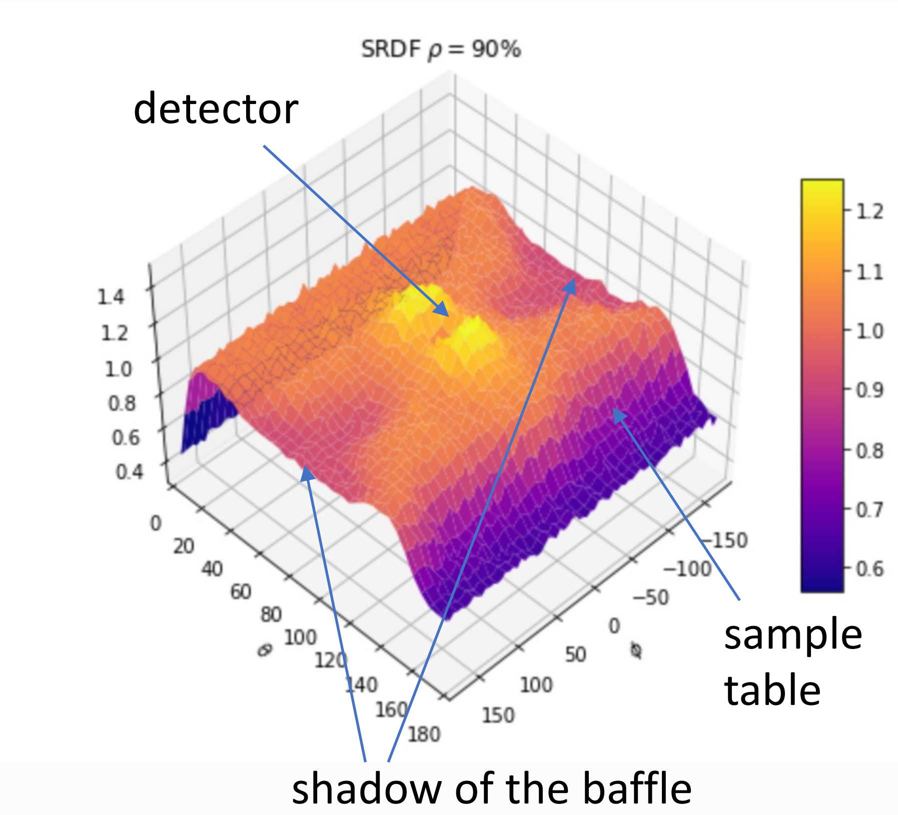
Raysect

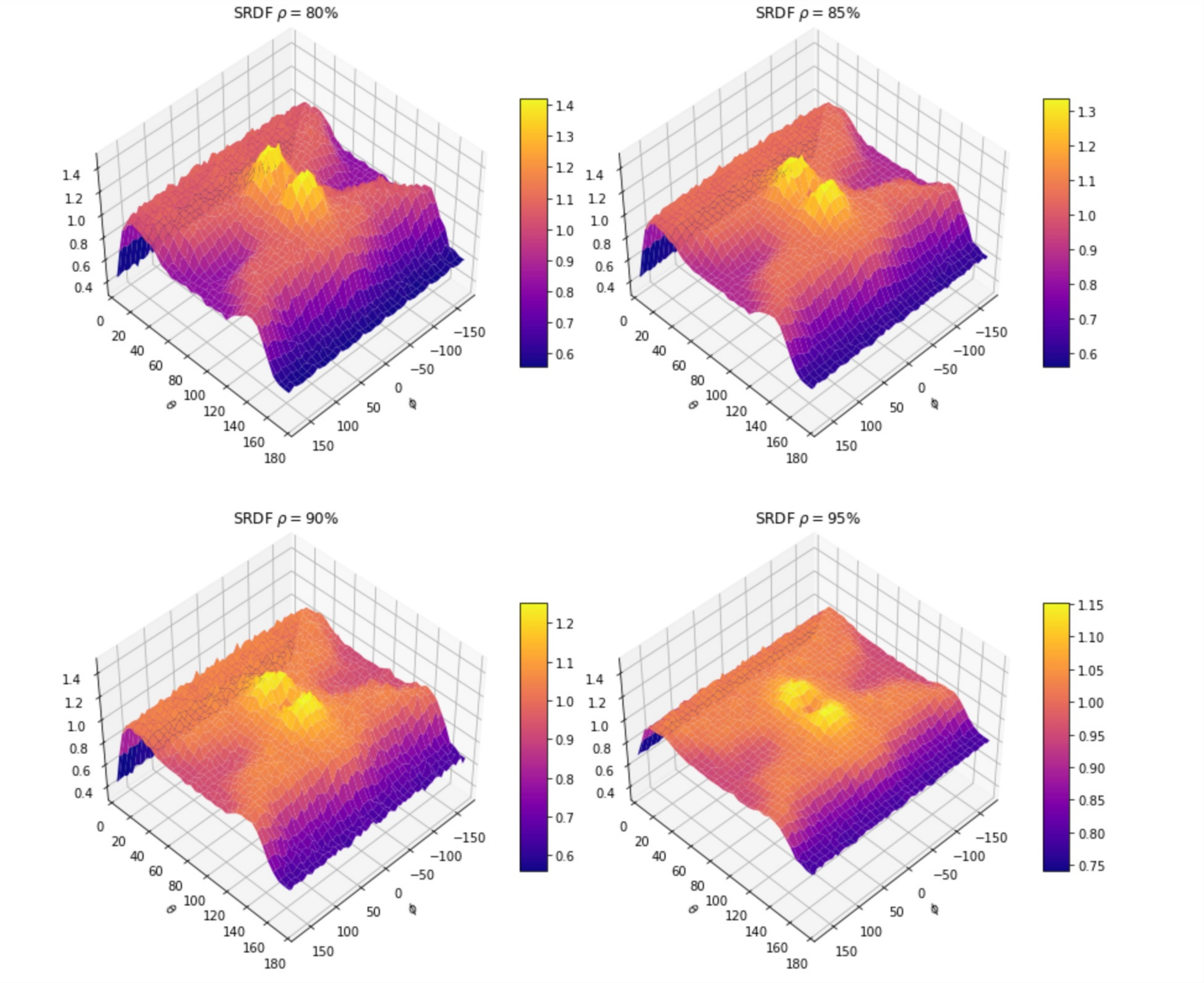
Welcome

Welcome to Raysect, an OOP ray-tracing framework for Python. Raysect has been built with scientific ray-tracing in mind. Some of its features include:

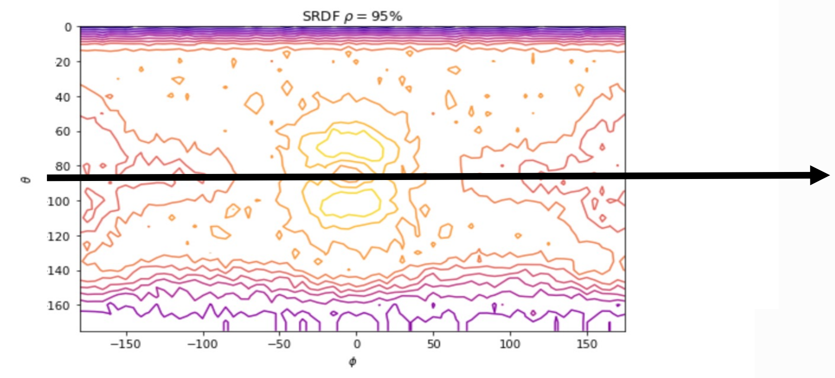
- Fully spectral, high precision. Supports scientific ray-tracing of spectra from physical light sources such as plasmas.
- All core loops are written in cython for speed.
- Easily extensible, written with user customisation of materials and emissive sources in mind.
- Different observer types supported such as Pinhole cameras and optical fibres.

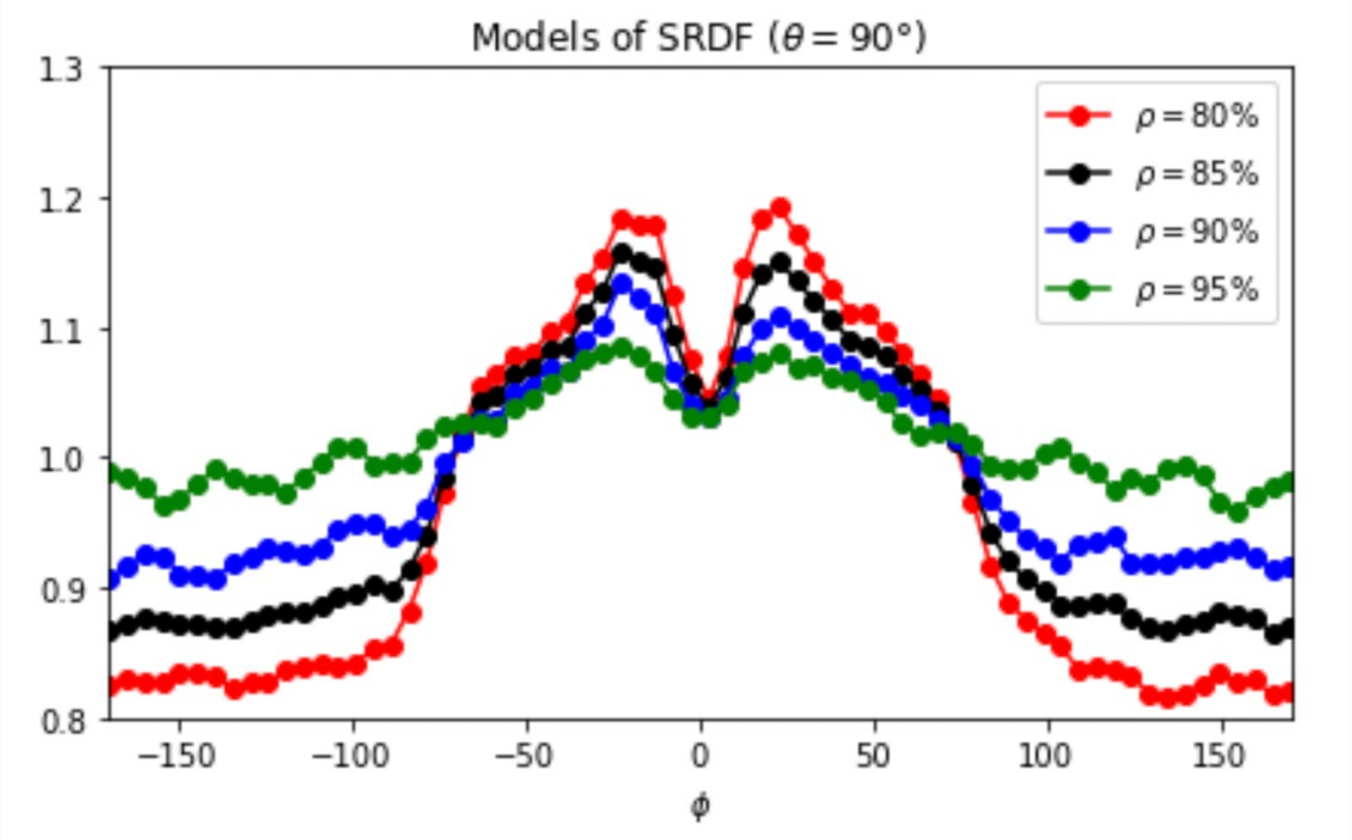
3. Analysis of the best reflectivity model





Simulated SRDF for different reflectivity values at $\theta = 90°$





Flux correction due to the non-uniformity [1]

Sphere response factor

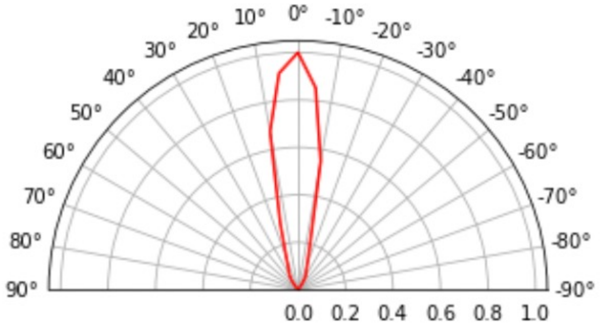
$$f_s = \frac{\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} K^*(\theta,\phi) I_{DUT}(\theta,\phi) sin\theta d\theta d\phi}{\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{DUT}(\theta,\phi) sin\theta d\theta d\phi}$$

where, $I_{DUT}(\theta, \phi)$ is the Luminous Intensity of the Device Under Test (neglecting correction from the reference lamp)

Correction factor $k_s = \frac{1}{f_s}$

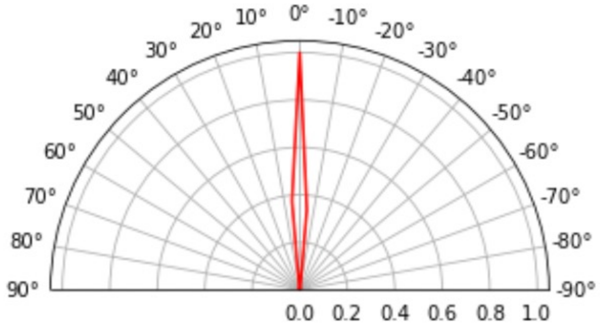
5 Headlights with different LIDs

V0 Sample #1



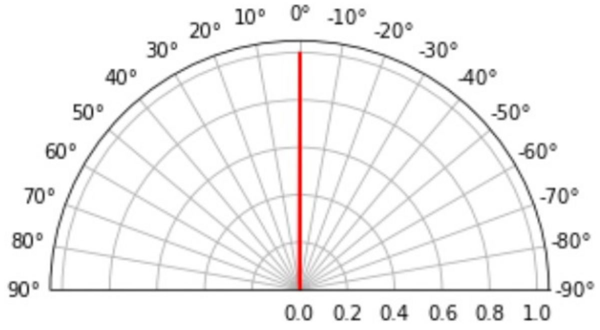
Type LED, Φ=915 lm

V0 Sample #2



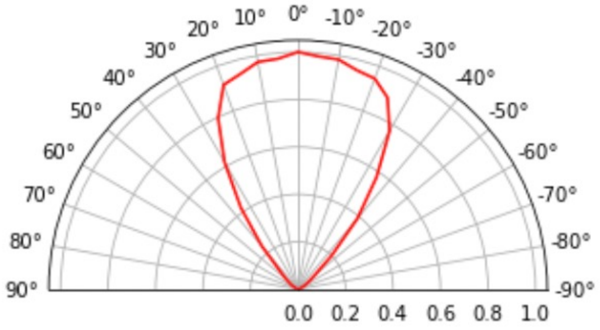
Type LED, Φ=551 lm

V0 Sample #3



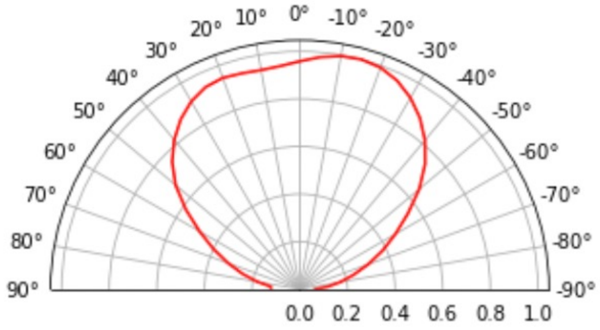
Type Halogen, Φ=1127 lm

V0 Sample #4



Type LED, Φ=3512 lm

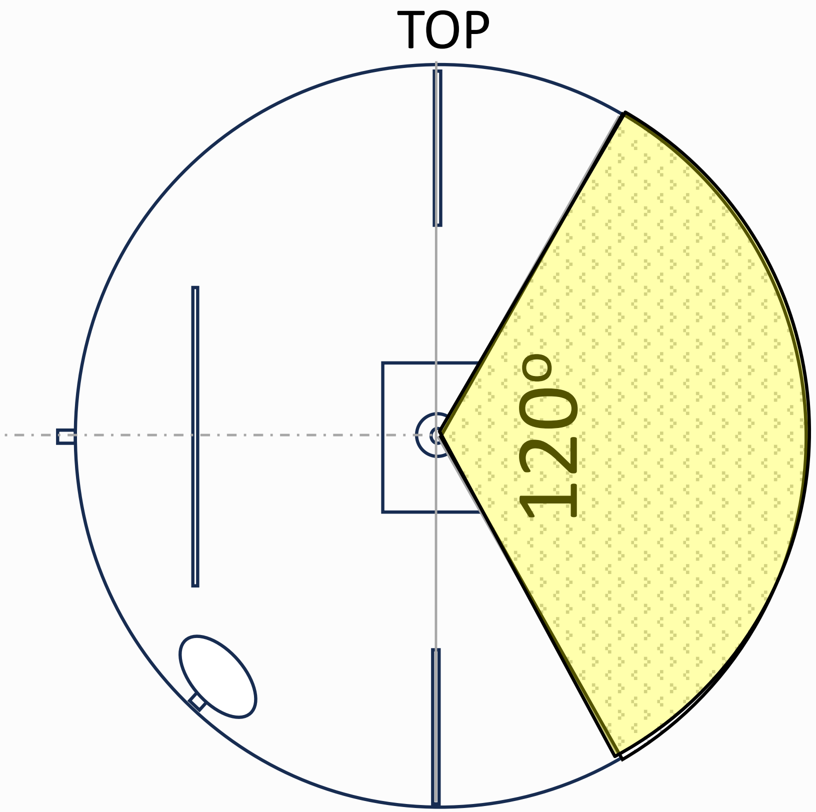
V0 Sample #5



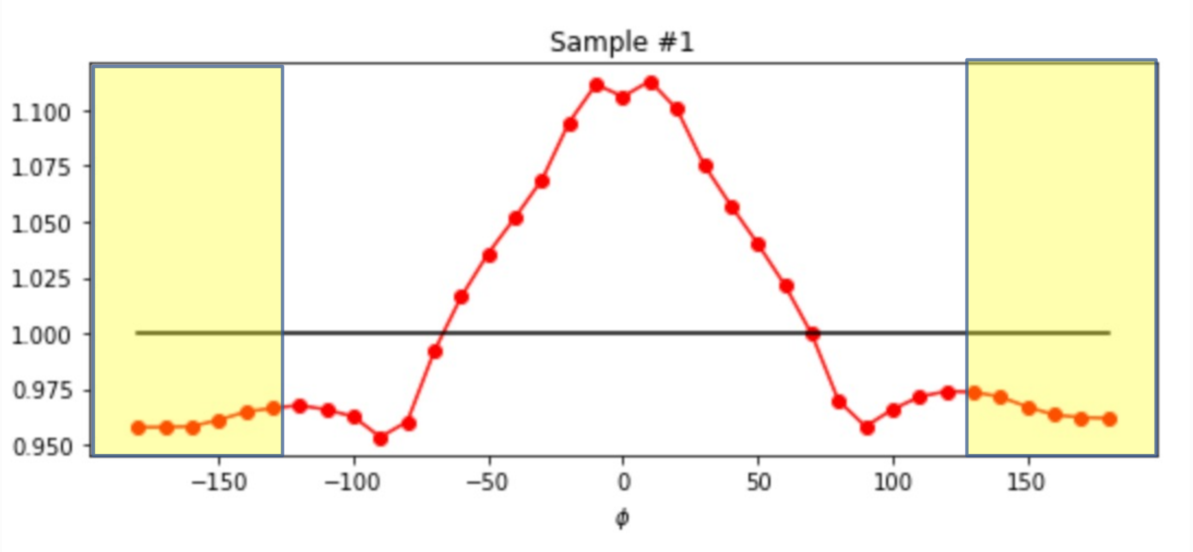
Type LED, Φ=57 lm

*All LIDs measured with our gonio-photometer at 3.16m

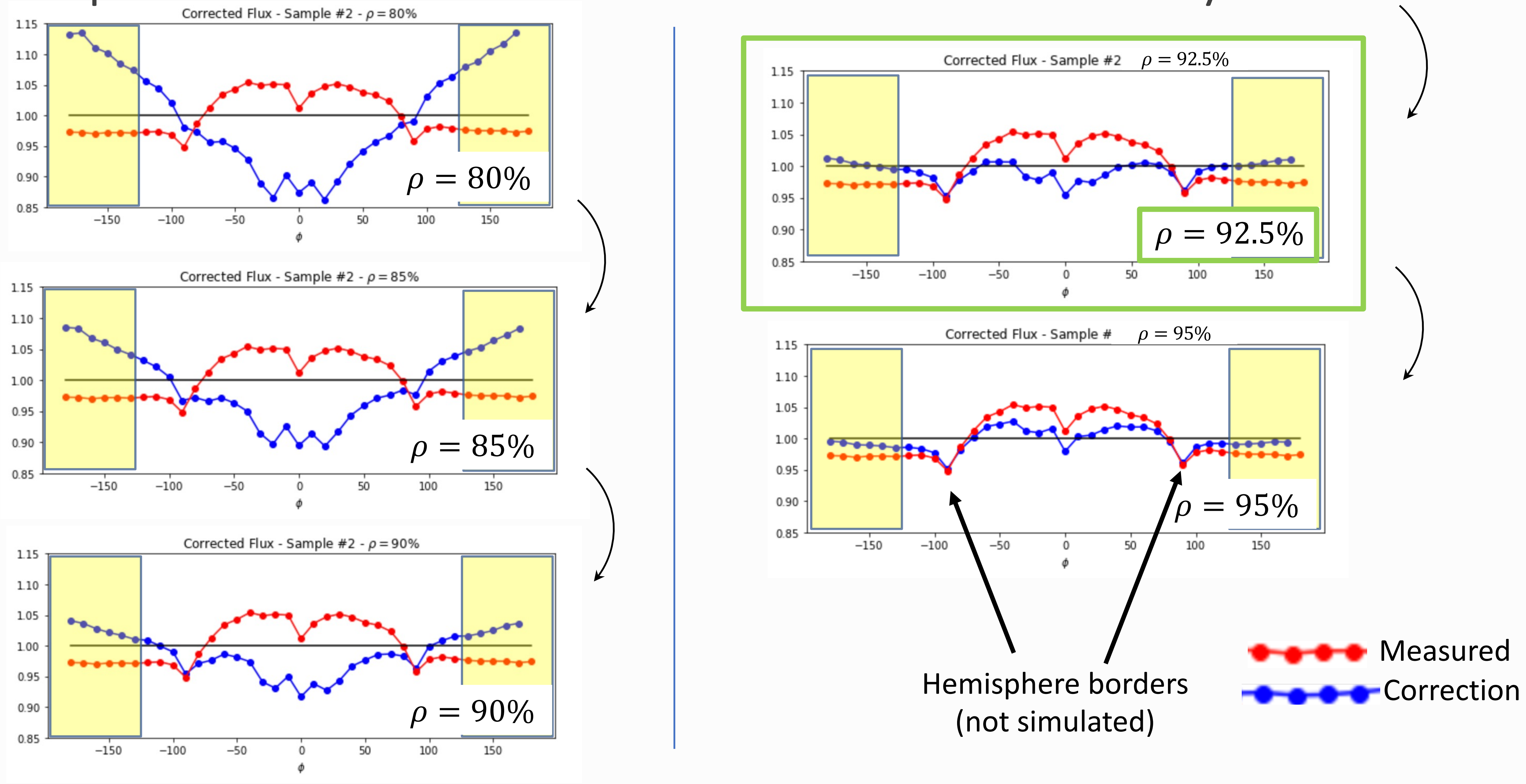
Measurement region



Optical axis parallel to the horizontal plane

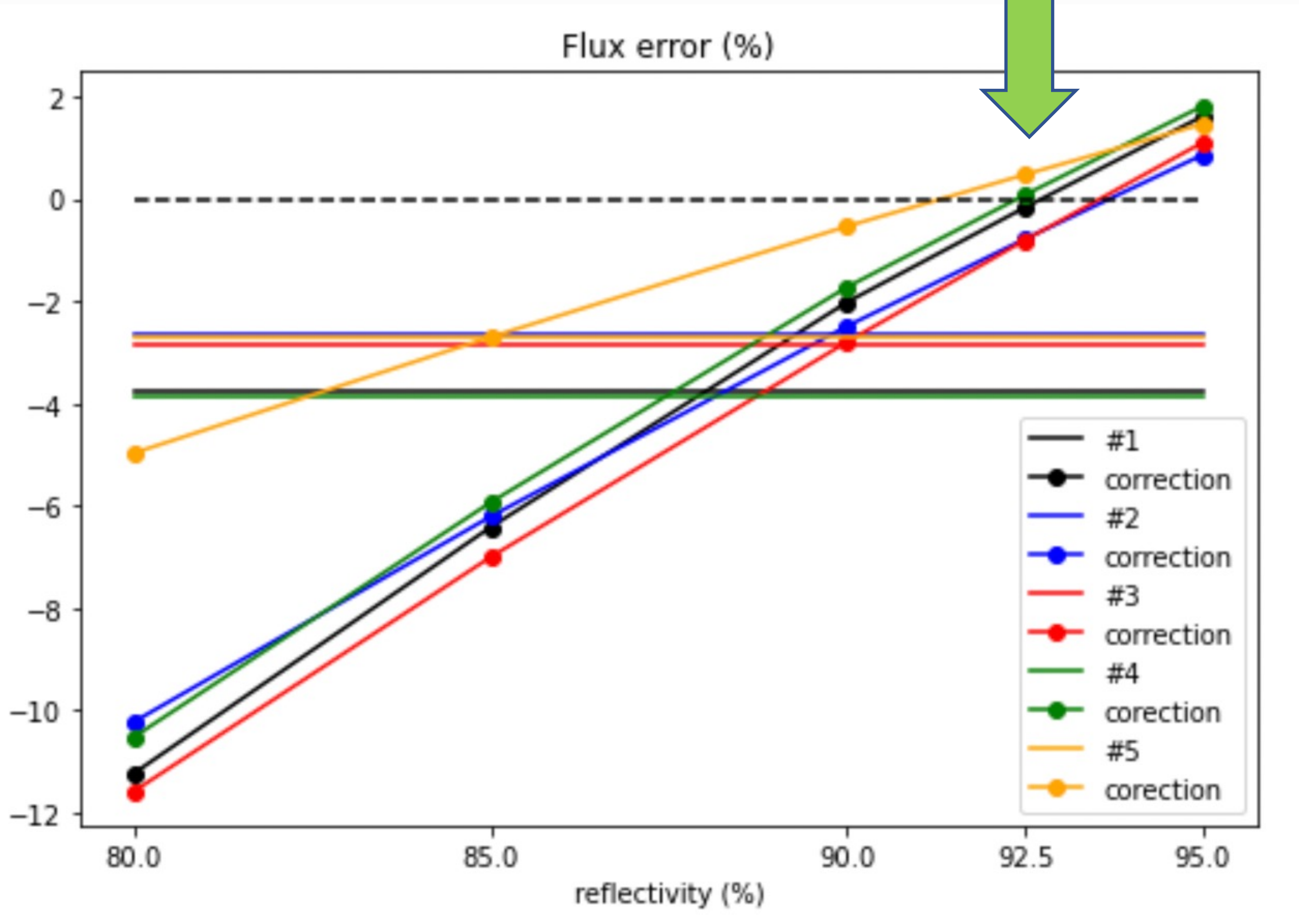


Example of corrections for different reflectivity values

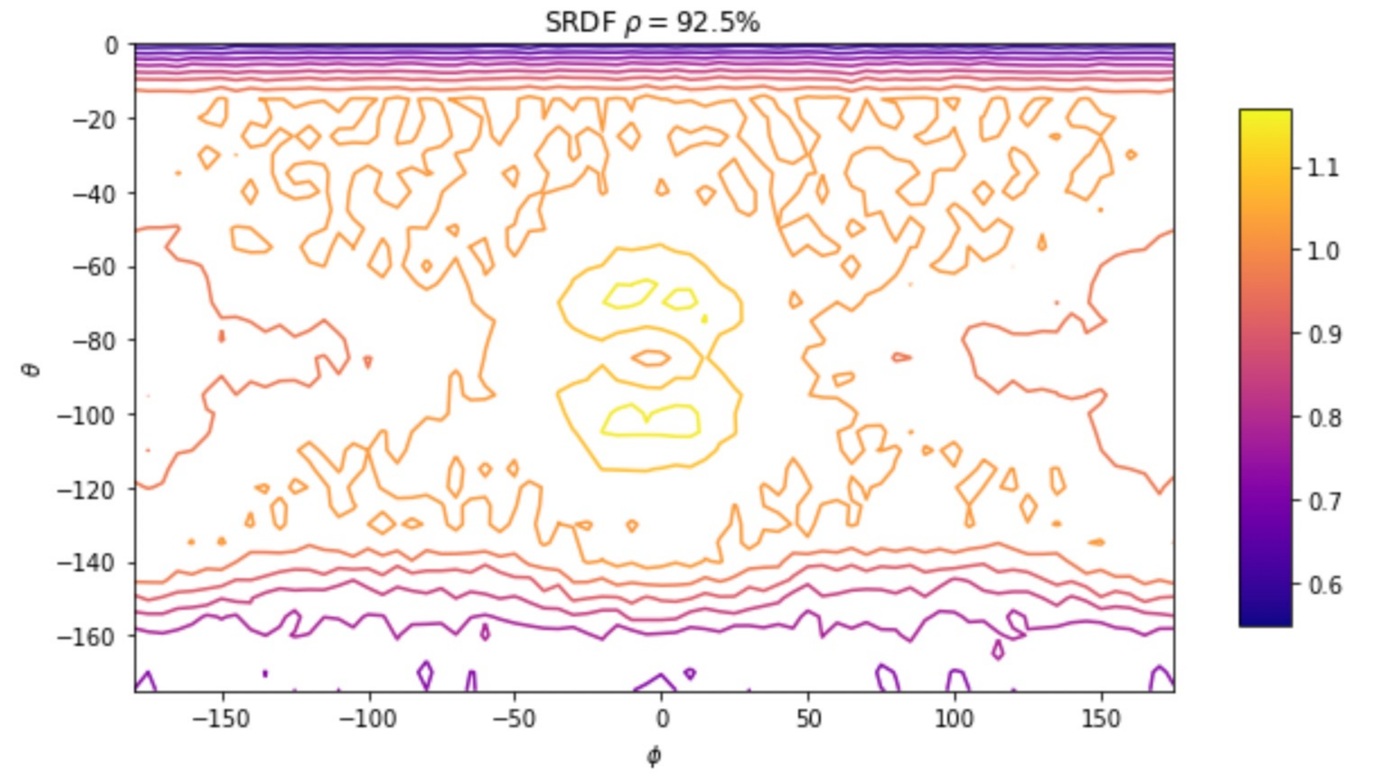


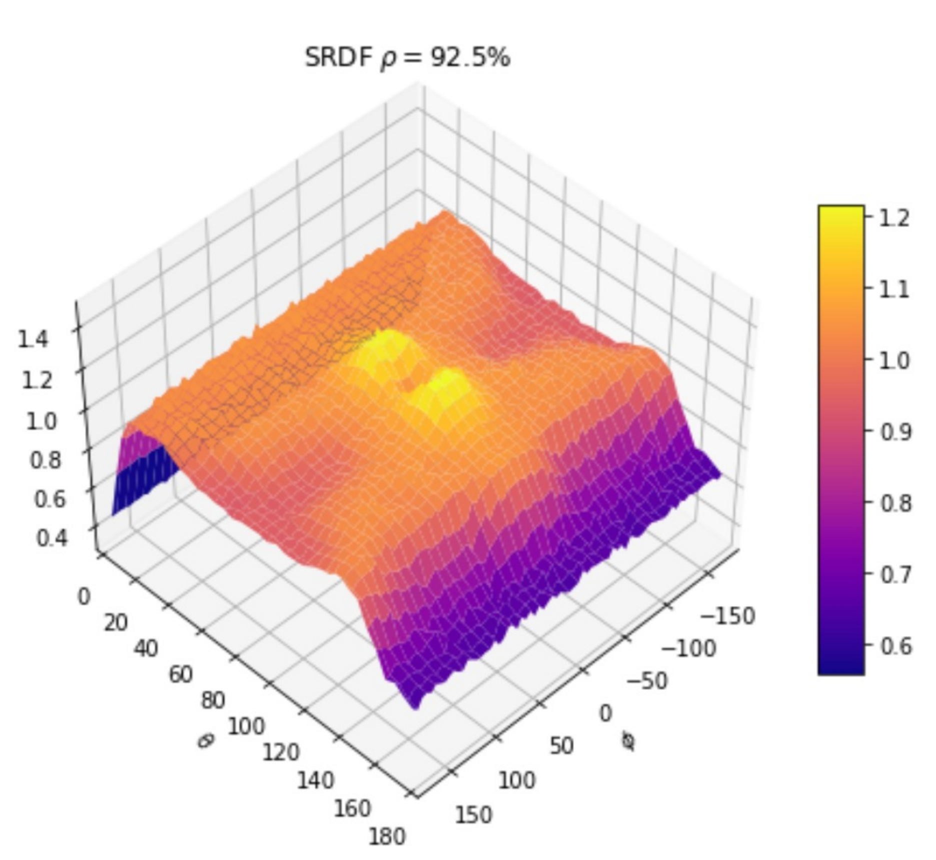
Accuracy of the corrected fluxes for different reflectivity values

Best correction $\rho = 92.5\%$

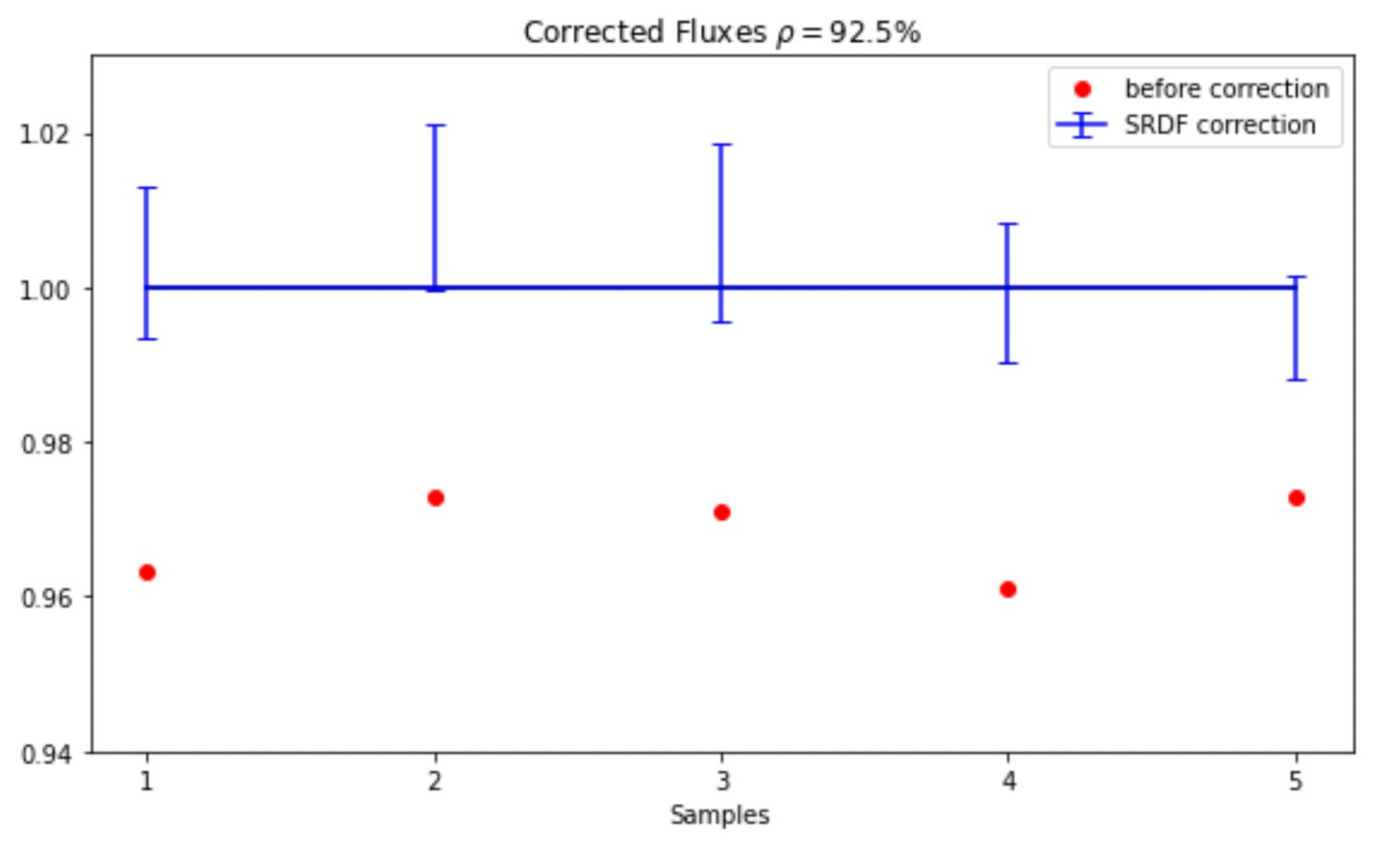


Best model for SRDF, $\rho = 92,5\%$





4. Corrections



The correction in the flux model [3]

$$\Phi = \Phi_R \cdot \frac{y}{y_R} \cdot \frac{y_{AR}}{y_A} \cdot \left(\frac{U.c_U}{U_0}\right)^{m_U} \cdot \left(\frac{J_R.c_R}{J_0}\right)^{m_{J_R}} \cdot \frac{corS_R}{corS}$$

where:

Φ_R is the flux of the reference lamp

$\frac{y}{y_R}$ is the factor of the signal of the test sample and the reference lamp

$\frac{y_{AR}}{y_A}$ is the self-absorption correction

$\left(\frac{U.c_U}{U_0}\right)^{m_U}$ is the correction of the measurement voltage of the test sample

$\left(\frac{J_R.c_R}{J_0}\right)^{m_{J_R}}$ is the correction of the measurement current of the reference lamp

The correction in the flux model [3] *(cont.)*

$$\Phi = \Phi_R \cdot \frac{y}{y_R} \cdot \frac{y_{AR}}{y_A} \cdot \left(\frac{U.c_U}{U_0}\right)^{m_U} \cdot \left(\frac{J_R.c_R}{J_0}\right)^{m_{JR}} \cdot \frac{corS_R}{corS}$$

where:

$$corS_R = (1 + \alpha_R \Delta T_{\alpha R} - \Delta sf_R - S_R - \gamma_R \Delta t_R)$$

$$corS = (1 + \alpha \Delta T_\alpha - \Delta sf - S - \gamma \Delta t)$$

$$\frac{corS_R}{corS} = \frac{1-\Delta sf_R}{1-\Delta sf} = \frac{1-0}{1-0.03} = 1.031$$

≈ 0

3% correction

where:

α is the relative temperature coefficient,

ΔT_α is the difference in ambient temperature during the measurement,

Δsf is the non-uniformity factor of the sphere: (k_s-1),

S is the factor of the influence of stray light,

γ is the luminous flux decrease coefficient due to source aging,

Δt is the total source usage time.

(Calibrated reference denoted with the subscript R)

The uncertainty budget [4]

$$\Phi = \Phi_R \cdot \frac{y}{y_R} \cdot \frac{y_{AR}}{y_A} \cdot \left(\frac{U.c_U}{U_0}\right)^{m_U} \cdot \left(\frac{J_R.c_R}{J_0}\right)^{m_{J_R}} \cdot \frac{corS_R}{corS}$$

$$Y = \Phi\,(\Phi_R, y, y_R, y_{AR}, y_A, U, c_U, m_U, J_R, c_R, m_{J_R},$$
$$\alpha_R, \Delta T_{\alpha R}, \Delta sf_R, S_R, \gamma_R, \Delta t_R, \alpha, \Delta T_\alpha, \Delta sf, S, \gamma, \Delta t)$$

GUM (Guide to the expression of uncertainty in measurement)[5]

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)} \qquad N = 23$$

Sample #3

Symbol	Type	Relative $u_{rel}(y)$ Headlamp	Relative $u_{rel}(y)$ Isotropic
ΔTa	B	0,02%	0,02%
α	B	0,00%	0,00%
Δsf	B	-1,56%	-0,05%
$S(\theta)$	B	-0,21%	-0,21%
γ	B	-0,69%	-0,69%
corS		**1,71%**	**0,70%**
$\Delta T_{\alpha R}$	A	0,02%	0,02%
α_R	B	0,00%	0,00%
Δsf_R	B	-0,05%	-0,05%
$S_R(\theta)$	B	-0,20%	-0,20%
γ_R	B	-0,01%	-0,01%
$corS_R$		**0,21%**	**0,21%**
Φ_R	B	2,10%	2,10%
y	A	0,82%	0,82%
y_R	A	-0,02%	-0,02%
y_A	A	-0,74%	-0,74%
y_{AR}	A	0,02%	0,02%
U	A	0,09%	0,09%
c_U	B	-0,11%	-0,11%
m_U	B	0,00%	0,00%
U_R	A	0,71%	0,71%
c_R	B	0,34%	0,34%
m_{JR}	B	-0,07%	-0,07%
Φ		**3,04%**	**2,61%**
	k=2	**6,08%**	**5,22%**

5. Conclusions and outlook

- ✓ Errors in luminous flux measurements of headlights due to spatial non-uniformity in the integrating sphere are not small and must be corrected.
- ✓ The SRDF of our sphere was simulated with various details using the method described by Ohno et al [1].
- ✓ It was demonstrated, with measurements from 5 samples, that the model with 92.5% reflectivity provides the best correction.
- ✓ The model was used to correct the luminous flux of the samples, with the error bars for all samples containing the corrected flux.
- ✓ The uncertainty budget is affected by the present corrections, and it can be calculated (example of Sample #3).
- ✓ The model can be improved in future simulations by adding details of the hemisphere borders.
- ✓ In a subsequent study, experimental measurement of the SRDF can further advance the characterization of our equipment, as shown by Winter at al. [6].

References

[1] 1. Yoshi Ohno & Ronald O. Daubach (2001) Integrating Sphere Simulation on Spatial Non-uniformity Errors in Luminous Flux Measurement, Journal of the Illuminating EngineeringSociety, 30:1, 105-115, DOI: 10.1080/00994480.2001.10748339

[2] Dr Alex Meakins, Matthew Carr, Sorchard1, Jack Lovell, Vlad Neverov, Koyo MUNECHIKA, Matej Tomes, & Mathias von Essen. (2023). raysect/source: v0.8.1 Release (v0.8.1). Zenodo, DOI: https://doi.org/10.5281/zenodo.7633656

[3] Cameron Miller (2014) Preview: IES Guide on Measurement Uncertainty for Lighting Equipment Calibration, CORM 2014 Annual Meeting - May 22nd, 2014 Workshop: Practical Uncertainty Analysis for Lighting Measurements

[4] Bergman, R. et al. *CALiPER Exploratory Study: Accounting for Uncertainty in Lumen Measurements*, Pacific Northwest National Laboratory, Washington, 2011.

[5] JCGM 100:2008. Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM)

[6] S Winter *et al (2009)* Convenient integrating sphere scanner for accurate luminous flux measurements, *Metrologia* 46 S248, DOI: 10.1088/0026-1394/46/4/S22

Thank you!

Questions?