Metrology for Solid State Lighting

Calibration of near-field goniophotometers

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Outline

- Task´s goal
- Motivation
- What is a near-field goniophotometer?
- Measurement principle
- Parameters involved in the calibration
- Uncertainty
- Validation

Goal

Task 1.4: Traceable near-field goniometric measurements and colour rendition

- The aim of this task is to develop a guideline for the calibration of near-field goniophotometer that are employed to resolve the angular luminance distribution of SSL sources for modeling the illuminance/luminous intensity distribution of that source in far-field conditions.

- ✓ **Develop a procedure to assign uncertainties traceable to SI for the calculation of LEDs sources using ray files**
- ✓ **Develop a guideline along this procedure for the calibration of near-field goniophotometers**
- ✓ Validate the procedure along a study of colour perception in road lighting by INRMI where a limit value of CRI is used as a decision parameter to reduce the lighting class of a system (“white light effect).

Motivation

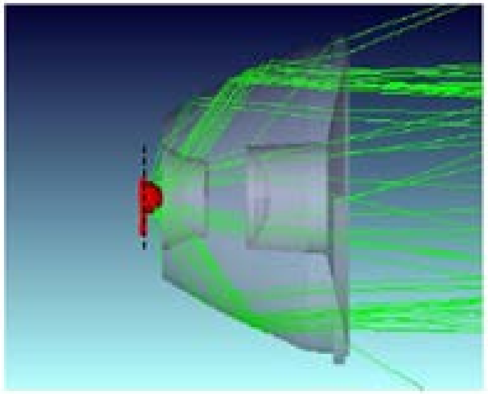
• LEDs are employed today in a great variety of applications:
⇒ Lighting, Traffic signal, Automotive, Medical lighting, etc.

• The small size of the LEDs allows to design high quality of lighting systems by using optical design software.

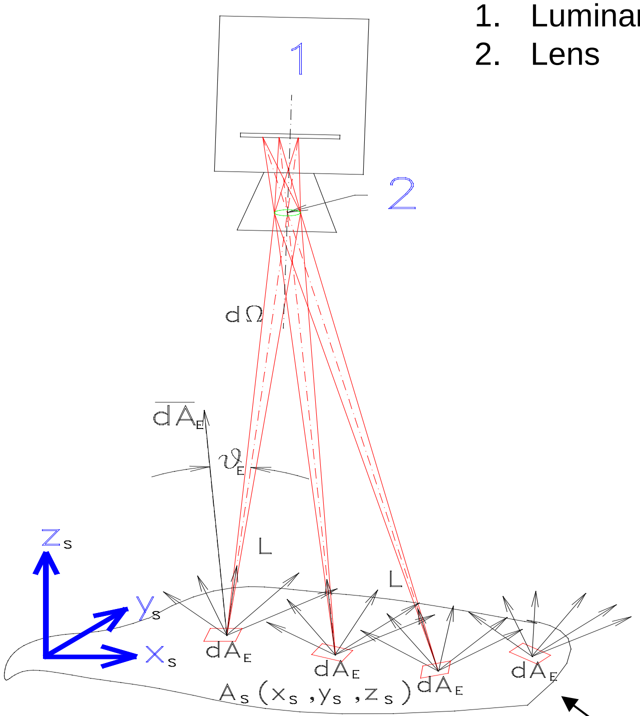
• For optical simulations, the complete distribution of the optical radiation of a light source is required (near-field model).

• **Traceability of near-field goniophotometric measurements is still missing!!**

⇒ **CIE TC-2-62: "Imaging-photometer-based near field goniophotometry", TC-2-59: "Characterization of imaging luminance measurement devices (ILMD)"**

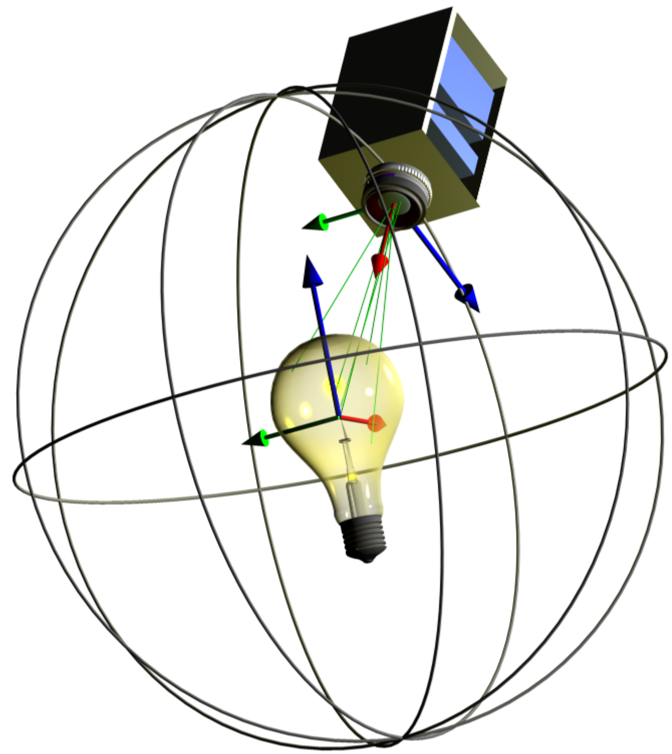


What is a near-field goniophotometer?



1. Luminance Meter (Camera)
2. Lens

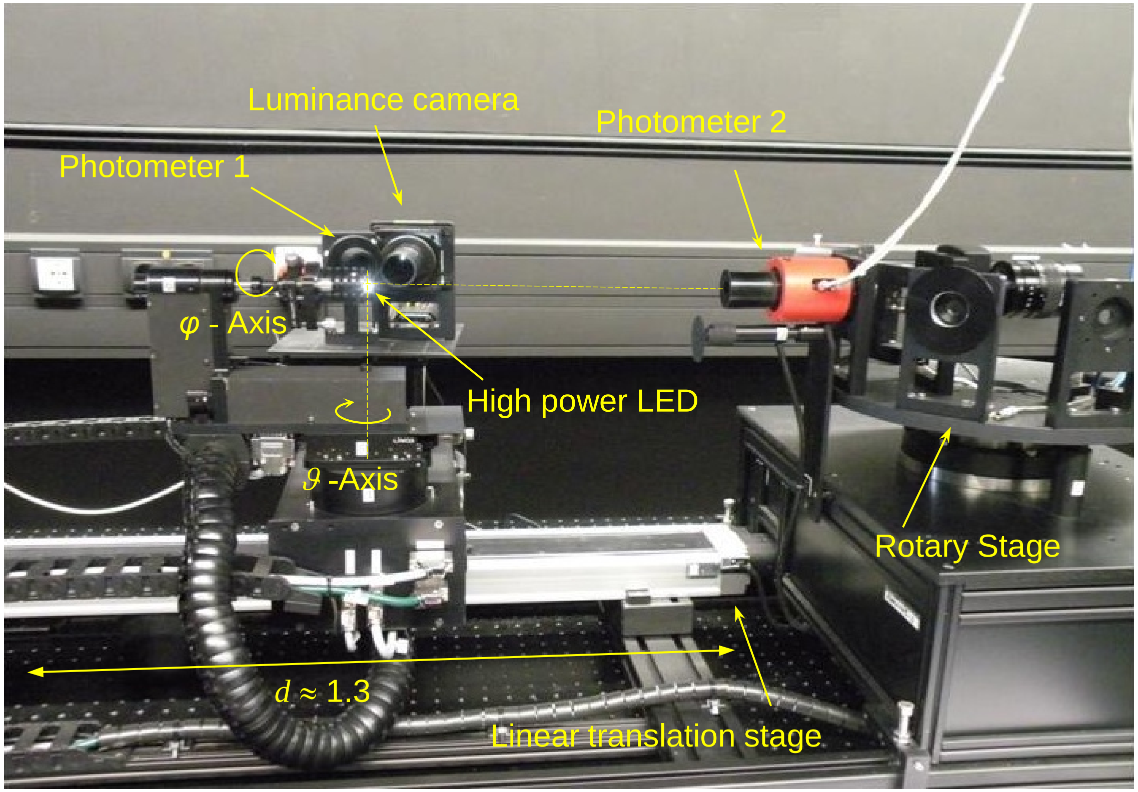
Luminance distribution



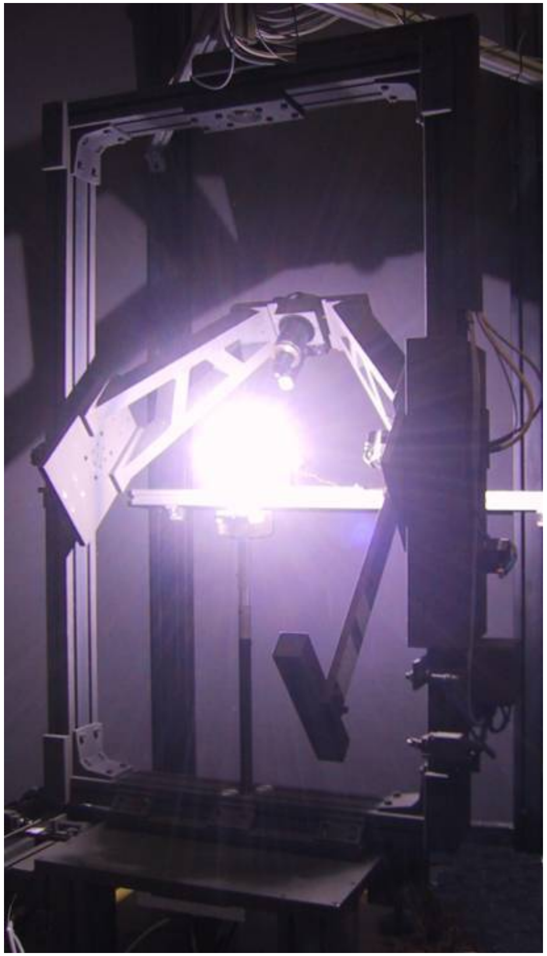
$$L_v(\vartheta_E,\varphi_E)=\frac{\mathrm{d}\Phi_v}{\mathrm{d}A_E\cdot\cos\vartheta_E\cdot\mathrm{d}\Omega(\vartheta_E,\varphi_E)}\qquad [\mathrm{cd/m^2}]$$

A near-field goniophotometer measures the luminance distribution of a light source from all light-emitting directions by using an imaging luminance measurement devices (ILMD)”

Near-field goniophotometers

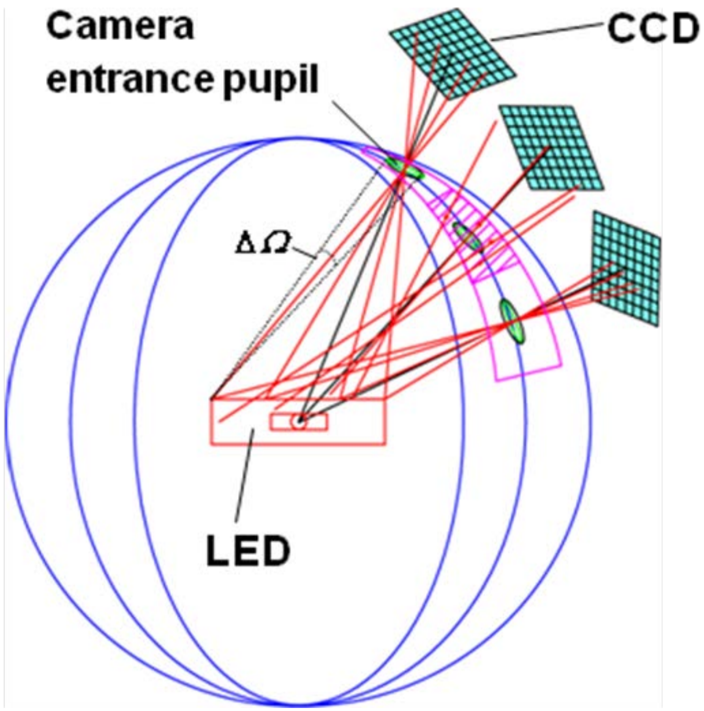


Joined far- and near-field LED-goniophotometer

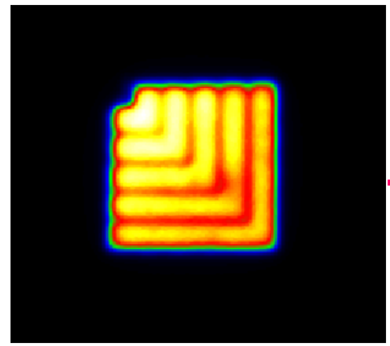


Near-field goniophotometer for Lamps

Measurement principle



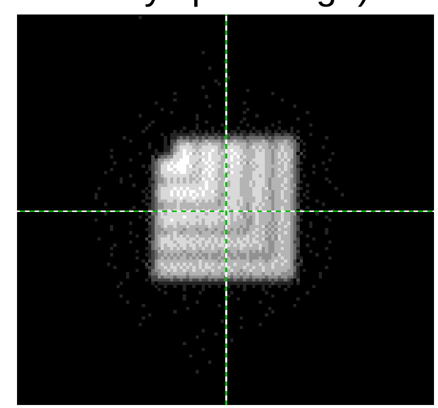
Luminance image

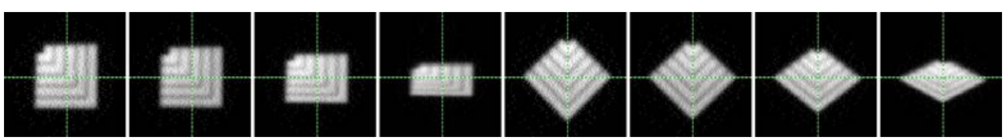


Luminance values to luminous flux portions

$$\Delta\Phi(i, j) = L(i, j)\cdot c\cdot\Delta\Omega(i, j)$$

Extracted rays (23000 rays per image)





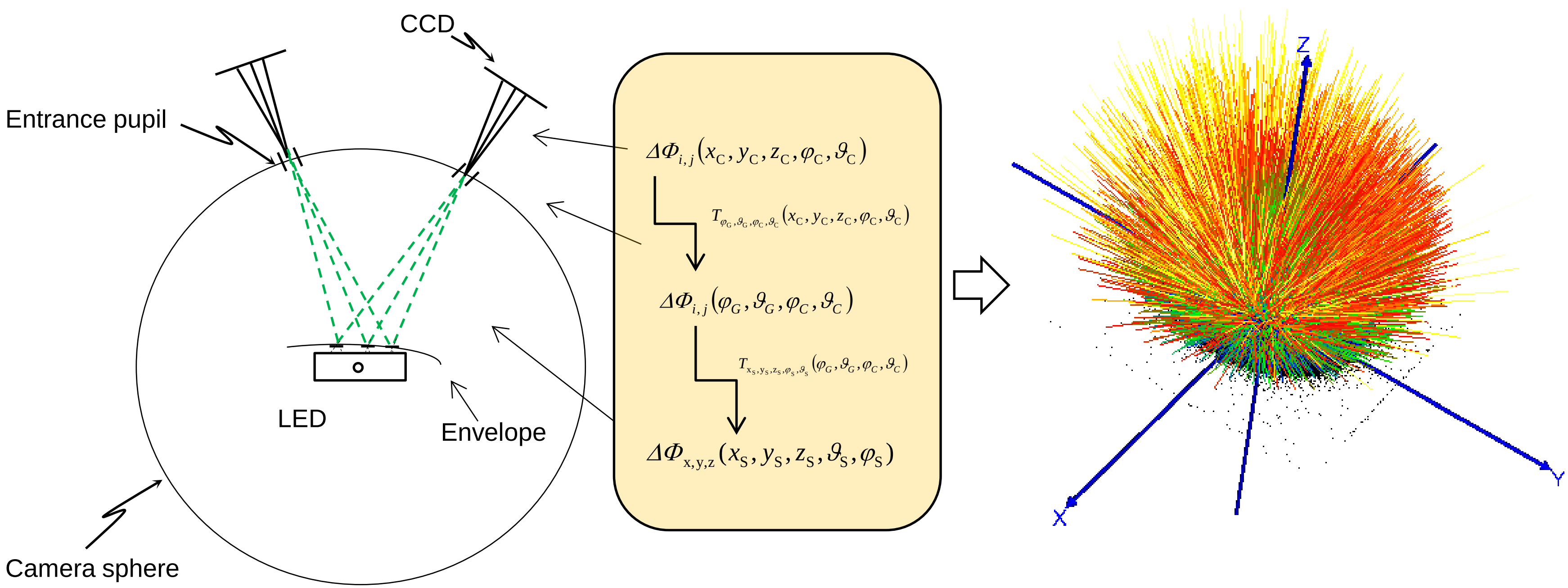
- Multiplication of each luminance pixel with is corresponding solid angle
- Extraction of rays (compression to approx. 23000 per image)

Ray-Data (“Ray-files”)

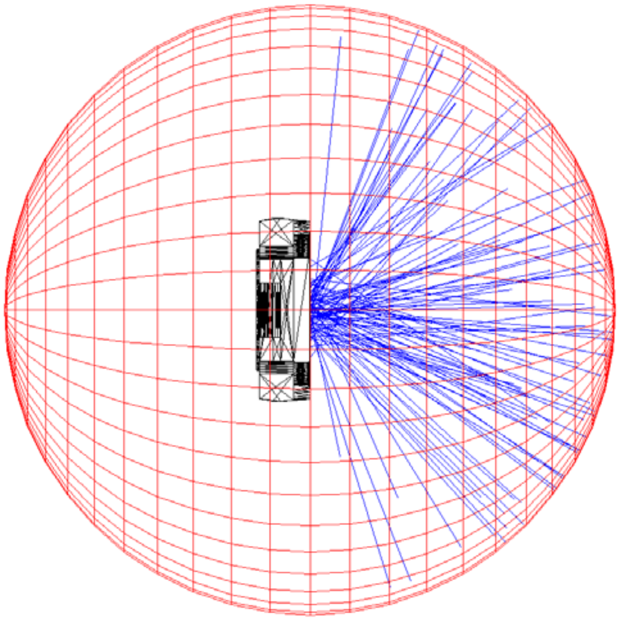
➢ Coordinate transformations are required to project the extracted rays from camera coordinates to object coordinates

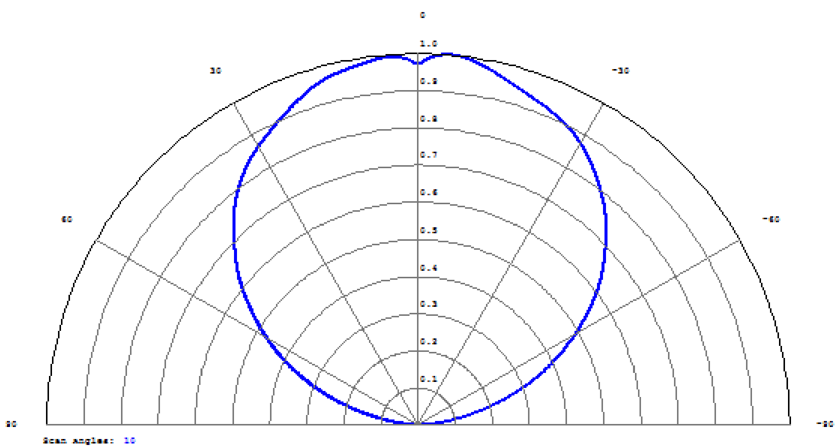
Forward tracing of vectors calculated at an addendum envelopes (green dashed) or back tracing at the real surface (black dashed)

Luminance images ⟶ coordinate transformations ⟶ Ray distribution



From near-field to far-field (with discrete values)





- **Luminous intensity distributions:**
  - ✓All rays going in one direction (solid angle) are added up

$$I(\vartheta_k,\varphi_l)=\frac{\sum\limits_{x,y,z}\Delta\Phi(x_S,y_S,z_S,\vartheta_S,\varphi_S)}{\Delta\Omega(\vartheta_k,\varphi_l)}\quad\forall\,\vartheta_S,\varphi_S\in\Delta\Omega(\vartheta_k,\varphi_l)$$

- **Total luminous flux:**

$$\Phi=\sum_{x_S,y_S,z_S}\;\sum_{\vartheta_S,\varphi_S}\Delta\Phi(x_S,y_S,z_S,\vartheta_S,\varphi_S)$$

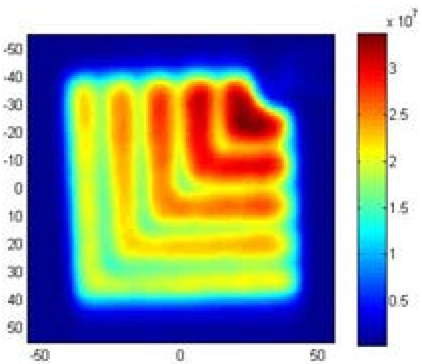
  - ✓All rays are added up

From near-field to far-field (with continues values)

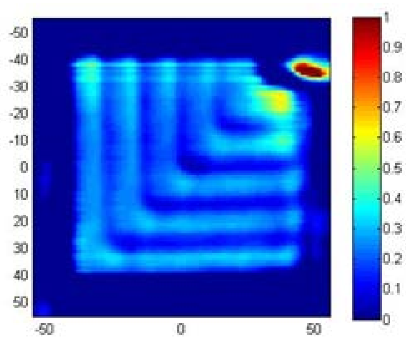
✓ Fitting the rays to a model:

$$L(x_i, y_i) = L_0(x_i, y_i) Cos^{g(i,j)}(\theta_i)$$

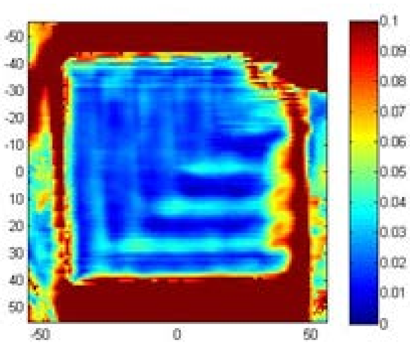
Coefficient: $L_0(x_i, y_i)$



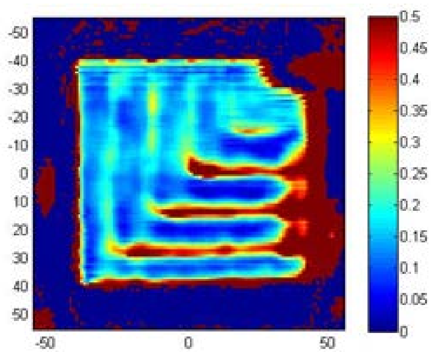
$g(i, j)$



RMS ($L_0(x_i, y_i)$)

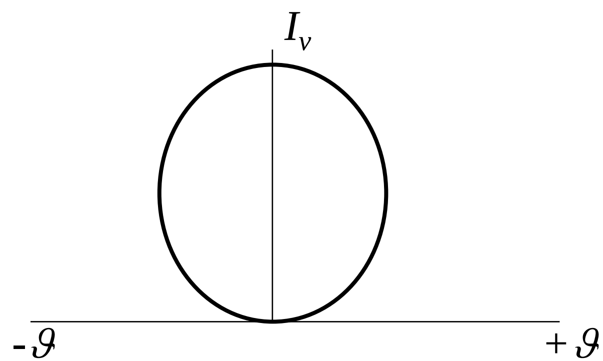


RMS ($g(i, j)$)



➢ **Luminous intensity distributions:**

$$I(\vartheta_S, \varphi_S) = \int_A L(x_S, y_S, z_S, \vartheta_S, \varphi_S)\, dA_P$$



The model allows to interpolate where measurement values are missing!

➢ **Total luminous flux:**

$$\Phi = \int\int_{A,\Omega} L(x, y, z, \vartheta, \varphi) \cdot dA \cdot \cos\vartheta \cdot d\Omega$$

Parameters involved in the measurement

- Luminance image
- Geometry

Model

$$\mathbf{L} = \frac{1}{A_{\mathrm{P}} \cdot \overline{\mathbf{P}\mathbf{P}}_{\mathrm{L}}} \cdot k_{\mathrm{L}} \cdot \frac{f_{\mathrm{NL}}(\mathbf{S} - D_0) \cdot (\mathbf{S} - D_0 - \overline{\mathbf{D}})}{k_{\mathrm{Sys}} \cdot t_{\mathrm{I}}}$$

Luminance image → $\mathbf{L}$

Calibration factor → k_{L}

Non-linearity correction → f_{NL}

Dark offset → D_0

Camera image → $\mathbf{S}$

Dark signal non-uniformity → $\overline{\mathbf{D}}$

Shading (lens, CCD) → $\overline{\mathbf{P}\mathbf{P}}_{\mathrm{L}}$

System transfer factor → k_{Sys}

Integration time → t_{I}

The calibration factor k_{L} transfers the unit cd/m^2 to the pixel´s signal .

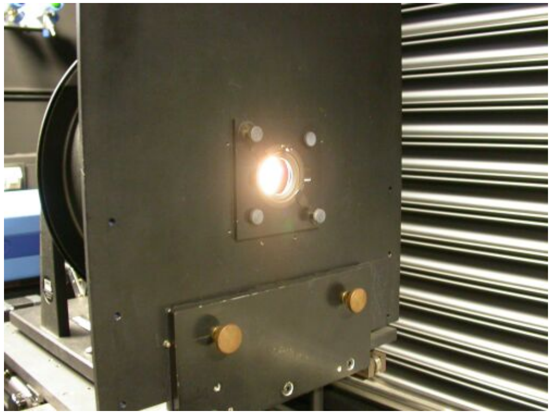
Traceability – Luminance –

a) by means of the luminous intensity and a reference aperture A_1

$$L_{\mathrm{m}} = \frac{I_{\mathrm{v}}}{A_1}$$

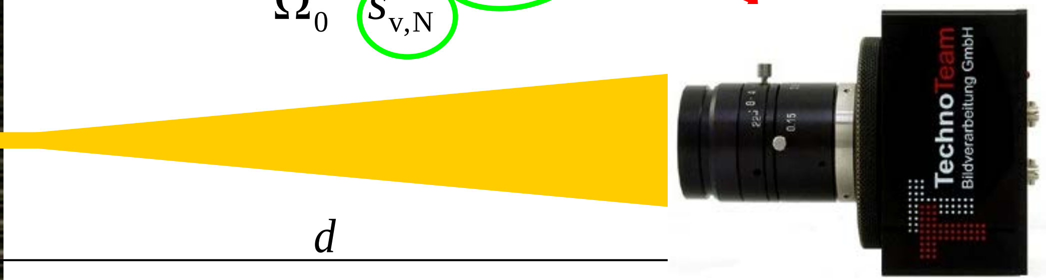
Average luminance on the aperture area

Unit: cd/m^2

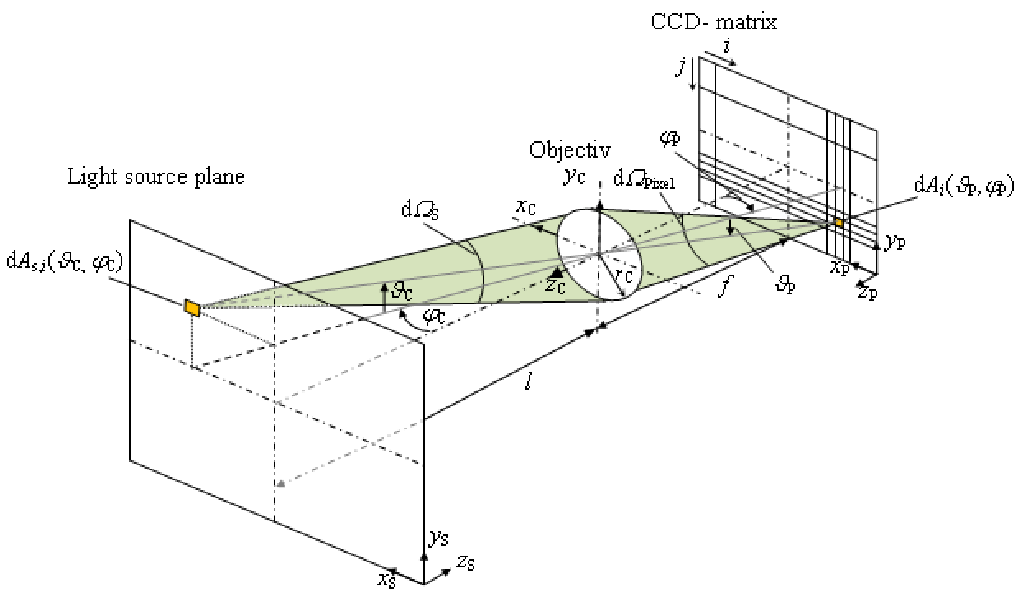


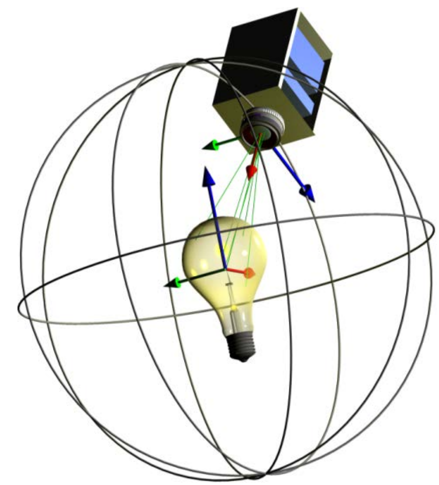
$$I_{\mathrm{v},i}\left(T_{\mathrm{v},i}\right) = \frac{d^2}{\Omega_0} \cdot \frac{y_i}{s_{\mathrm{v,N}}} \cdot F(T)$$

y_i

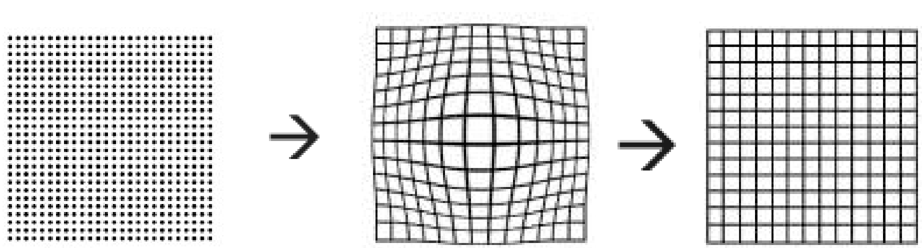


Traceability - Geometry (Position and direction) -





Camera Shading / Vignetting



Reference grid

Image

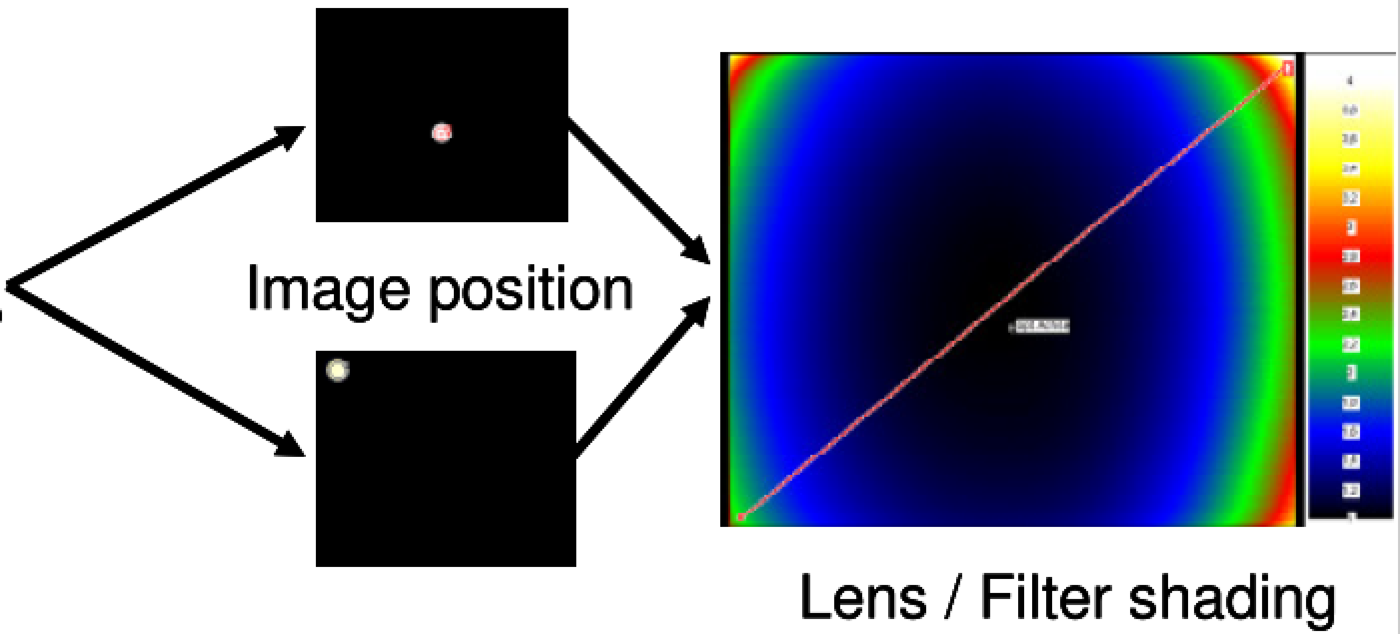
Corr. Image

Camera/Goniophotometer Axis

- Measurement of the entrance pupil position of the camera
- Measurement of the camera position in goniophotometer coordinates

Example of camera shading

Influence of the image position?



Source of shading:

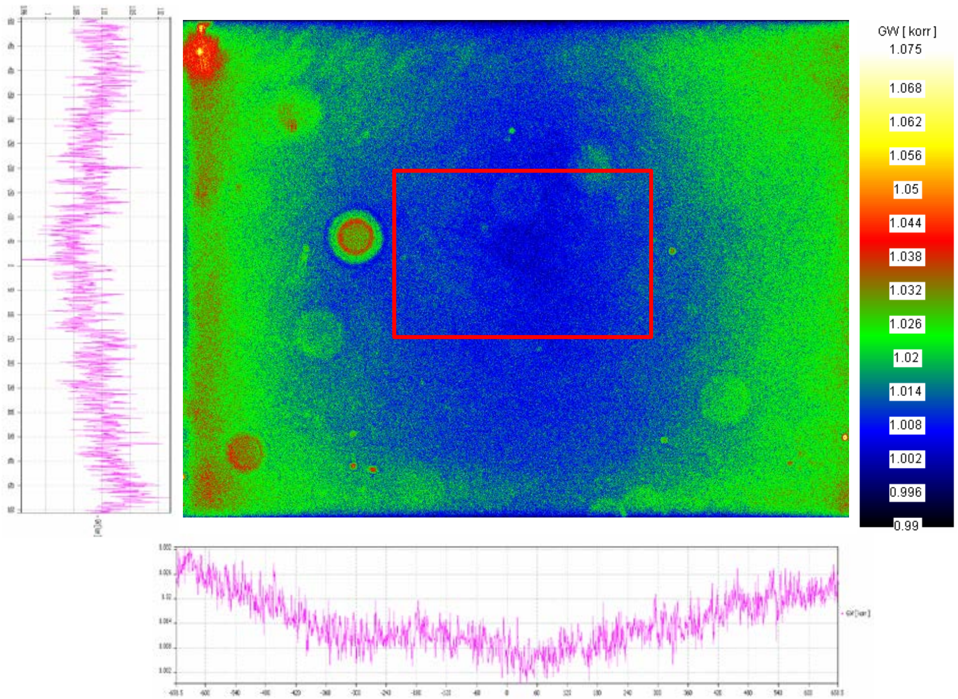
- ✓ Optical lens
- ✓ Angle-of-view of the lens
- ✓ Micro-lens (image sensor)

Shading correction factor is required to correct the influence of the different pixel sensitivities of the CCD and the distortion/vignetting of the lens. This correction has a spatial dependence on the CCD and depends also from the objective type used. The matrix correction is obtained by means of a flat field measurement or several measurements of a small light light source.

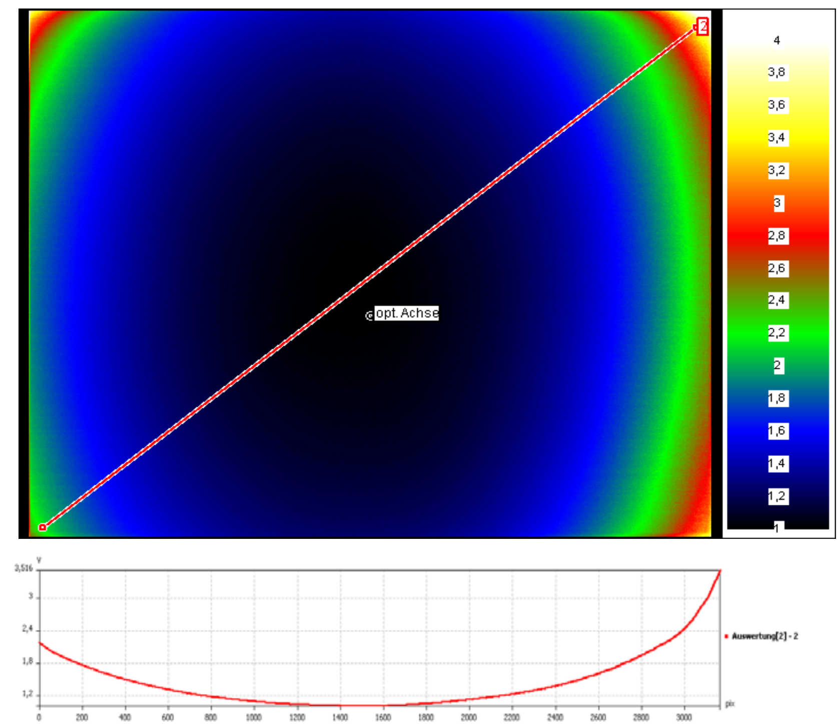
Shading correction matrix

Example of shading correction:

TT- Makro 50 mm



TT- 12 mm



Uncertainty budget

Example of an uncertainty budget for a pixel:

Evaluation model: $\mathbf{L} = \frac{k_L}{\overline{\mathbf{P}} \cdot \mathbf{P}} \left(\frac{(\mathbf{S} - D_0) \cdot (\mathbf{S} - D_0 - \mathbf{D})}{t_i \cdot A_p} \right) c_{\text{Elec}} \cdot c_{\text{Str.light}} \cdot c_{\text{Spectral}} \cdot \mathbf{c}_{\textbf{Dist}}$

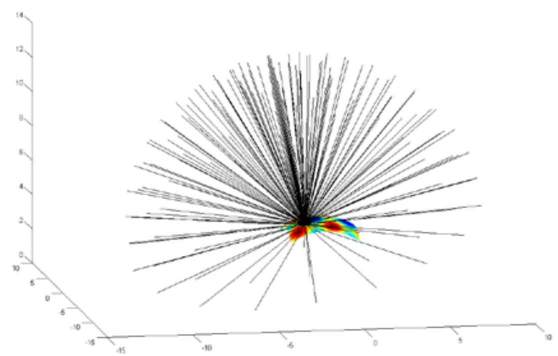
No.	Quantity	Symbol	Value	Standard uncertainty	Type	Dist.	Degree of freedom	Sensitivity Coefficient	Uncertainty contribution / (cd/m²)
1	Signal value	S_{00}	3500 LSB	105 LSB	A	Normal	10	10.9	1144.8
2	Calibration factor	k_L	1.063×10^{-2} cd/ m² ·LSB· /s	8×10-4 cd/LSB·m2	A	Normal	∞	3.39×10^6	2712
3	Shading	*P*	1.002	0.005	A	Normal	10	-35972.5	-179.9
4	*PRNU*	*P0*	1.002	0.008	B	Uniform			-287.8
5	Global dark signal	D_0	60 LSB	10 LSB	A	Normal	10	-10.89	-109
6	Dark signal no uniformity	D_{00}	0.2	0.02	B	Uniform	10	-10.89	-0.218
7	Nonlinearity	f_{NL}	1.02	0.004	B	Uniform	10	35338	141
8	Integration time	t_i	0.001 s	0.000001 s	A	Normal	10	-3.6×10^7	-3.6
9	Spectral mismatch	c_{Spectral}	1.002	0.002	A	Normal	10	35972	71.94
10	Electrical conditions	$c_{\text{Elec.}}$	1.005	0.00005	A	Normal	10	35865	1.79
11	Stray light	$c_{\text{Str\_light.}}$	1.000	0.002	A	Normal	10	36044	72.1
12	Objective distorsion	$c_{\text{Dist.}}$	1.002	0.007	A	Normal	10	35972	251.8
	Luminance	**cd/m²**	**36044**					***u*=**	**2981.35**

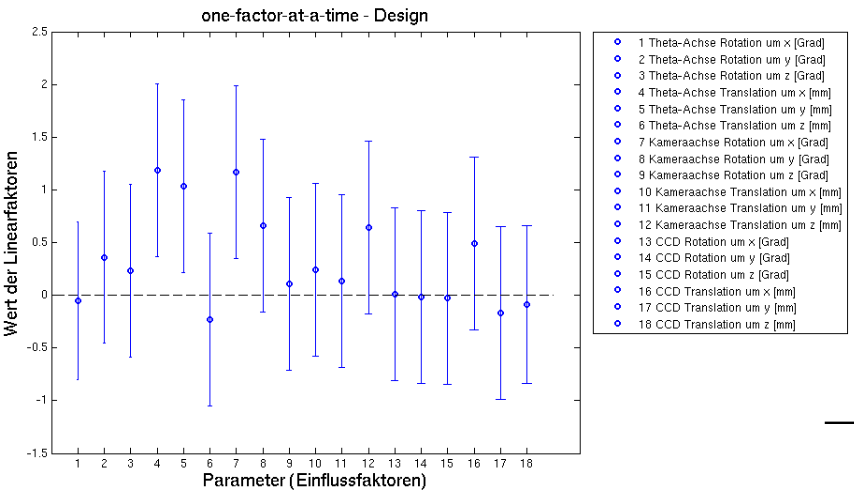
Geometric parameters (Sensitivity analysis)

- Near-field goniophotometer simulation based on the pinhole camera approach

Sensitivity analysis by means of a computer model of a near-field goniophotometer

D:\Franko\Folien\Simu_animated.gif





Sensitivity / Importance	Weight	Parameter
1	55	Theta-Axis Translation x (4)
2	54	Camera- Axis Rotation θ_y (8)
3	52	Camera-Axis Rotation θ_x (7)
4	47	Theta-Axis Translation y (5)
5	44	Camera-Axis Translation z (12)
6	42	Camera-Axis Translation x (10)
7	38	Camera-Axis Translation z (6)
8	38	Camera-Axis Translation y (11)
9	35	CCD Translation x(16)
10	26	CCD Translation y (17)
11	24	Theta-Axis Rotation z (3)
12	23	Theta-Axis Rotation y (2)
13	19	Theta-Achse Rotation x (1)
14	16	Camera- Axis Rotation z (9)
15	12	CCD Translation z (18)
16	5	CCD Rotation x (13)
17	5	CCD Rotation z (15)
18	3	CCD Rotation y (14)

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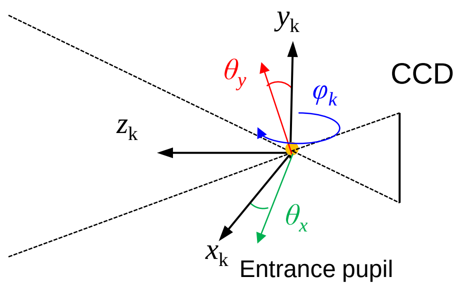
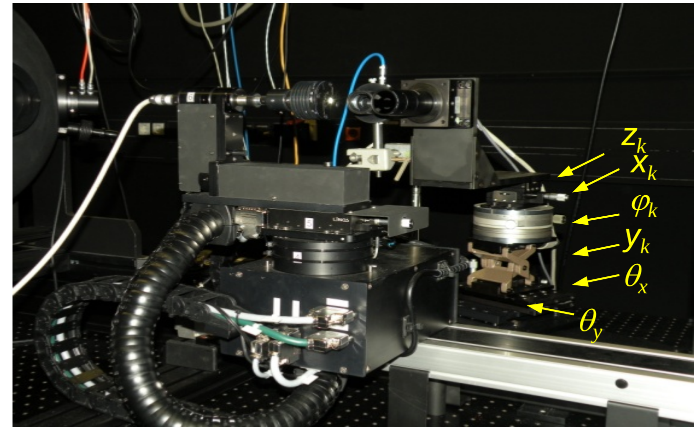
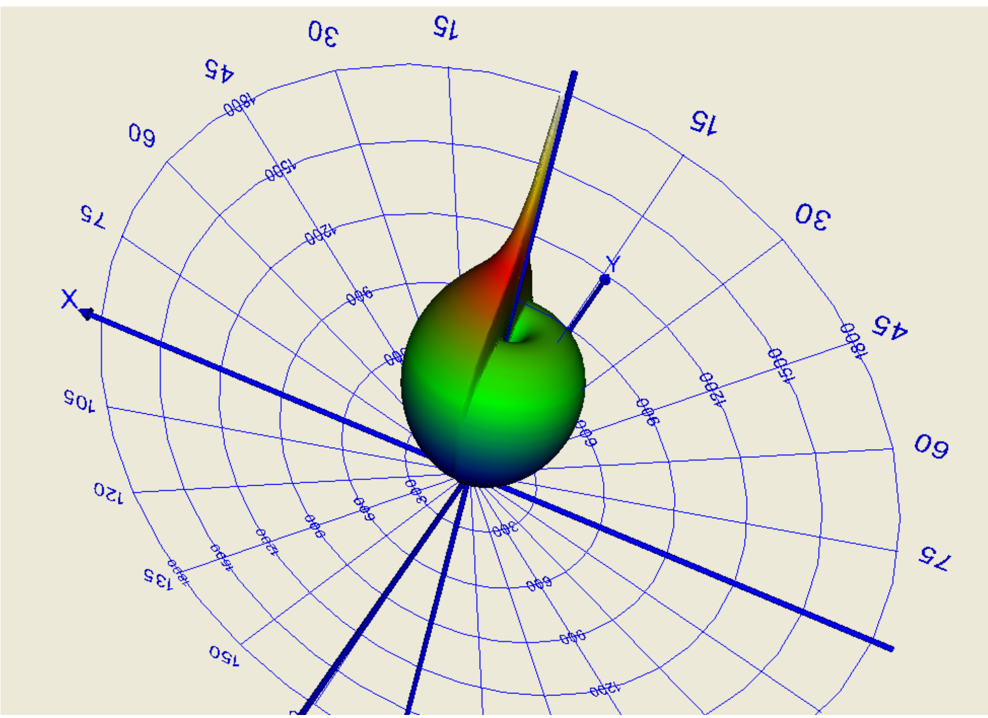
Validation of the simulation: Rot. x-Axis

Angel rotation Θ_x: 1.0°

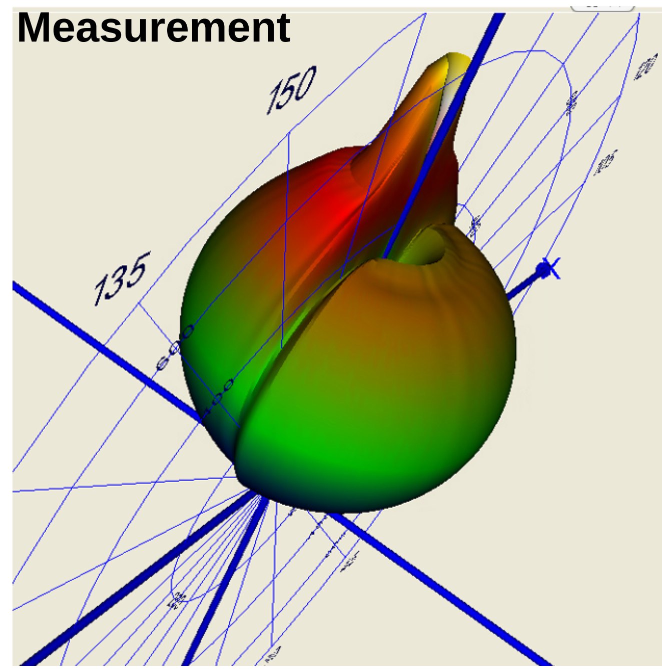




Simulation



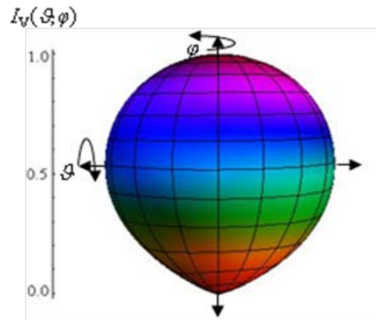
Measurement

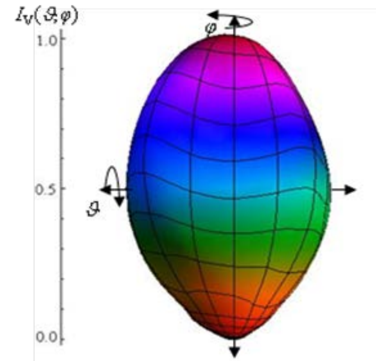


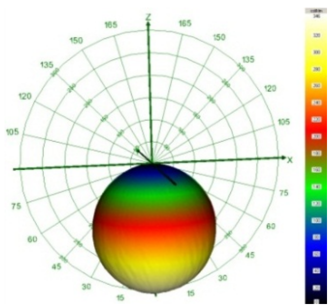
Transfer standards

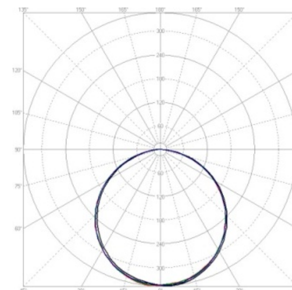
LED based transfer standards:

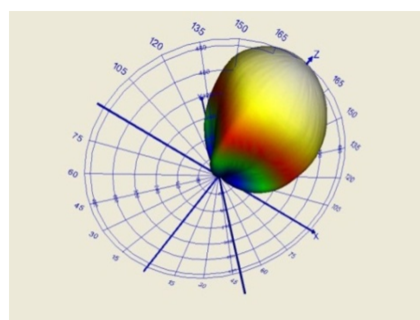
Luminous distribution:

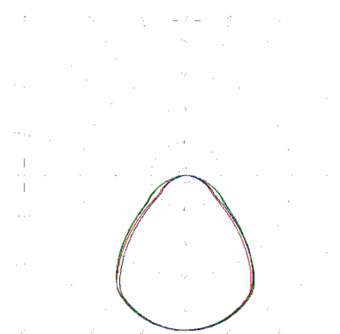






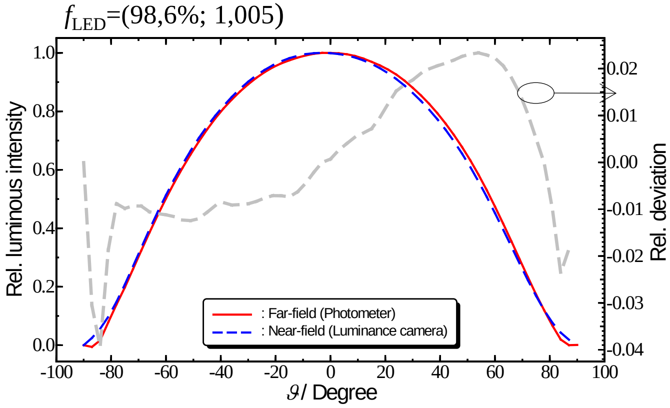


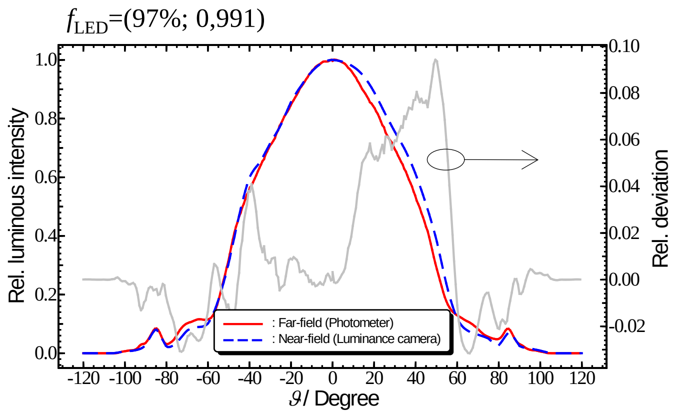




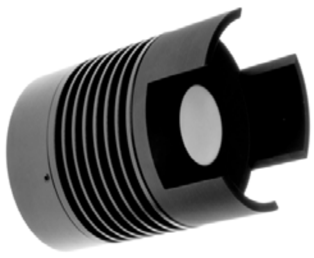
Comparison of luminous intensity distributions (Far- and Near- field)

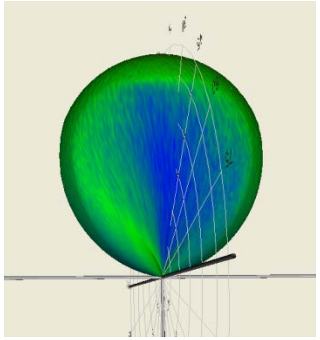
PTB LED based transfer standards:

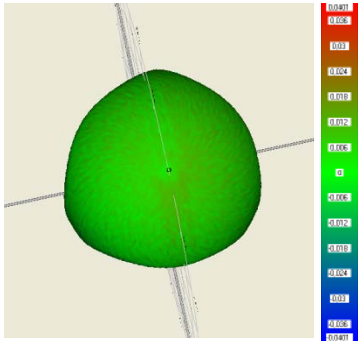




Commercial LED based transfer standards:







Distance	Average deviation		Maximal deviation		
	[cd]	[%]	[cd]	[%]	Direction (ϑ,φ) [°]
TT – PTB-3m	7.49×10^{-3}	2.02	0.0313	8.4	(72, 36)
TT – PTB-4m	7.25×10^{-3}	1.95	0.0301	8.1	(179, 41)
TT – PTB-5m	7.18×10^{-3}	1.93	0.0302	8.1	(182, 36)

For more information:

<u>Traceability WP1:</u>

- ✓ D1.4.1 Validated procedure to assign uncertainties traceable to SI for calculation of SSLs sources using ray files
- ✓ Guideline for calibration of near-field goniophotometer

<u>Applications WP2:</u>

- ✓ Protocol of the spectral, thermal and temporal interdependencies and their influence on the reliability of ray files of LED
- ✓ Proposed guideline for the implementation of auxiliary data with ray files to increase the robustness of ray files with respect to LED specific properties, feeding this proposal into standardising bodies

Thank you for your attention!