Karlsruhe Institute of Technology

Lux junior 2017

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Colour Measurement with Colorimeter: Mismatch of Colour Matching Functions

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Motivation I

- Applications with special requirements
  - Operating room lighting
    - Error free optical medical tasks
  - Automotive lighting
    - Chromatic errors
  - Aircraft interior lighting
    - Aesthetic aspects
- Colour analysis
  - Chromaticity coordinates and homogeneity

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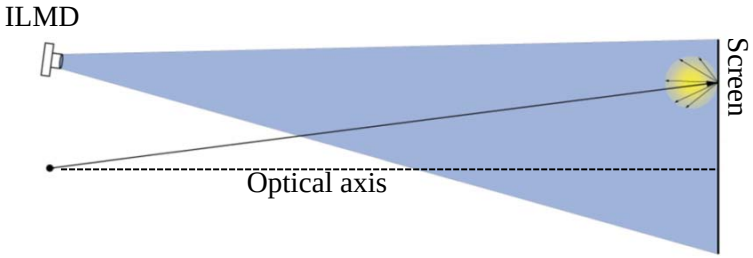
Colour measurement: State of the art

- Measurement tristimulus values *X*, *Y* and *Z*
  - Integrating sphere
    - Spectrometer
  - Goniometer
    - Spectrometer
    - Colorimeter
    - Luminance camera + white screen

↑ angular resolution
↑ measurement time



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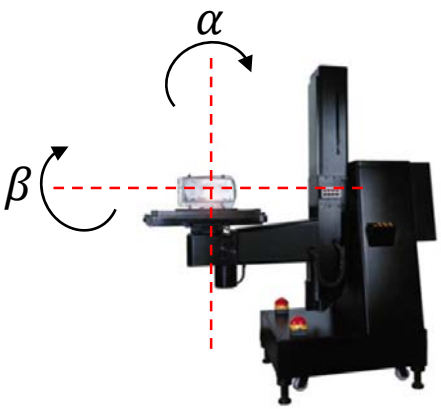
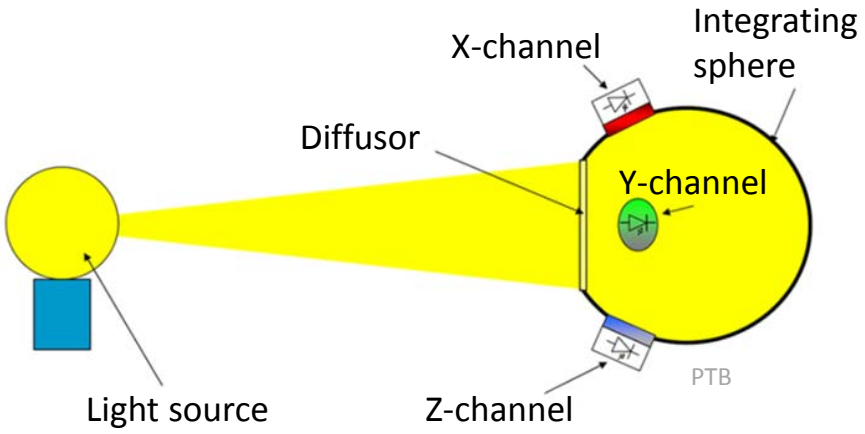
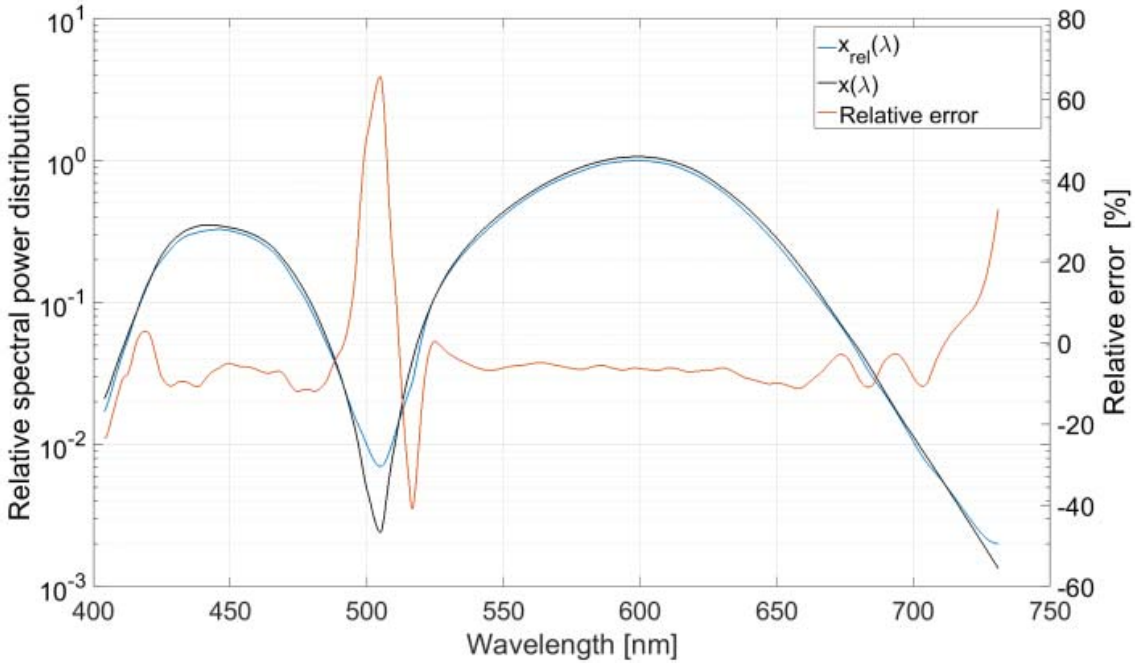


Gonio-Colorimeter: spectral mismatch

- Colour matching functions

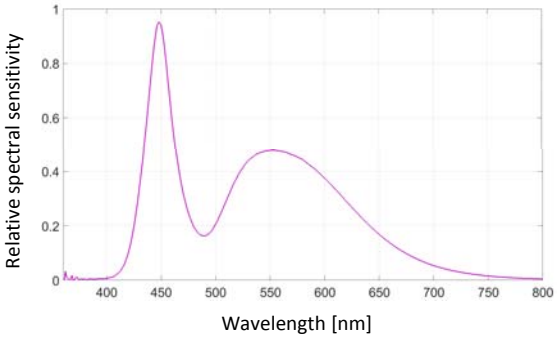
$$X = k \int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda$$

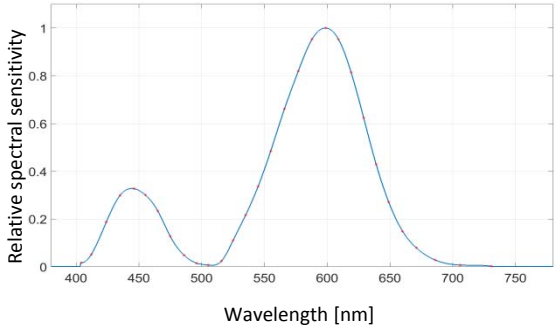




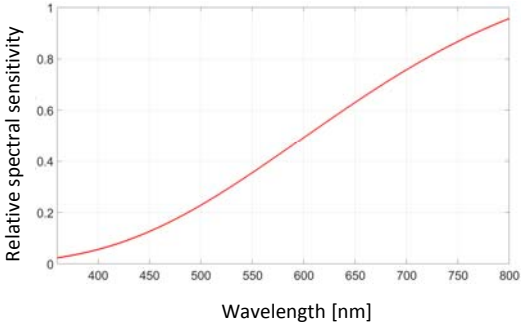
Correction

- SMCF: spectral mismatch correction factor



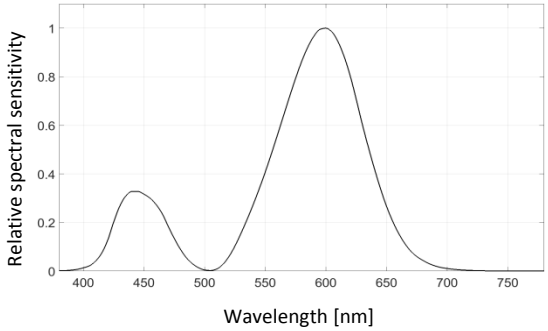


$$a^*{}_X = \frac{S_Z}{S_A} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda,\theta,\phi) \cdot x_{rel}(\lambda) \cdot d\lambda \,/\, \int_{360}^{830} S_Z(\lambda,\theta,\phi) \cdot \bar{x}(\lambda) \cdot d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} S_A(\lambda) \cdot x_{rel}(\lambda) \cdot d\lambda \,/\, \int_{360}^{830} S_A(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda}$$



$$SMCF(\theta,\phi) = \frac{1}{a^*} = \frac{S_A}{S_Z}$$

$$SMCF = 1$$



Measurement concept I

- Necessary steps to correct tristimulus values:

Step 1 — Measurement of tristimulus values

↓

Step 2 — Spectral measurements

↓

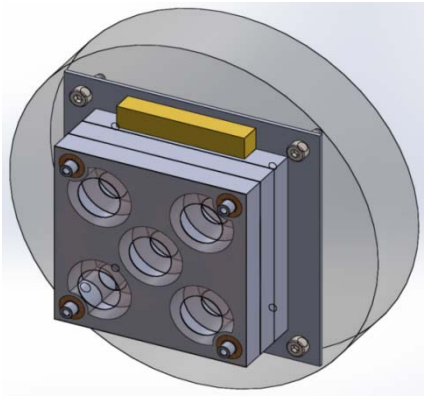
Step 3 — Luminance camera measurements

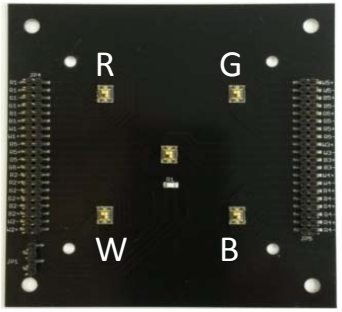
↓

Step 4 — Pixel spectral power distribution / SMCF } $S_Z(\lambda, \theta, \phi)$ for all points

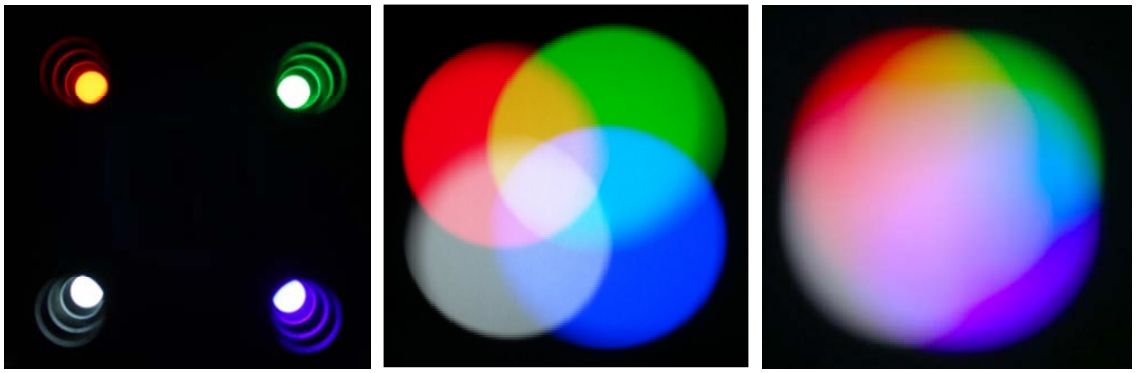
Device under test (DUT)

- Special DUT with known photometric quantities
  - Metal circuit board with 5 RGBW LEDs
  - Defined LID
    - Aperture system
  - Fixed working point (temperature)
    - Stable spectra
    - Stable photometric values
  - Colour mixing effects





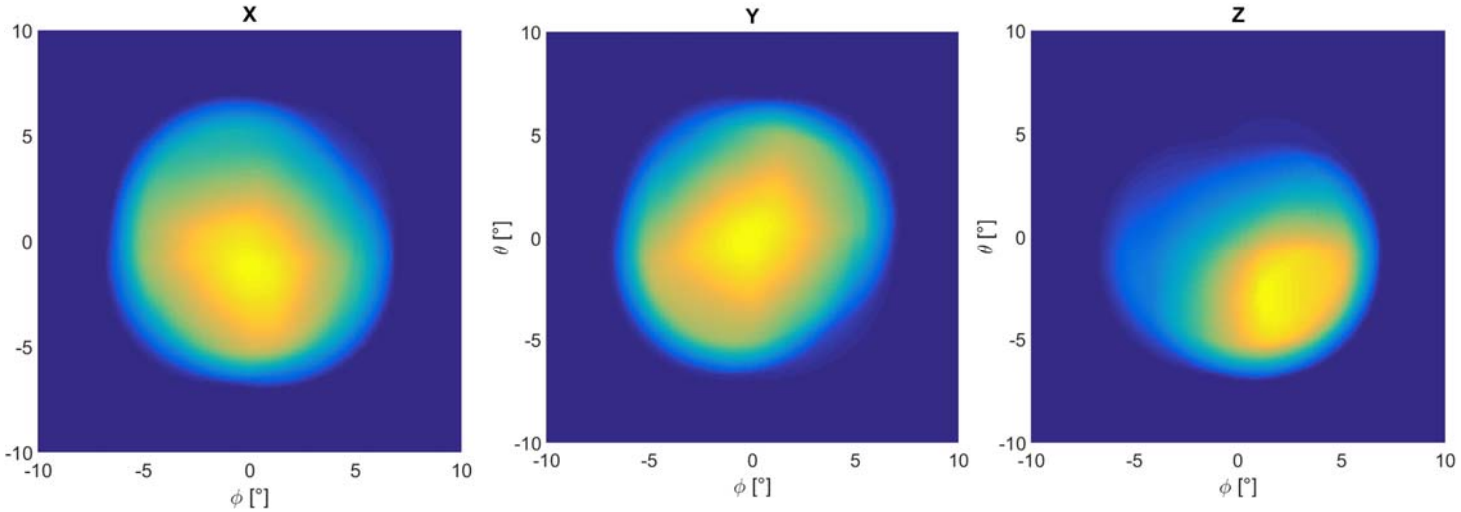
- R-G-B-W setup

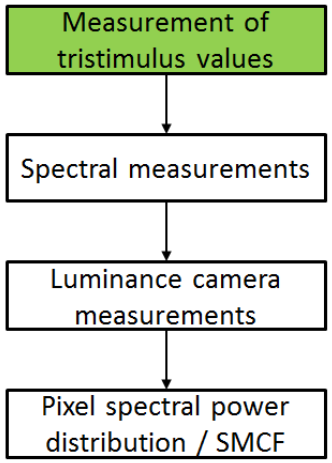


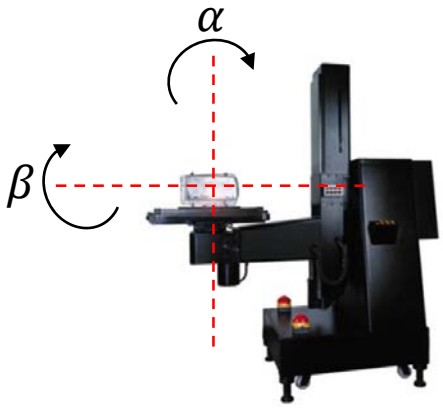
Near field | 0.3 m Far field | 10 m

Measurement concept: step 1

- Measurement of tristimulus values with gonio-colorimeter
  - Resolution: 0.1°







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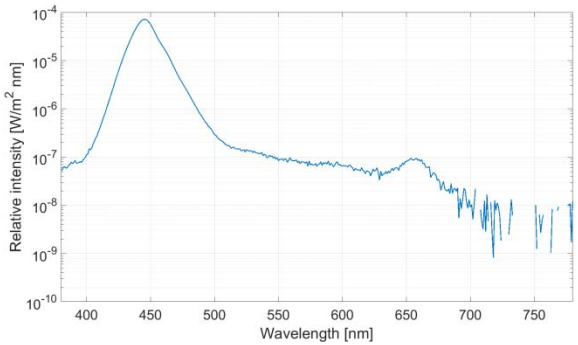
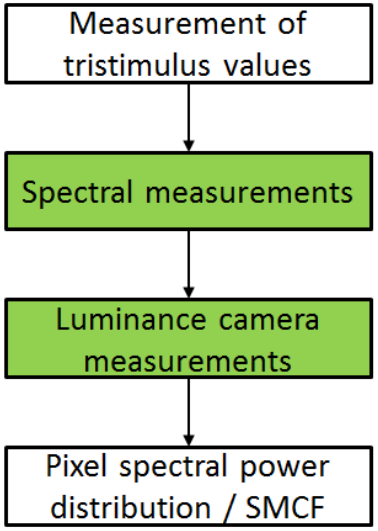
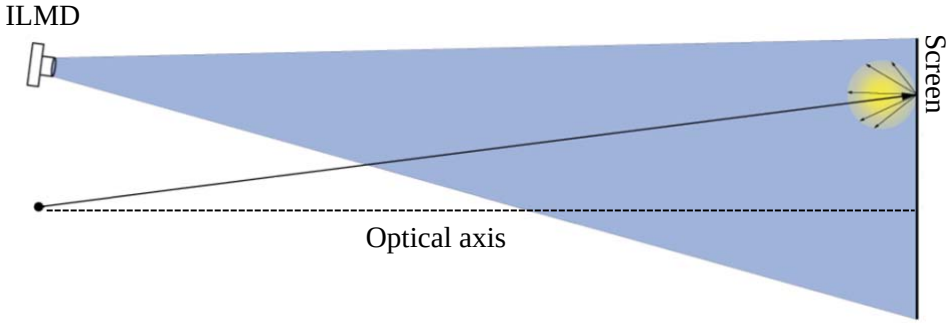
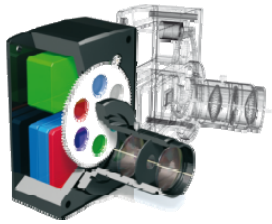
Measurement concept: step 2 and step 3

- SMCF correction using sensor fusion:
  - One spectral measurement per LED source
  - One luminance camera measurement per LED source
    - Glass filter



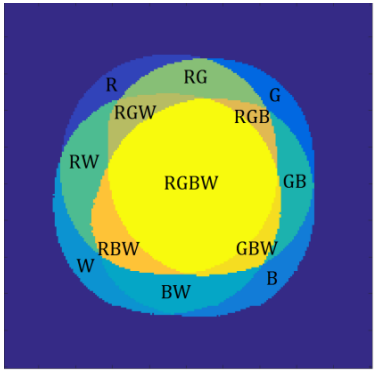


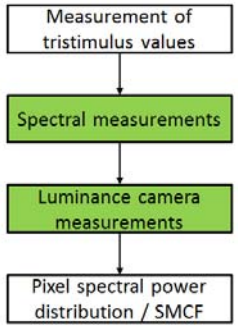


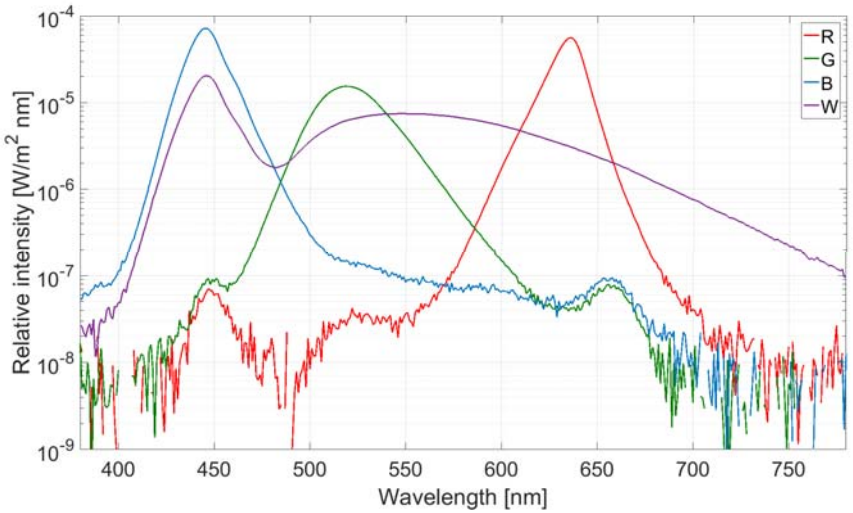


Measurement concept: step 2 and step 3

- Spectral amplitude ∝ grey value luminance images → weight factor





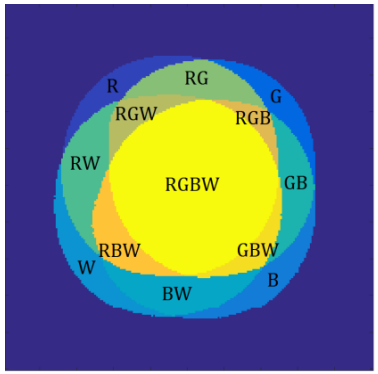


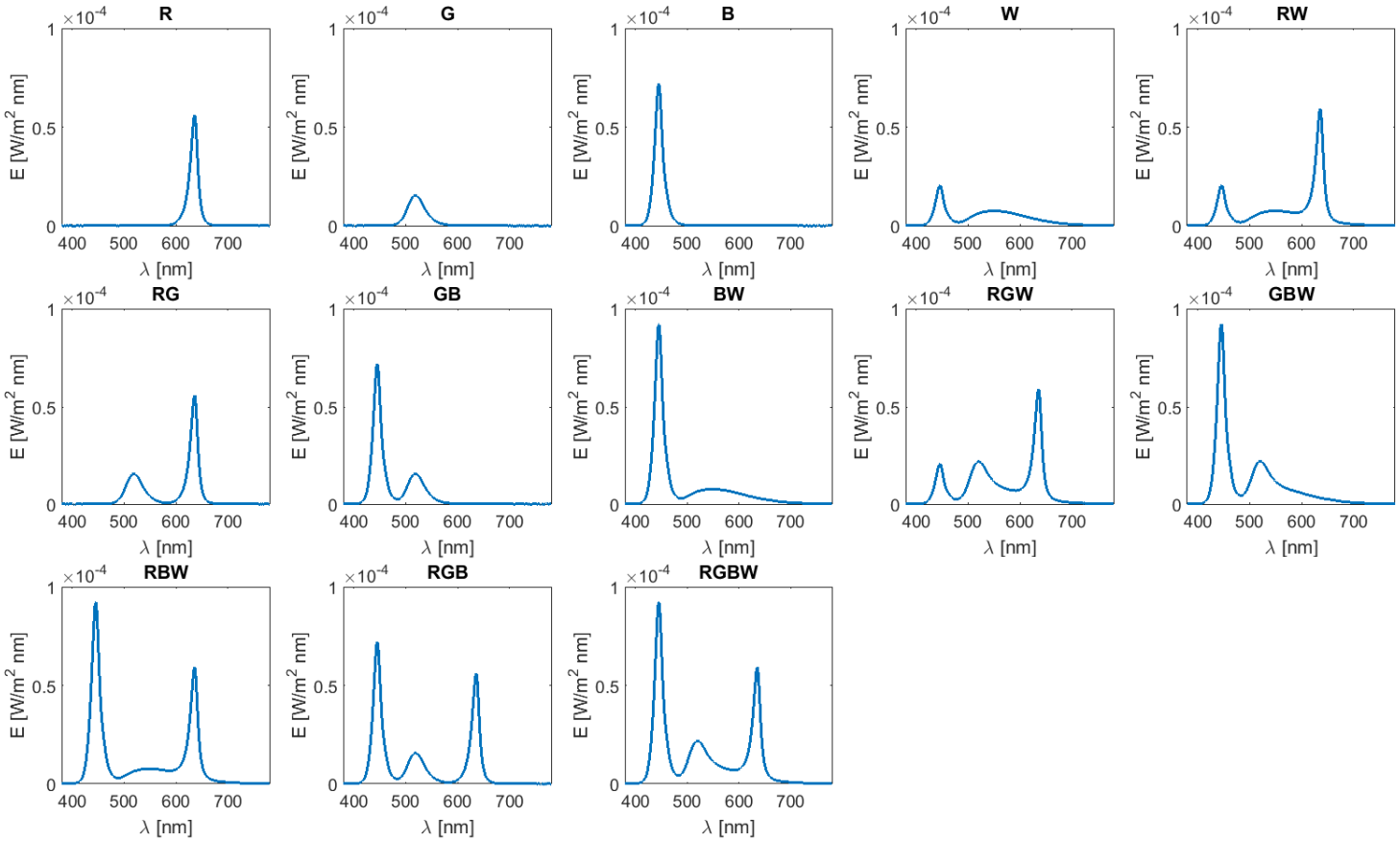
Measurement concept: step 4

- Spectra possibilities:

$$a^*{}_X = \frac{S_Z}{S_A} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda,\theta,\phi)\, x_{rel}(\lambda)\cdot d\lambda \,/\, \int_{360}^{830} S_Z(\lambda,\theta,\phi)\cdot \bar{x}(\lambda)\cdot d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} S_A(\lambda)\cdot x_{rel}(\lambda)\cdot d\lambda \,/\, \int_{360}^{830} S_A(\lambda)\cdot \bar{x}(\lambda)\cdot d\lambda}$$

Measurement of tristimulus values
↓
Spectral measurements
↓
Luminance camera measurements
↓
Pixel spectral power distribution / SMCF





Measurement uncertainty analysis I

- MU tristimulus values *X*, *Y* and *Z*
  - LED spectra don't have any uncertainty
  - MU relative spectral responsivity using f_1'
    - Deliberately big amplitude variations
- Interpolation
- Monte-Carlo method
  - Wavelength: correlated,
    - normal PDF  with $\pm 0.25\ nm$
  - Amplitude: uncorrelated
    - rectangular PDF  with

$\bar{x}_{rel}(\lambda)$	$\bar{y}_{rel}(\lambda)$	$\bar{z}_{rel}(\lambda)$
1.2%	1%	1.2%

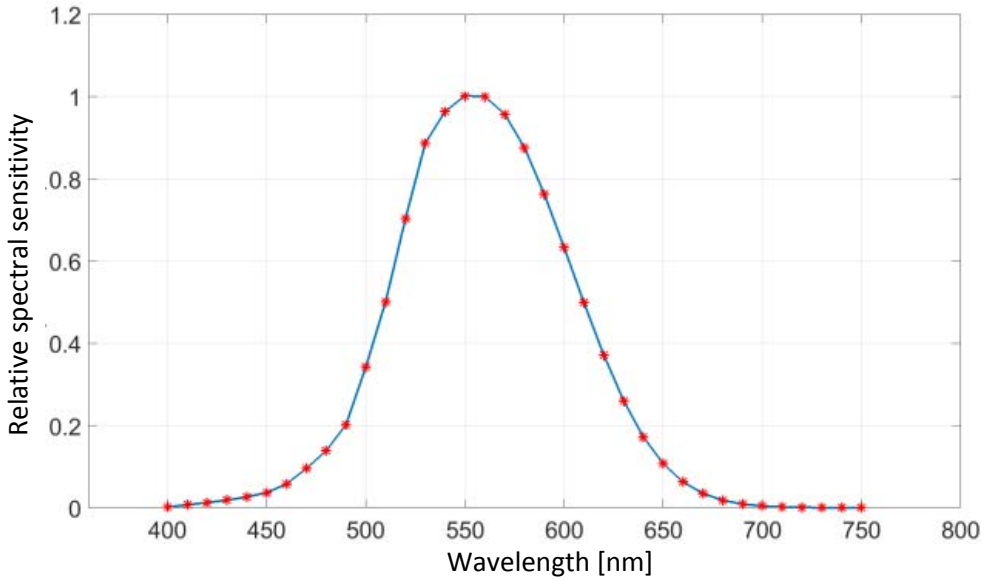
$$X = k \int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda) \cdot \bar{x}_{rel}(\lambda) \cdot d\lambda$$

$$Y = k \int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda) \cdot \bar{y}_{rel}(\lambda) \cdot d\lambda$$

$$Z = k \int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda) \cdot \bar{z}_{rel}(\lambda) \cdot d\lambda$$

Measurement uncertainty analysis II

- MU SMCF terms:
  - $S_A(\lambda)$, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are CIE definitions
  - Spectral measurements
  - Spectral relative sensitivities
- Monte-Carlo method
  - Wavelength: correlated
    - PDF  with $\pm 0.2\ nm$
  - Amplitude: uncorrelated
    - PDF  with $\pm 1.2\ \%$

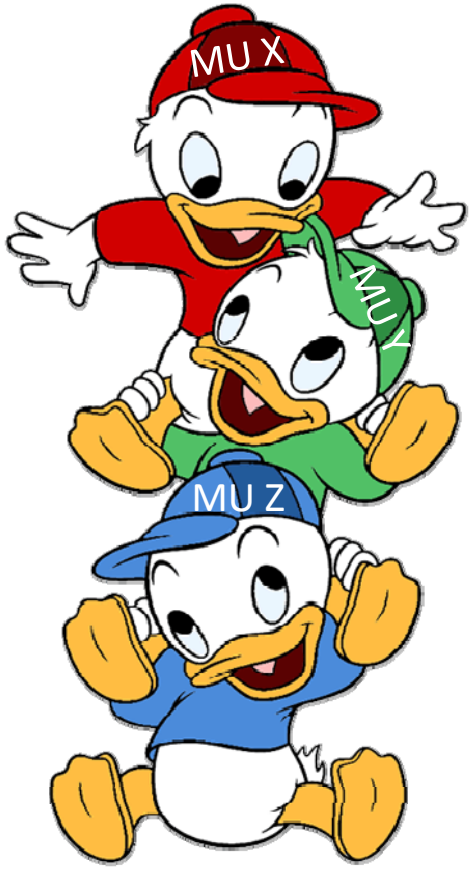


$$a^*{}_X = \frac{S_Z}{S_A} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} S_Z(\lambda,\theta,\phi)\cdot x_{rel}(\lambda)\cdot d\lambda \,/\, \int_{360}^{830} S_Z(\lambda,\theta,\phi)\cdot \bar{x}(\lambda)\cdot d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} S_A(\lambda)\cdot x_{rel}(\lambda)\cdot d\lambda \,/\, \int_{360}^{830} S_A(\lambda)\cdot \bar{x}(\lambda)\cdot d\lambda}$$

Results: MU tristimulus values and SMCF

LED	MU X	MU Y	MU Z	SMCF X	SMCF Y	SMCF Z
R	± 1,59%	± 1,85%	± 12,87%	0,988±0,012	1,002±0,015	2,62±0,335
G	± 2,34%	± 0,96%	± 2,69%	1,018±0,028	0,998±0,013	1,017±0,023
B	± 0,3%	± 2,39%	± 0,31%	0,995±0,003	1,036±0,028	0,946±0,008

Tick, Trick, Track



Results:

- Correction of measured colour distribution using calculated SMCFs:

$$X(\theta,\phi) = SMCF_X(\theta,\phi) \cdot X_{meas}(\theta,\phi)$$

$$Y(\theta,\phi) = SMCF_Y(\theta,\phi) \cdot Y_{meas}(\theta,\phi)$$

$$Z(\theta,\phi) = SMCF_Z(\theta,\phi) \cdot Z_{meas}(\theta,\phi)$$

- New Monte-Carlo simulation using calculated MUs and PDFs:
- Example RED:

$$X(\theta,\phi) = SMCF_X(\theta,\phi) \pm 0.006 \cdot X_{meas}(\theta,\phi) \pm 0.8\%$$

$$Y(\theta,\phi) = SMCF_Y(\theta,\phi) \pm 0.007 \cdot Y_{meas}(\theta,\phi) \pm 0.9\%$$

$$Z(\theta,\phi) = SMCF_Z(\theta,\phi) \pm 0.16 \cdot Z_{meas}(\theta,\phi) \pm 6.4\%$$

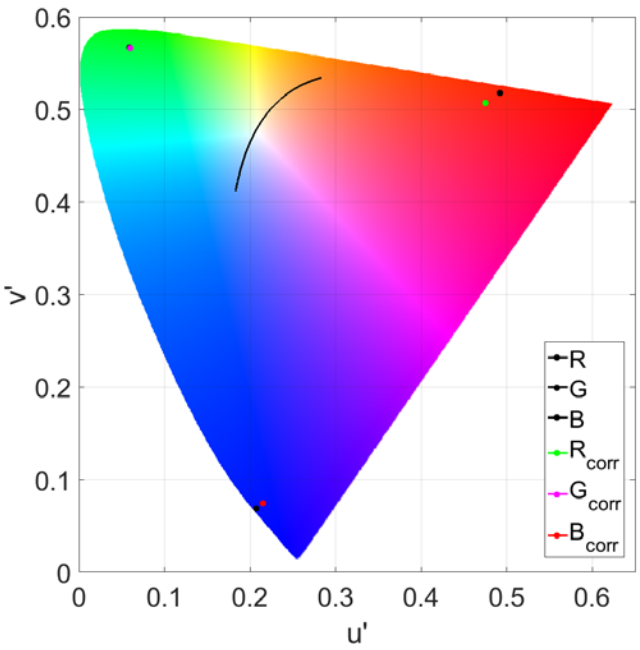
$$x = \frac{X}{X+Y+Z}$$

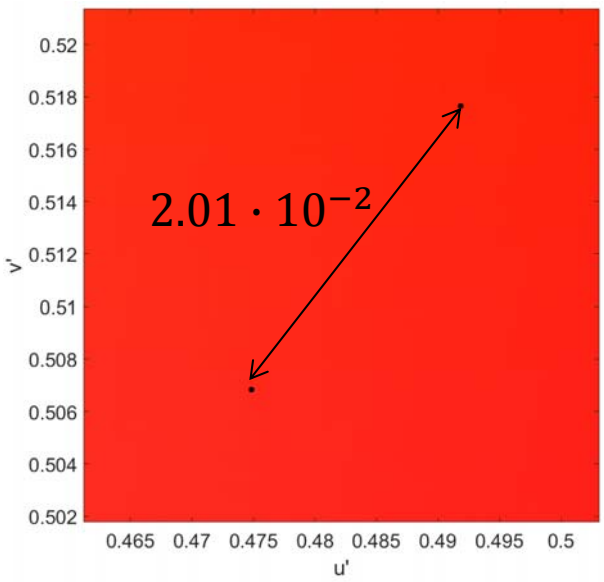
$$y = \frac{Y}{X+Y+Z}$$

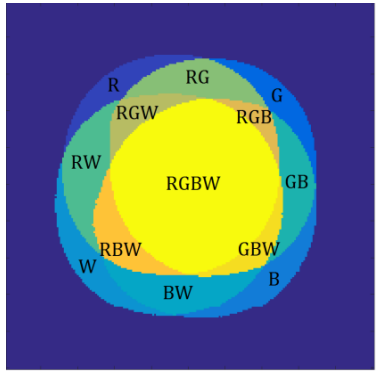
$$z = \frac{Z}{X+Y+Z}$$

Results: chromaticity coordinates

LED	x	y	x korrigiert	y korrigiert	$\sqrt{\Delta x^2 + \Delta y^2}$	Korrelation
R	0,6341	0,3008	0,6638±0,0042	0,3105±0,0041	$3{,}13 \cdot 10^{-2}$	-1
G	0,1635	0,6882	0,1613±0,0039	0,6922±0,0042	$4{,}6 \cdot 10^{-3}$	-0,86
B	0,1599	0,0245	0,1537±0,0038	0,0226±0,0008	$6{,}5 \cdot 10^{-3}$	0,65

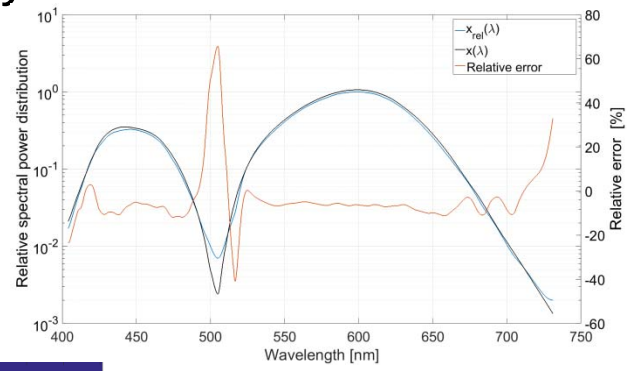




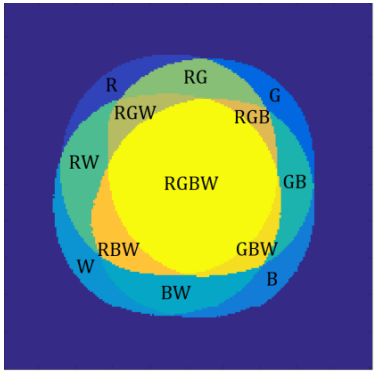


Summary

- Colorimeters' spectral responsivity should always be corrected when using LEDs



- Sensor fusion technique to calculate SMCF
  - One spectral measurement per LED source
  - One ILMD measurement per LED source



- Chromaticity coordinates with MU
  - Advantages:
    - Reduction of measurement time
    - High resolution
- Alternative:
  - Colour measurements using luminance camera
  - Extra parameters to be considered:
    - Stray light
    - Optical filter's thickness

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Thank you for your attention!

Federal Ministry of Education and Research

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UNILED II

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