JETI Technische Instrumente GmbH

Color measurement of light sources

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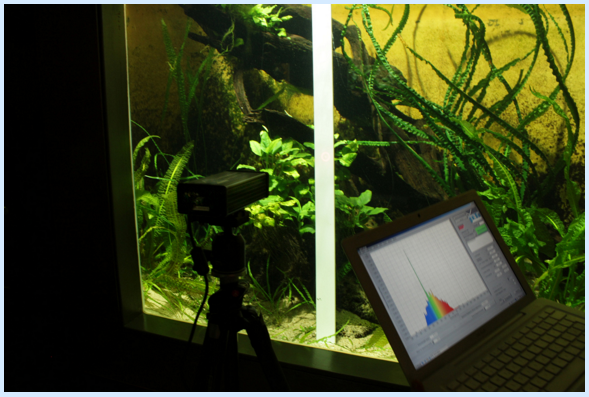
JETI Technische Instrumente GmbH Jena



Outline

1. Introduction
2. Light measuring quantities
3. Measuring techniques
4. Spot meters on the market
5. Measuring uncertainty
6. Measurement examples
7. Conclusions

JETI Technische Instrumente GmbH

- founded in 1998
- Development, production and sales of measuring instruments and components of spectroscopy
- Employees: 14
- Location: Jena/ Thuringia/ Germany
- URL: www.jeti.com

Product range

Spectroradiometry

- Precise, easy to handle and economic
- Currently fourth generation of instruments (specbos 1100, 1200, **1201, 1211**)

Read out electronics for array detectors

- Versions for approx. 50 different array detectors
- Modular concept
- Low noise/ high dynamics
- Precise TE cooling

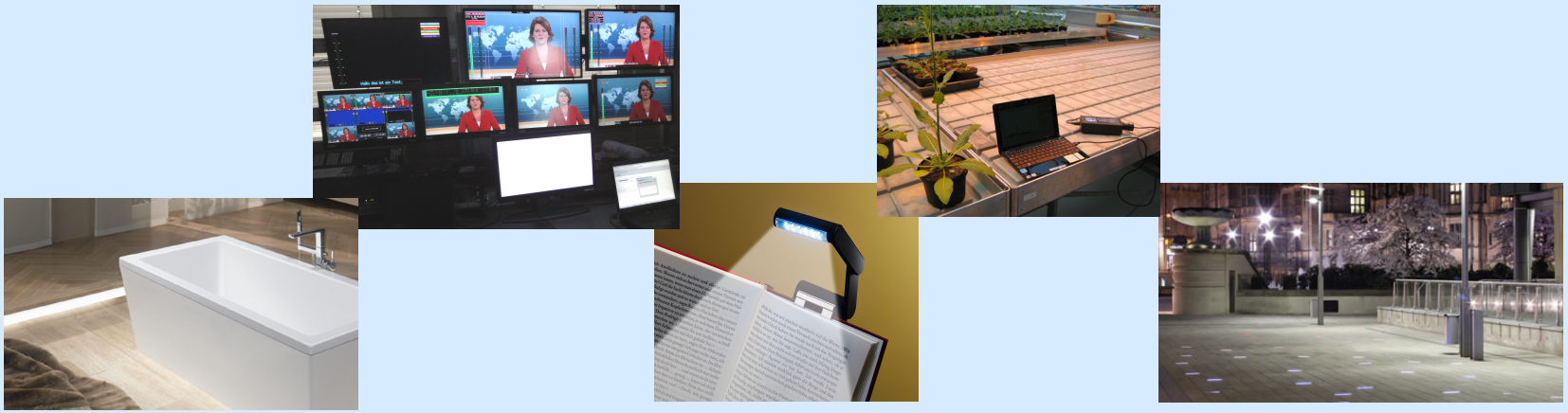
OEM spectrometer

- Models for UV to NIR
- Focal lengths 20mm to 140 mm
- Wavelength ranges

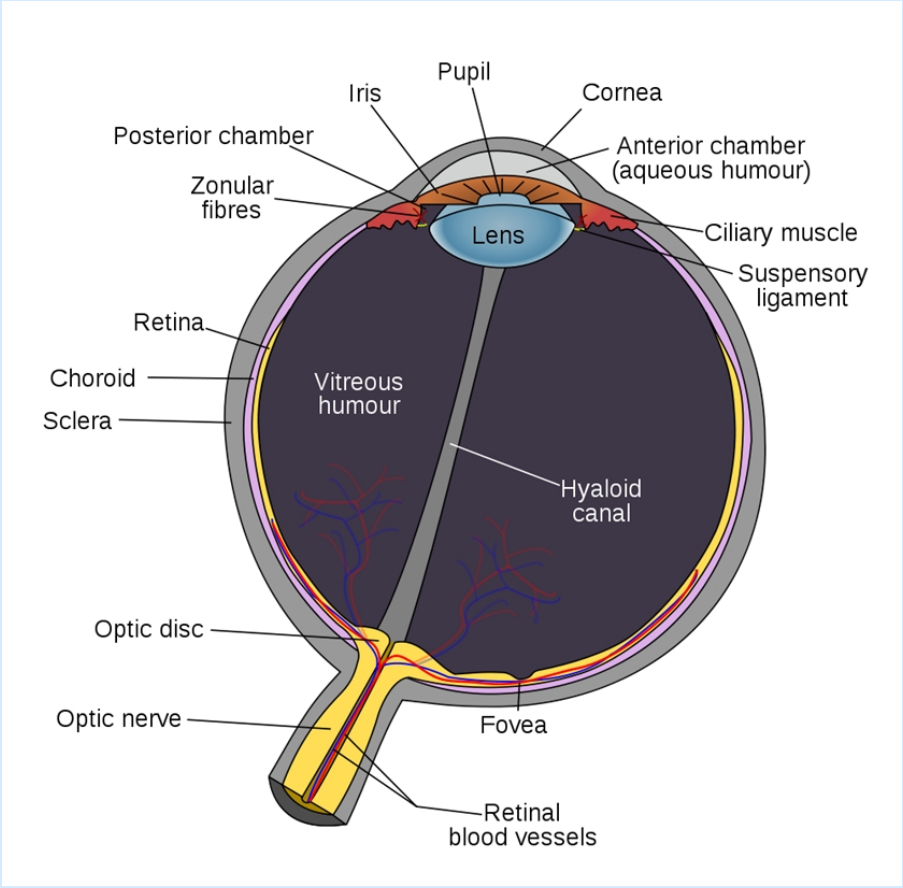
  190 nm to 1050 nm (Si)
  900 nm to 2700 nm (InGaAs)

Examples for color and brightness measurement of light sources

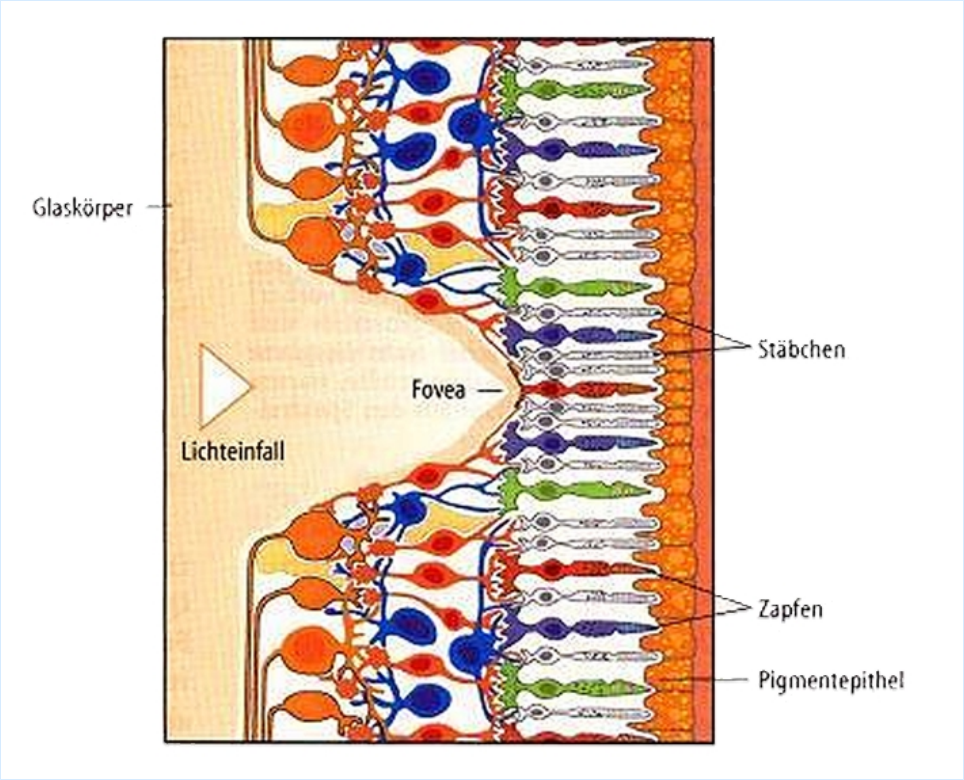
- Part of the quality control in production of light sources
- Agreement of colors of different parts, e.g. of a luminaire or a video wall
- Impact on special processes, e.g. plant growing in a green house, optical hazard on human skin and eye or aging of cultural heritage objects by radiation
- Creation of a desired color impression, e.g. of a movie in cinema or TV
- Security aspects, e.g. in road lighting

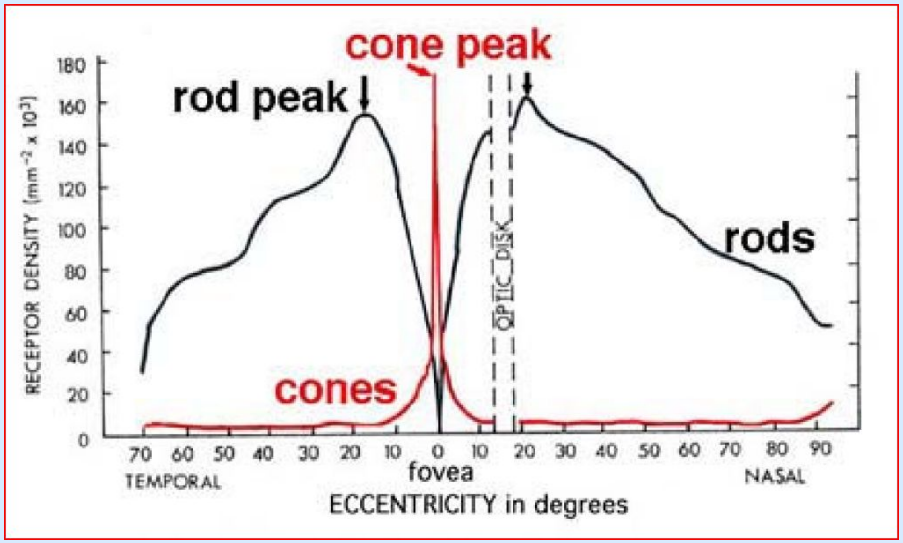


Construction of human eye



System of human retina

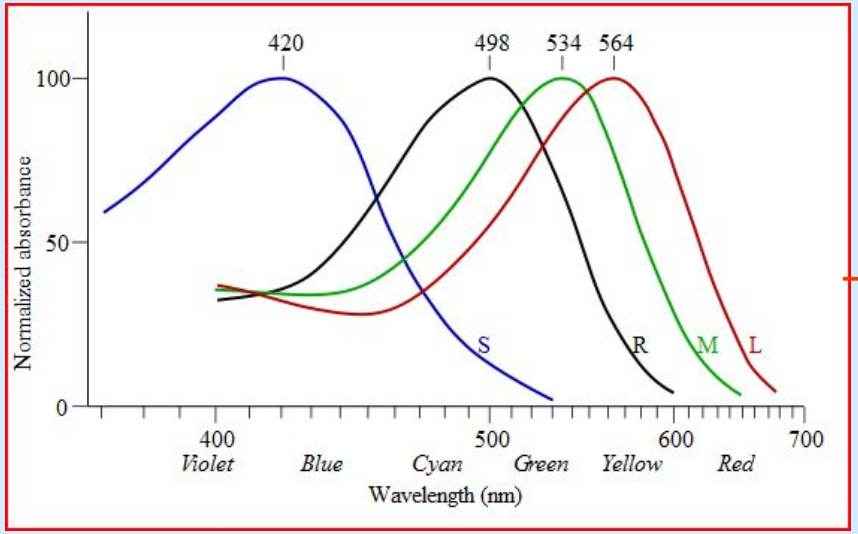




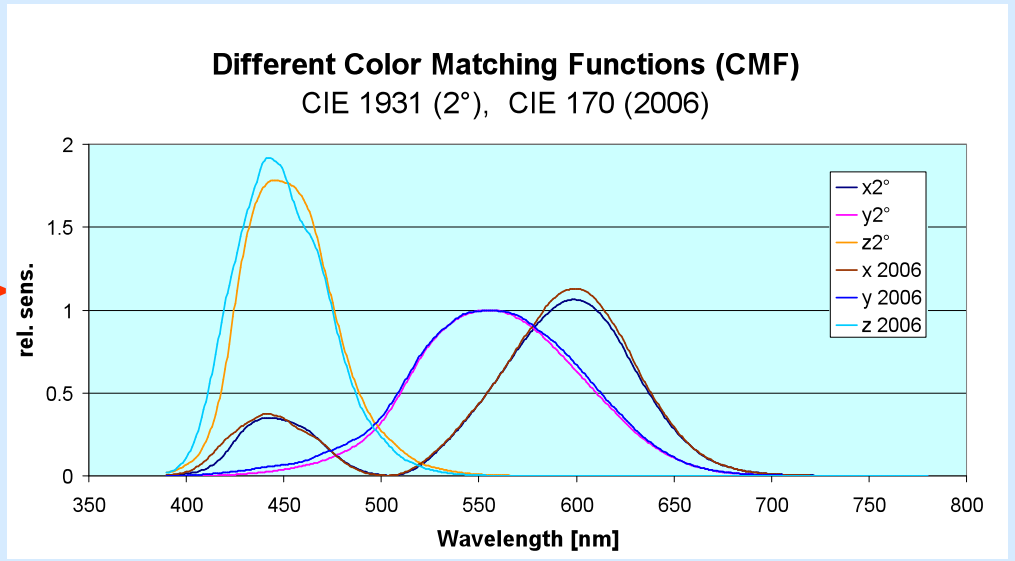
Cones: Color vision

Rods: Brightness vision

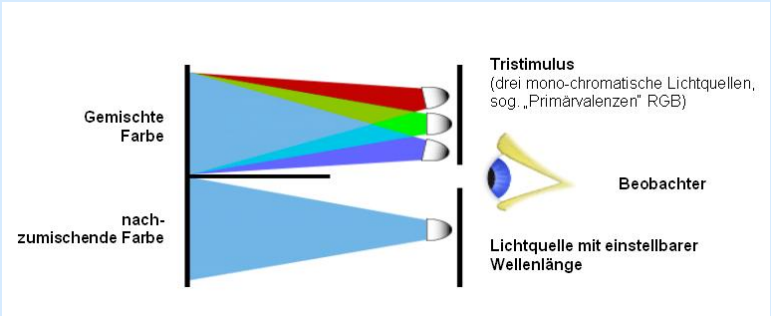
Technical simulation of human vision



Spectral sensitivities of different „sensors“ of the human retina



Color matching functions (CMF), V(λ)



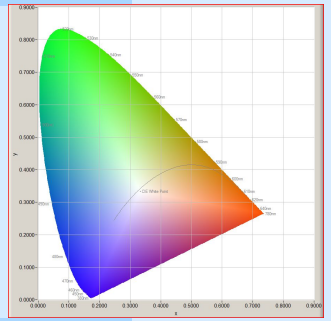
Resulting color measuring quantities

3 types of cones -> Complete measuring values – 3 dimensional

XYZ direct result of weighting of spectrum with CMFs

Different color spaces: xyY, L*a*b*, Lch, ...

RGB related to primary colors



• Reduced to 2 dimensions – only chromaticity

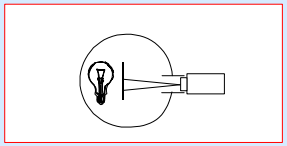
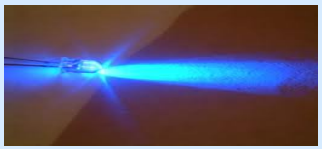
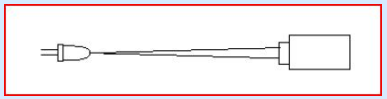
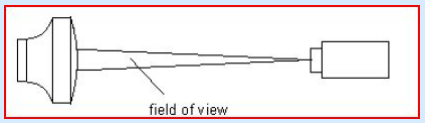
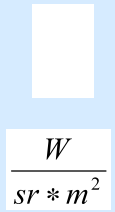
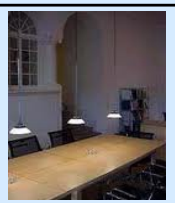
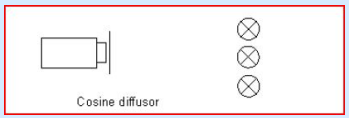
e.g. xy, u´v´, λ_{dom} PE

• Reduced to one dimension – limited information

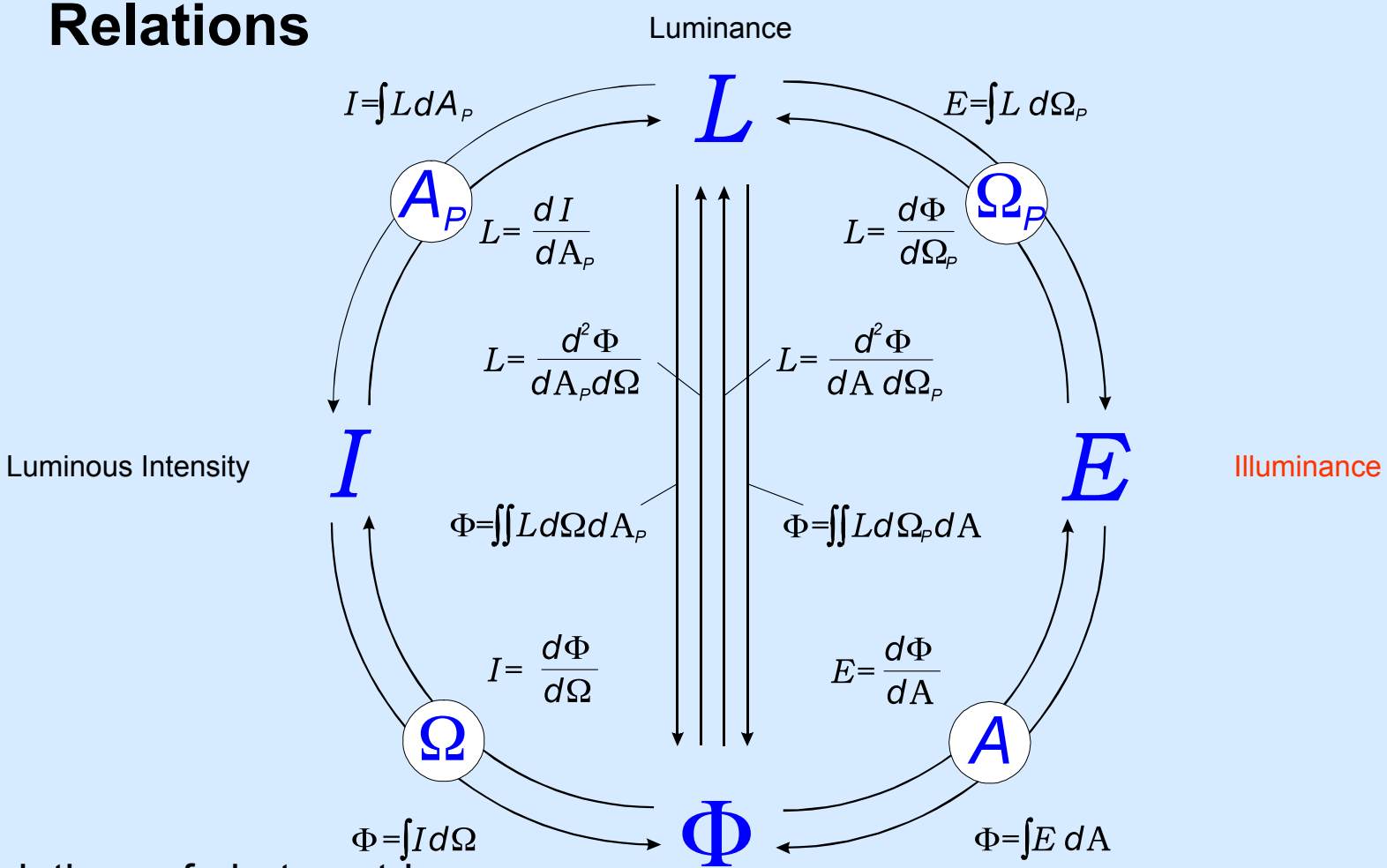
Correlated Color Temperature (CCT) – near Planckian locus

Brightness based on $\bar{y}_{2^\circ}$ (= V(λ))

Overview of brightness definitions

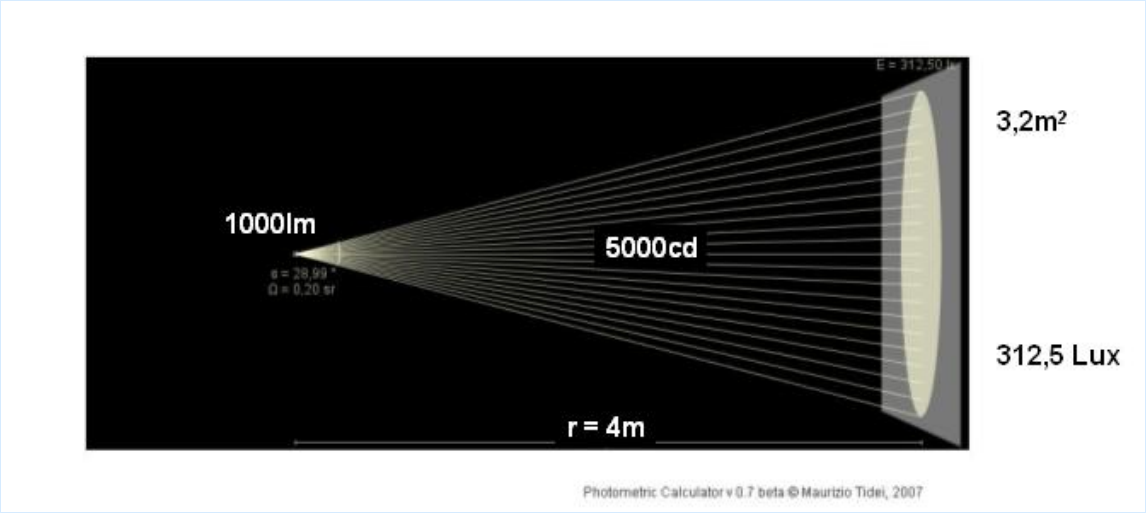
Application	Measuring object	Measuring geometry	Photometr./ Radiometric quantity	Unit
	All around radiating sources like incandescent lamps or LEDs (full space or half space)		Luminous Flux Radiant Flux	lm W
	Point like sources such as single LEDs or lamps with reflector		Luminous Intensity Radiant Intensity	cd W/ sr
	Homogeniously radiating areas such as displays and video screens, but also segments of alphanumeric displays		Luminance Radiance	
	Illuminated areas such as working tables		Illuminance Irradiance	lx

Relations



Relations of photometric quantities

Relations between photometric quantities



Animation

Source: http://www.stromsparlampen.eu/fotometrie_applet.html

Measuring techniques

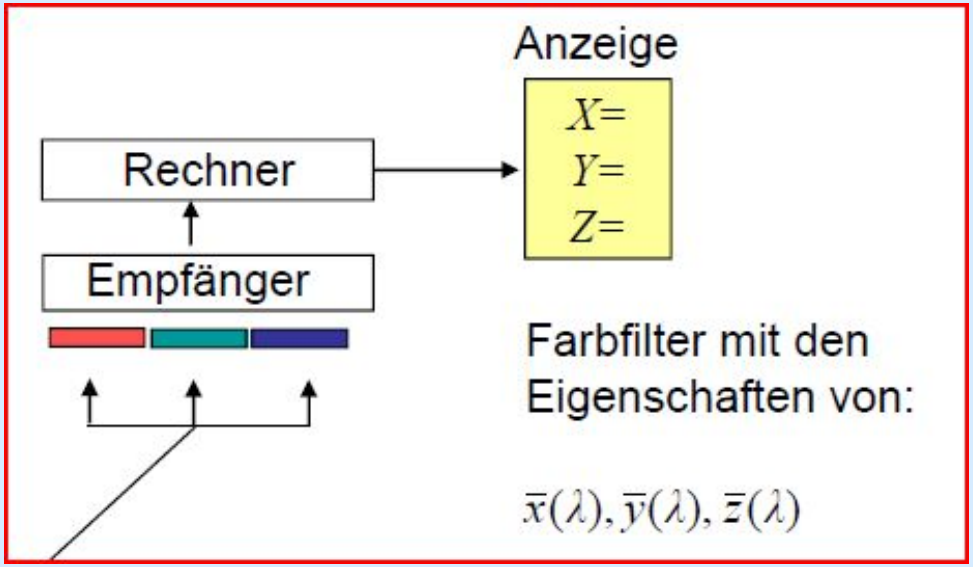
- **Tristimulus – 3 channels for the 3 CMFs**

  Filter device (Photometer/ Tristimulus meter)

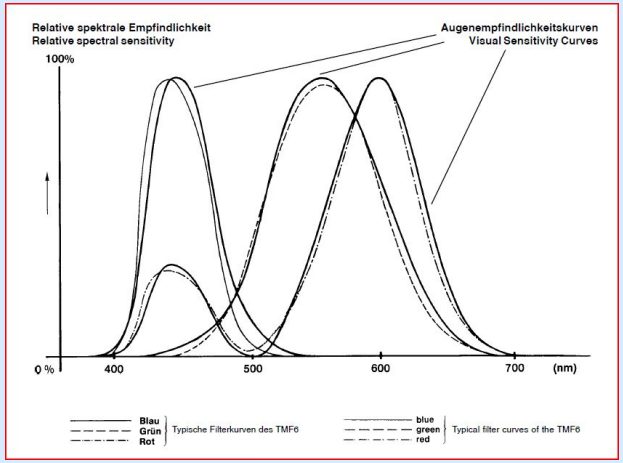
- **Spectral – much more channels, e.g. 400**

  Spectroradiometer

Tristimulus technique

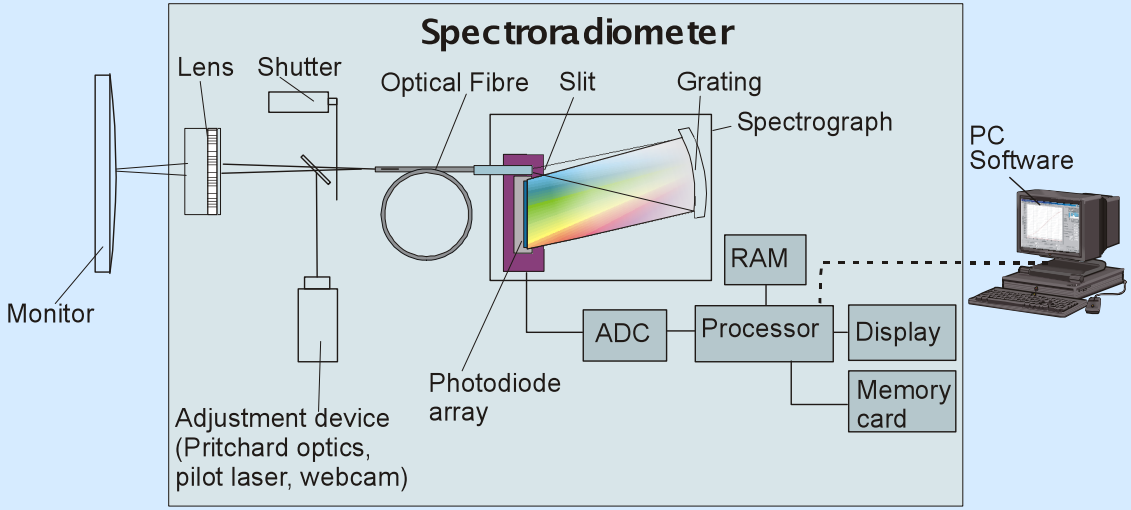


Filter: full area or partial



K-10 (Klein)
PM 5639 (DK Technologies)
CA-210 (Minolta)
Hubble (X-rite)
TMF 6 (Thoma)
329801/21 (Yokogawa)
Spyder 2 Pro (Datacolor)

Spectral technique



Mathematical realization of CMFs

> Matching error $f_1 = 0$

CS-200, CS-2000 (Minolta)

PR 655, PR 670, PR 705 (Photo Research)

CAS 140 (Instrument Systems)

OL 770 (Optronics Laboratories)

SR 3 (Topcon)

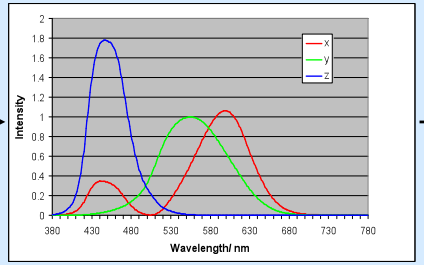
Eye One Pro (X-rite)

specbos 1211 (JETI)

LXChroma (IBA Dosimetry GmbH)

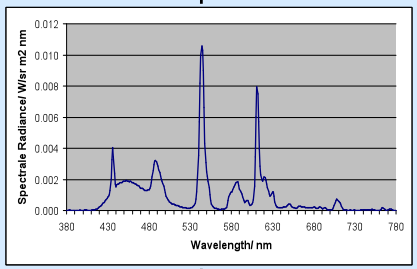
Principles of color measurement

Tristimulus



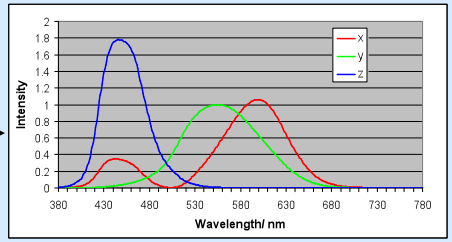
3 raw signals

CMFs -> Detector sensitivities

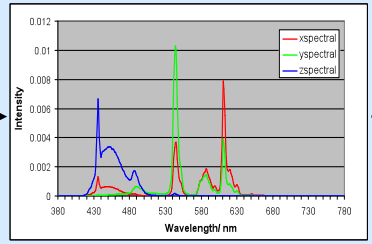


Monitor spectrum

CMF data stored in software



Weighted spectra



Primaries

XYZ → xyY → RGB

Tristimulus meter versus Spectroradiometer

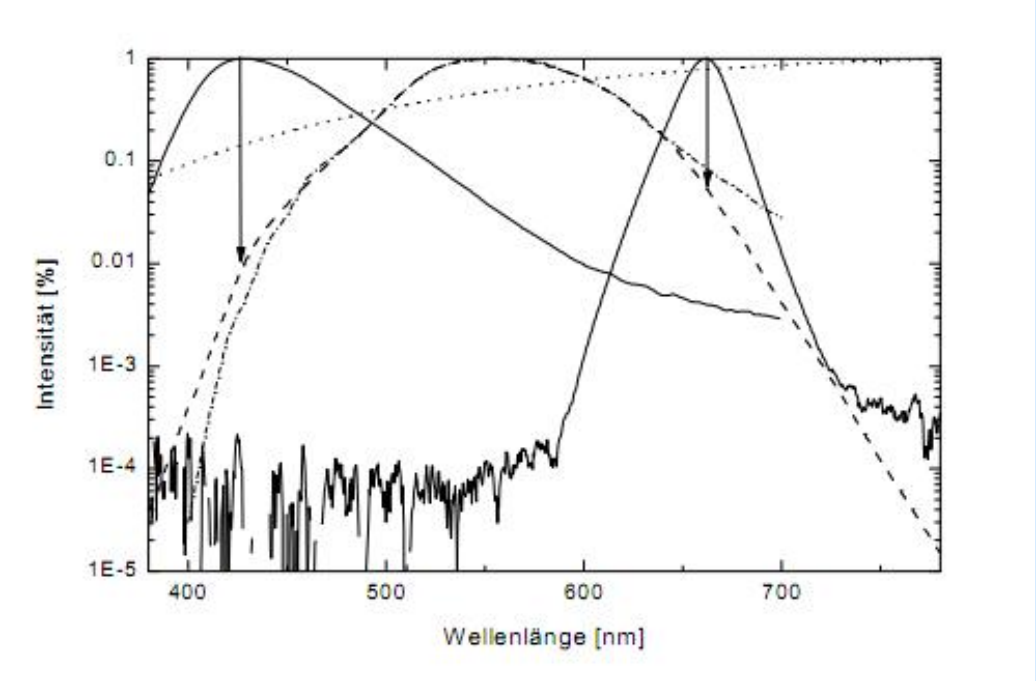
	Photometer/ Tristimulus meter	Spectroradiometer
Principle	Realize the V(λ) and Color Matching Functions (CMF) by hardware (filters)	Measurement of full radiometric spectrum + Numerical integration
Advantages	• Fast measurement • High sensitivity • Quite stable responsivity • Easy set up, easy to use • Straightforward number of influences to measuring uncertainty • More economic	• No V(λ)/ CMF adaption error f_1 • Spectral data available -> extended calculation possibilities, e.g. of Color Rendering Index or spectral weighted data
Disadvan-tages	• V(λ) adaption error f1 • therefore adaption to individual spectrum necessary • No spectral information	• No real time mode • More influences to measuring uncertainty • Wavelength/ sensitivity stability/ straylight • More expensive

Luminance measurement on different monitors

Monitor	Technology	CS-2000 (Spectroradio-meter)	PR 650 (Spectroradio-meter)	specbos 1201 (Spectroradio-meter)	TMF 6 (Tristimulus)
Sony LMD 2451	LCD/ LED	100.1	98.7	100.3	90.4
Barco CVM 3501	CRT	88.6	85.0	88.0	85.0
VTS TFT 20W	LCD/ CCFL	95.4	94.2	95.8	68.4
Tamuz QCM 137W	LCD/ CCFL	126.8	125.7	128.3	90.0

- Values in cd/m^2
- TMF 6 calibrated for CRT monitor
- Spectra specific matrix correction is necessary to obtain small measuring uncertainty

Problem of Tristimulus measurements



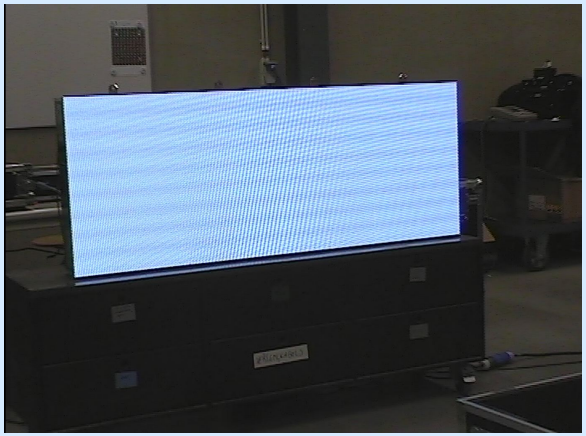
Effect of CMF matching error for blue and red LED spectra

Connection between both techniques

Profiling of filter devices

Simple: Photometric correction

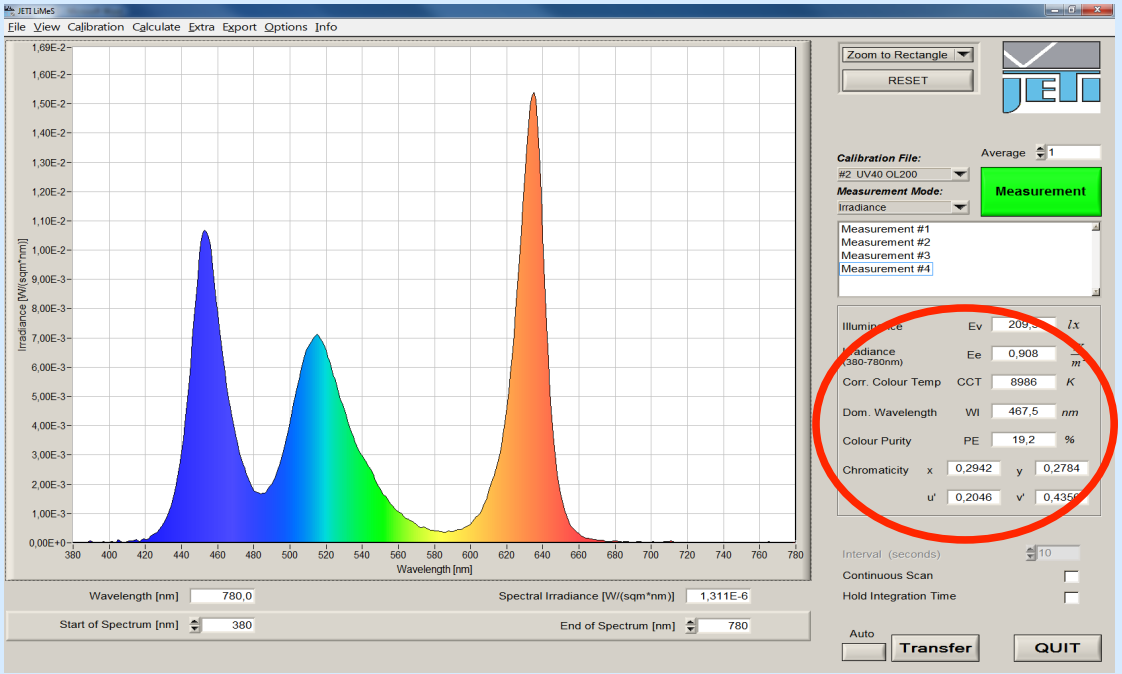
$$CCF = \frac{L_{Spektralradiometer}}{L_{LMK}} = \frac{\int L_{e\lambda} \cdot V(\lambda) d\lambda}{L_{LMK}}$$

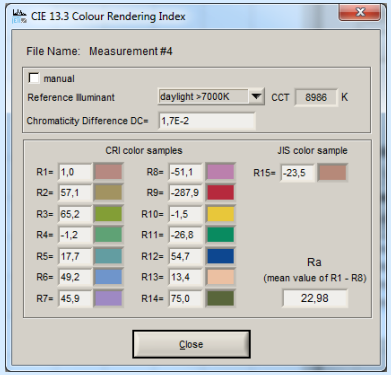


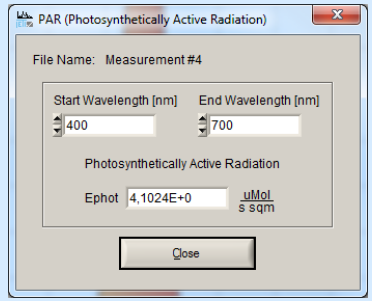
Valid for more spectra: 4-color-correction, Multicolor-correction

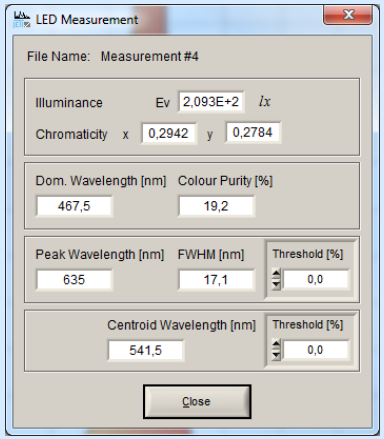
Flexibility of spectral measurements

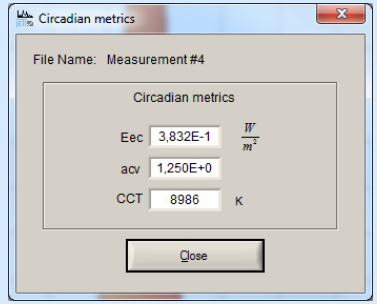
Measuring values







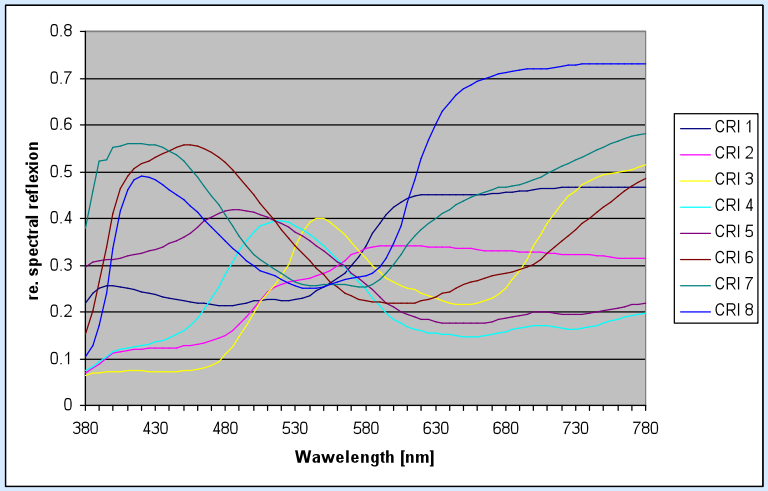




Flexibility of spectral measurements

Color Rendering Index CRI

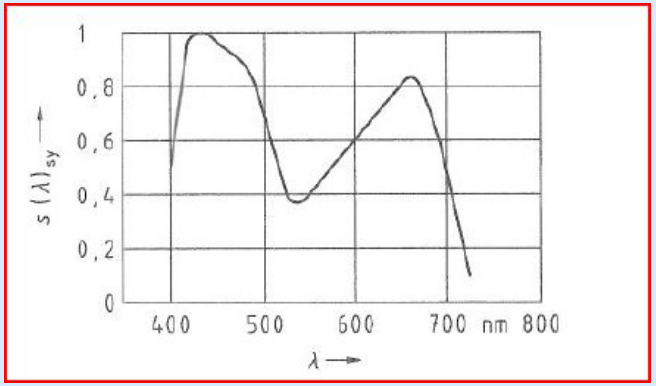
- 14 CIE test color samples (virtual, definition of spectral reflexion)
- Calculation of colorimetric values with reference illuminant and light source to be tested
- Calculation of color differences for each test sample
- Relating to ideal rendering of 100
- Averaging sample 1 ... 8 = R_a



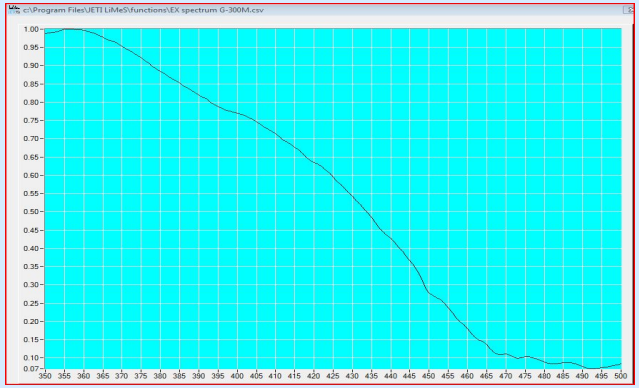
- Determination of CRI only possible with spectroradiometer
- Significant problem of classical CRI calculation with LED sources
- > CQS

Flexibility of spectral measurements
Action spectra

- Effect of optical radiation is often wavelength dependent
- Modeling by Weighting (action) spectra
- Classical examples: V(λ), CIE 1931 standard observer
- Maximum of action spectra is mostly = 1 (100 %)



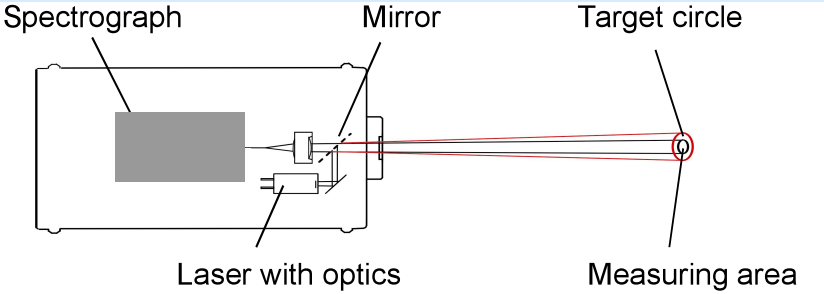
Efficiency of Photo synthesis



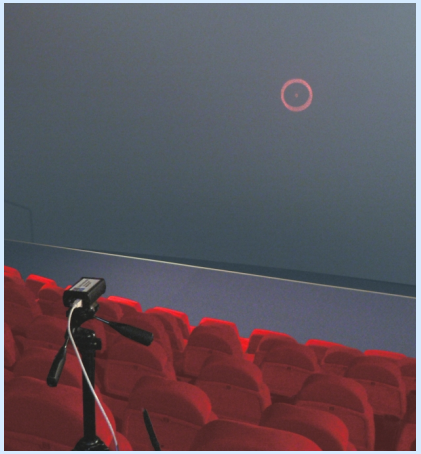
Charging efficiency of photochrome material for safety signs in airplanes

Measuring principles

- **Spot measurement**



Luminance



JETI specbos1201

Luminous intensity

Illuminance

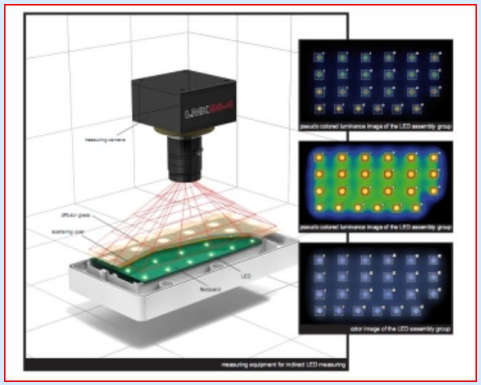
Minolta CS-200

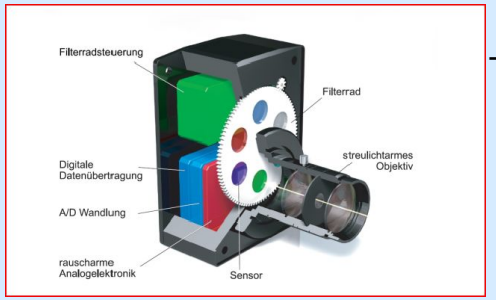
Photometrically, tristimulus or spectral based

For: Luminance, Illuminance, Luminous intensity

Measuring principles

- **Video photometer**





TechnoTeam LMK98-4 color

Radiant Imaging ProMetric

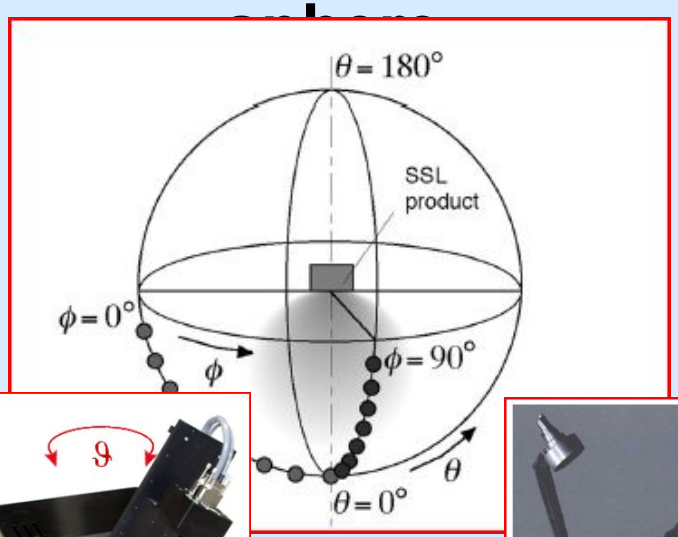
Space resolved

Photometrically or Tristimulus based

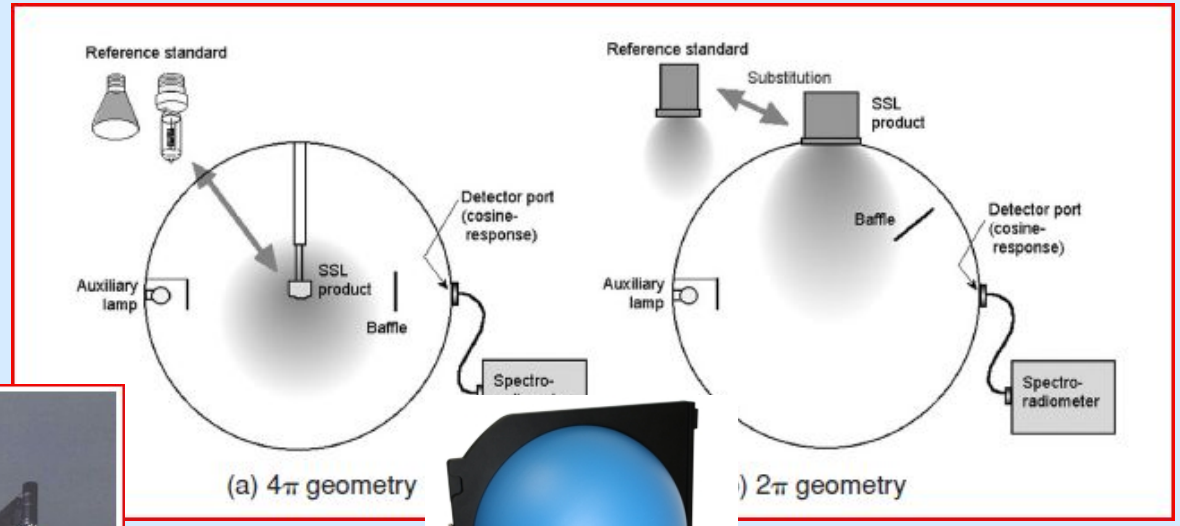
For: Luminance, Luminous intensity

Measuring principles

Goniometer



Integrating



Source: IES LM79-08

Full space

Photometrically/ Tristimulus or spectrometer

For: Luminous flux

General peculiarities of LED measurement

- small sources, often radiation only in one half sphere
- sometimes low bandwidth spectra
- Color characteristics may be angle dependent

List of selected commercial spot meters

Both principles: tristimulus and spectral resolving

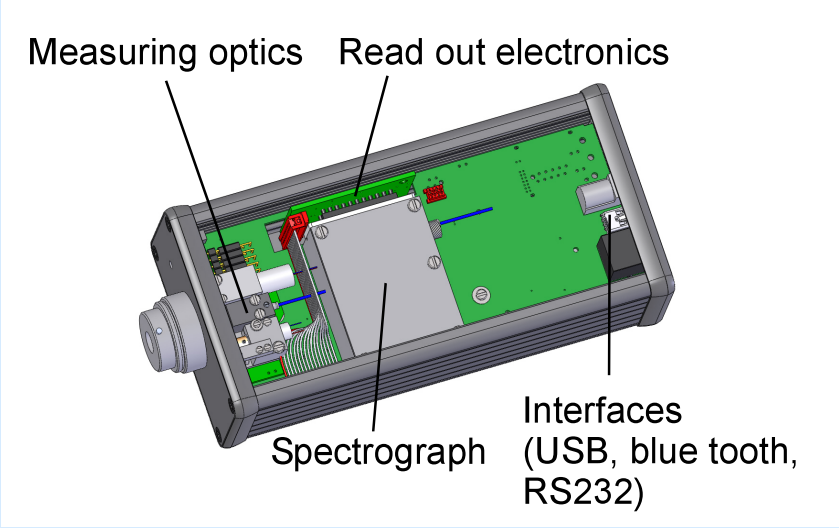
Konica Minolta – CA-210, CA-310, CS-200, CS-2000
X-Rite – Hubble, ColorMunki, Eye one, Eye one pro, Chroma 5
Klein – K-10
DK Technologies – PM 5639
Datacolor – Spyder 2, Spyder 3
Photo Research –PR-655, PR-670, PR-680, PR-705/ 715
Gooch&Housego – OL 770VIS-DMS
Instrument Systems – CAS140CT, MAS 40
Sencore – ColorPro
Ultra Stereo Labs, inc – PCA100
Just Normlicht – GLoptic mini, GLoptic profi
IBA – LXchroma
Majantys – Probe4Light
Gamma Scientific – GS-1280 RadOMAcam
Opsira – spec´3, SPR´3
Ocean Optics – 4000, Jaz
OrbOptronix – SP-75
Gretag McBeth – spectrolino
International Light – ILT 950
JETI – specbos 1201, specbos 1211
…….

Selected data of often used (monitor) measuring instruments

Tristimulus	**K-10**	**PM 5639**	**CA 210**	**Hubble**
Manufacturer	Klein	DK Technologies	Konica Minolta	X-rite
Kind of measurement	distance, contact	distance	contact	distance
xy accuracy @ 40 cd/m²	±0.002	±0.002 on white	±0.005 on white	±0.003
Remark			table instrument	target finder
Price	~ EUR 9 000	~ EUR 9 000	~ EUR 8 000	~ EUR 4 200
Spectral	**CS-2000**	**CS-200**	**specbos 1211**	**Eye one pro**
Manufacturer	Konica Minolta	Konica Minolta	JETI GmbH	X-rite
Kind of measurement	distance	distance	distance	contact
Bandwidth	≤ 5 nm	10 nm	4.5 nm	10 nm
xy accuracy @ 40 cd/m²	x: ±0.0015, y: ±0.001	±0.003	±0.002 @ 2856 K	±0.002
Remark	1°, 0.2°, 0.1°	1°, 0.2°, 0.1°, battery	target finder	also reflectance
Price	~ EUR 24 000	~ EUR 13 000	~ EUR 7 500	~ EUR 1 000

Example of a spectral measuring device

specbos 1211



specbos 1211

- Luminance and illuminance mode, optionally: luminous flux and intensity mode
- Automatic detection of accessory
- Luminance mode: Fixed measuring optics – measuring diameter is increasing with increasing distance, Measuring area is marked by a red circle
- Illuminance mode: diffusor
- Spectrometer: imaging grating and high sensitive detector array (back thinned CCD)

specbos 1211

Operation with

- PC-Software (e.g. with Netbook, flexible with Bluetooth)
- Radiometric DLL (e.g. JETI Radio.dll)
- Firmware commands (e.g. *meas:chromxy)
- Virtual Instruments (VI for LabView)

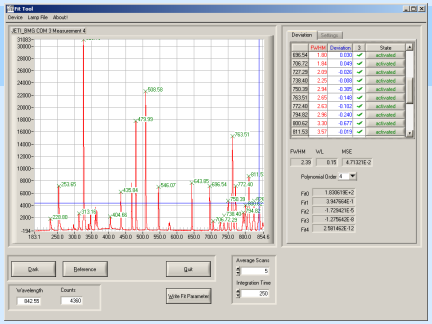
specbos 1211 vs. specbos 1201

	specbos 1211	specbos 1201
Wavelength	350 (250) ... 1000 nm	380 ... 780 nm
Optical resolution (FWHM)	< 4.5 nm	5 nm
Measuring range luminance (Illum. A)	0.2 ... 2 500 cd/m^2 (higher values with optional filter)	2 ... 70 000 cd/m^2
Measuring range illuminance (Illum. A)	2 … 10 000 lx (higher values with optional more dense diffusor)	20 ... 200 000 lx
Measuring time @ gray LED monitor	approx. 0.3 s at 100 cd/m^2 approx. 2 s at 5 cd/m^2	approx. 2.5 s at 100 cd/m^2 approx. 30 s at 5 cd/m^2
Interfaces	USB, Bluetooth, RS 232	USB
Software	Radiometric software LiMeS Monitor software MoDiCal	Radiometric software LiMeS
Power supply	USB; battery; 9V-power supply	USB
Weight	450 g	350 g
Dimensions	180 mm x 82 mm x 53 mm	140 mm x 60 mm x 34 mm

Calibration of a spectroradiometer for LED measurement

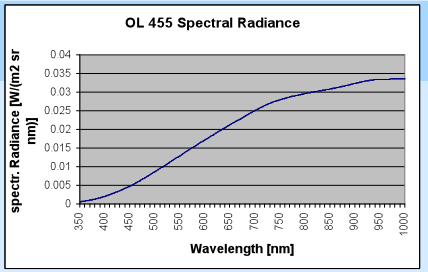
- Wavelength

HgAr low pressure gas discharge lamp



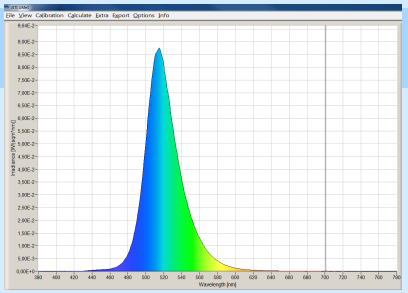
- Spectral sensitivity

Incandescent lamp standard



- Absolute calibration

Green LED standard



What „precision“ of measuring results can be achieved?

Measuring precision?

Tolerance?

Measuring error?

Reproducibility?

Uncertainty calculation

Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (GUM)

- List all contributions to uncertainty and determining a mathematical formula combining them

$$cf(\lambda) = \frac{Rohd_{Kal}}{\frac{Rohd_2}{Rohd_1} \cdot Le_{\mathrm{Re}\,fhorm} \cdot s_{\mathrm{Re}\,fhorm}(\lambda) \cdot t_{\mathrm{int}}} \cdot (1-k)$$

Model

- Determination of type (evaluation by statistical methods/ other means)
- Listing of value, relative uncertainty, DOF and sensitivity coefficient for each contribution
- Calculation of combined uncertainty using the „root-sum-of-squares“
- Calculation of extended uncertainty (mainly extension factor 2)

Budget for calibration uncertainty

Quantity	Symbol	Value	Relative uncertainty	Degreee of freedom	Type	Rel. Sensitivity coefficient	Contribution to uncertainty
distance	d_m	500 mm	1.36e-4	30.7	B	$2cf(\lambda)/d_m$	= f(λ)
Maximum spectral irradiance	E_{emax}	range	8.65e-3	∞	A	$-cf(\lambda)/E_{0max}$	= f(λ)
Integration time	t_{int}	500 ms	5.77e-6	∞	B	$-cf(\lambda)/t_{int}$	= f(λ)
etc.	....	....					

Selected contributions to the uncertainty of a spectroradiometer

Example Luminance specbos 1201: 1000 cd/m^2 +/- 44 cd/m^2 (k=2)

What „precision“ of measuring results can be achieved?

- Specification only for calibration status -> defined spectrum

Measuring ranges and accuracies

Measuring range luminance	0.1 ... 2500 cd/m² (higher values with optional filter)
Measuring range illuminance	2 … 10 000 lx
Luminance accuracy	± 2 % (@ 1 000 cd/m² and 2856 K)
Luminance repeatability	± 1 %
Chromaticity accuracy	± 0.002 x, y (@ 2856 K)
Color repeatability	± 0.0005 x, y
CCT repeatability	± 20 K (@ 2856 K)

Accuracy: Chromaticity (Standard light source A)*1	x,y :±0.003 (0.003 to 0.005 cd/m²) x,y :±0.002 (0.005 to 0.05 cd/m²) x : ±0.0015 y : ±0.001 (0.05 cd/m² or more)
Repeatability: Luminance (2σ) (Standard light source A)*2	0.4% (0.003 to 0.05 cd/m²) 0.3% (0.05 to 0.1 cd/m²) 0.15% (0.1 to 5,000 cd/m²)

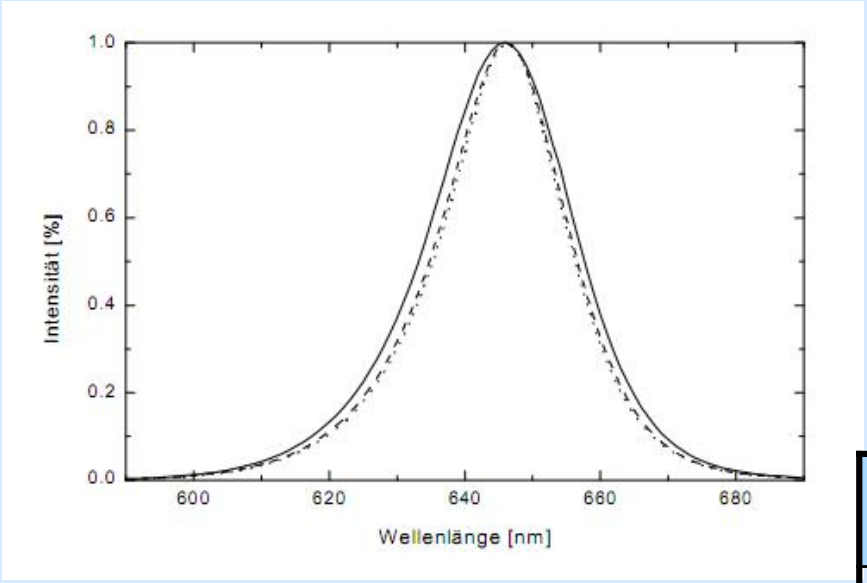
- Real measuring situation -> additional influences

Effect of wavelength error

	Correct values		Spectral shift by + 1 nm		Differences	
	x	y	x	y	Δx	Δy
R	0,7005	0,2977	0,7016	0,2965	0,0011	-0,0012
G	0,1615	0,6572	0,1661	0,6637	**0,0046**	**0,0065**
B	0,1509	0,0370	0,1499	0,0387	-0,0010	0,0017
W	0,3770	0,3509	0,3787	0,3512	0,0017	0,0003
RGB	0,2241	0,2324	0,2230	0,2366	-0,0011	**0,0042**

spectra: RGBW power LED

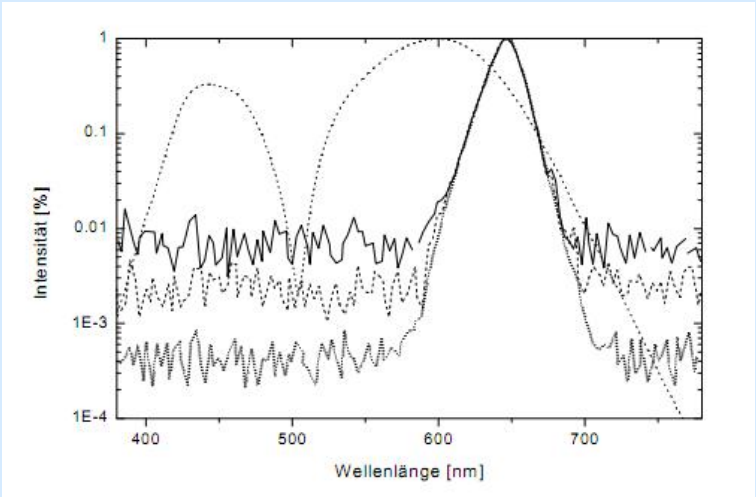
Effect of bandwidth (optical resolution)

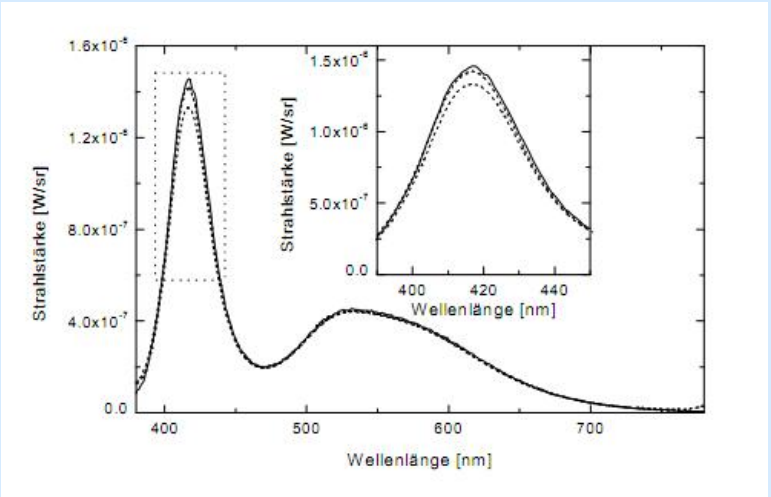


Band pass [nm]	λ_{dom} [nm]	$\lambda_{centroid}$ [nm]	FWHM [nm]
0.5	634.18	644.71	20.75
1	634.16	644.59	20.8
2	634.13	644.62	20.95
5	633.91	644.56	21.82
10	633.26	644.44	24.49

Source: Handbuch der LED-Messtechnik, Instrument Systems Munich

Effect of

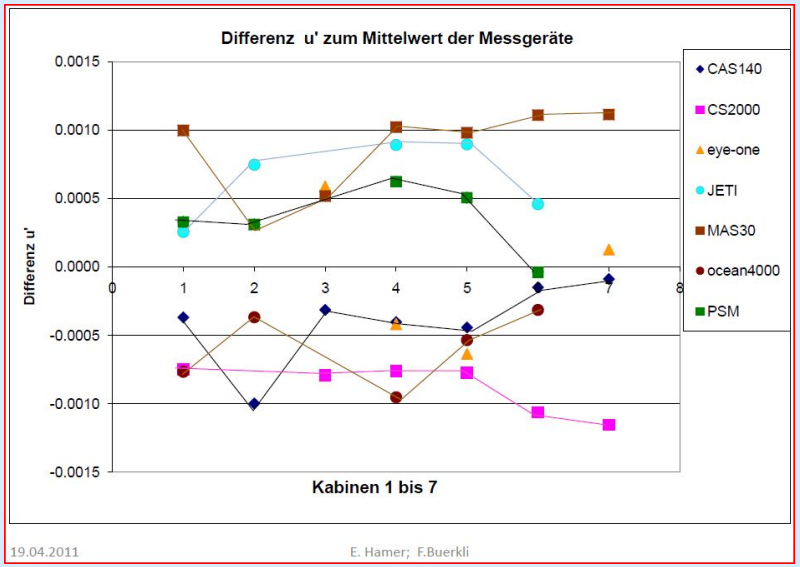


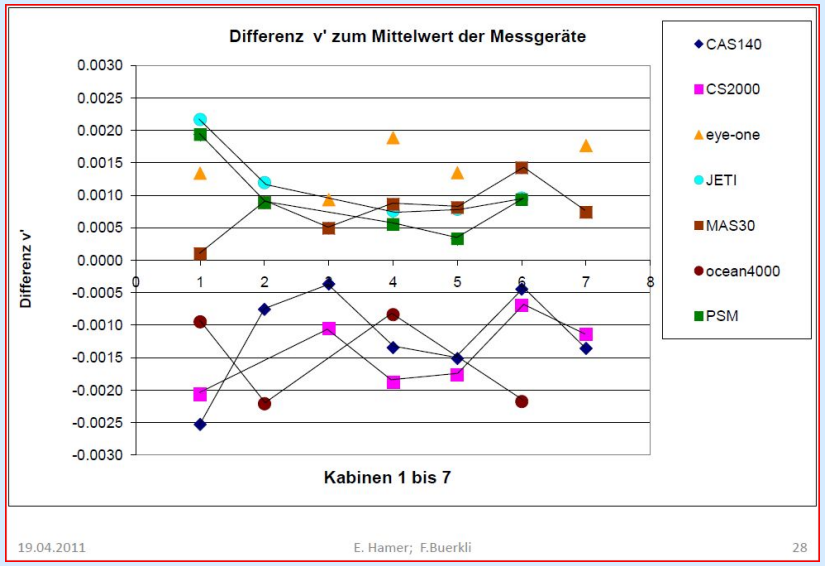


Dynamics	x	y	λ_{dom} [nm]	PE [%]
1e2	0.675	0.282	648.1	87
1e2.5	0.701	0.286	637.0	96
1e3.5	0.714	0.287	634.3	100

Stray light	x	Δx	y	Δy
solid	0.2894	-	0.3041	-
dot 1	0.2903	0.0009	0.3065	0.0024
dot 2	0.2915	0.0021	0.3098	0.0058

FOGRA test (measurement of viewing cabinets)





Differences in u´v´ to mean value of 7 cabinets

Comparability of different instruments

Possible reasons for differences in readings can be

(in the following order):

1. Differences in device parameters (optical resolution, digital resolution, wavelength precision, stray light, dynamics, ...)
2. Individual status of calibration (wavelength, sensitivity)
3. Individual measuring errors (ambient light, adjustment, drift of sample, temperature, ...)

specbos 1211 – Comparability with CS 2000 (for arbitrary spectra)

- Deviation xy up to 0.002
- therefore differences in CCT up to 150 K
- Differences in L_v in the range of 1 ... 2 %

- Caused by differences in
  - Wavelength fit
  - Level calibration
  - Individual parameters (stray light, non linearity, bandwidth ...)

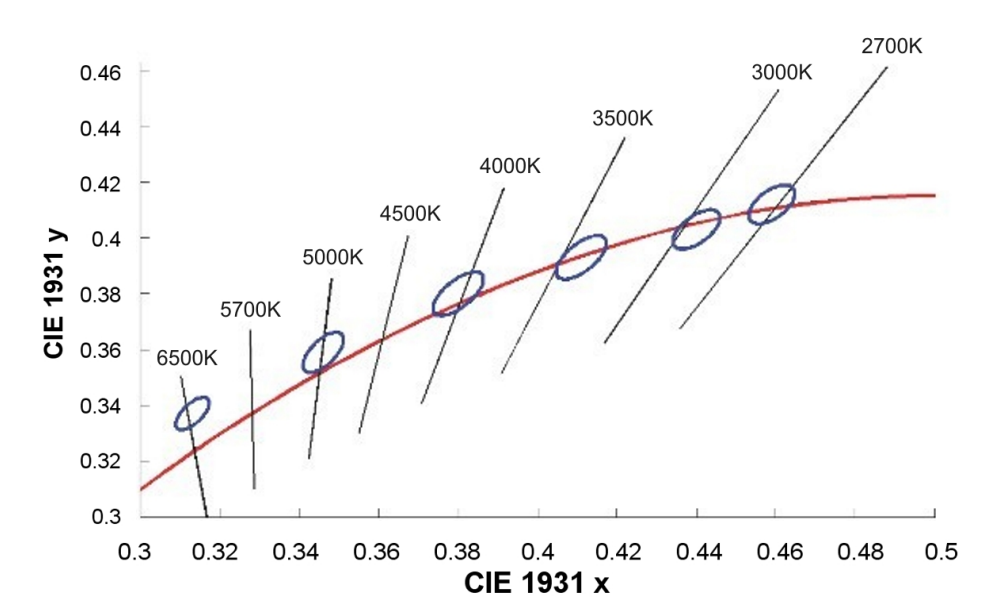
What instrument to use?

Application	Instrument
Comparison measurements of sources with equal spectra	filter instrument
Absolute measurements of sources with same spectra	filter instrument, profiled by a spectroradiometer
Absolute measurements of sources with arbitrary spectra	spectroradiometer
Measurement of values except xyY and related quantities	spectroradiometer

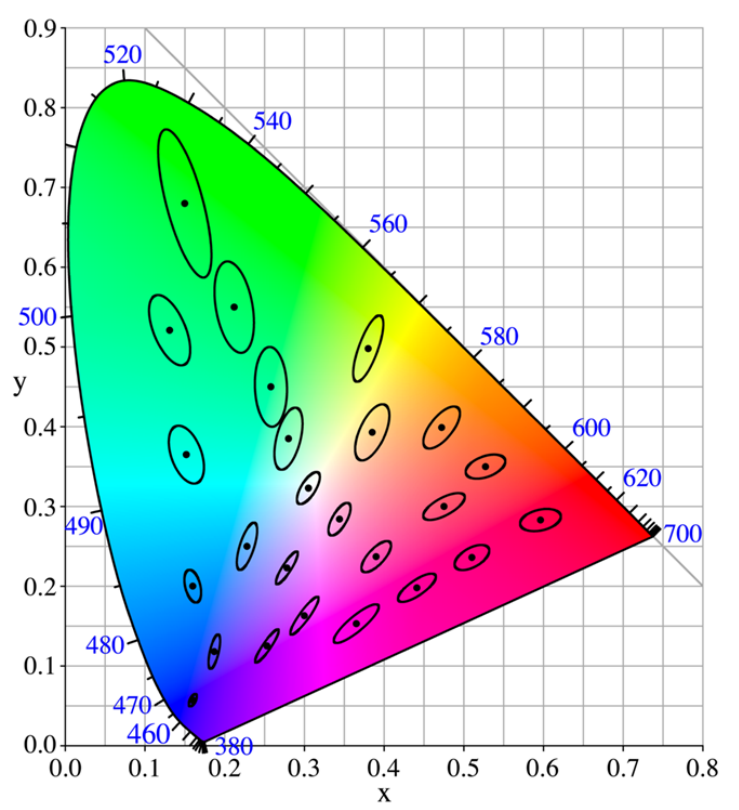
Which color differences can be distinguished?

Which color difference Δx, Δy can be distinguished?

- McAdam Ellipses



McAdam-Ellipses (3-fold magnified)



McAdam-Ellipses (10-fold magnified)

Which color difference Δx, Δy can be distinguished?

- dependent from location in color diagram (McAdam Ellipses) and of brightness (and of individual observer)
- average value for monitor (setting D 65, 80 cd/m²): ΔE ~ 2 ... 3
- ΔE = sqrt (ΔL* + Δa* + Δb*)
- roughly determined value for Δx, Δy: +/- 0.004 ... 0.006

JETI specbos series

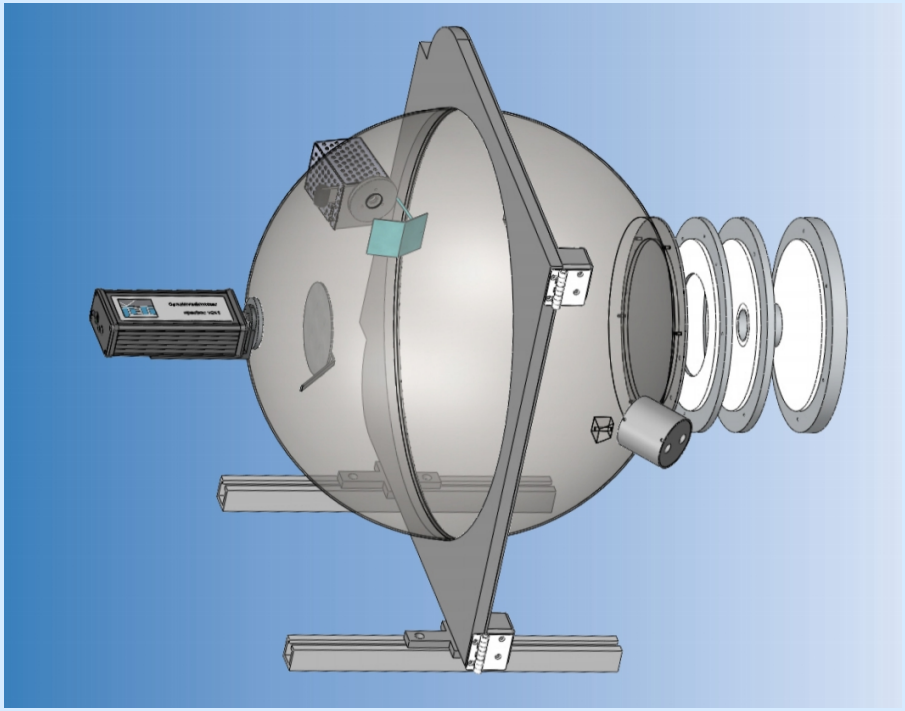
specbos 1201 focus

specbos 1201 flash

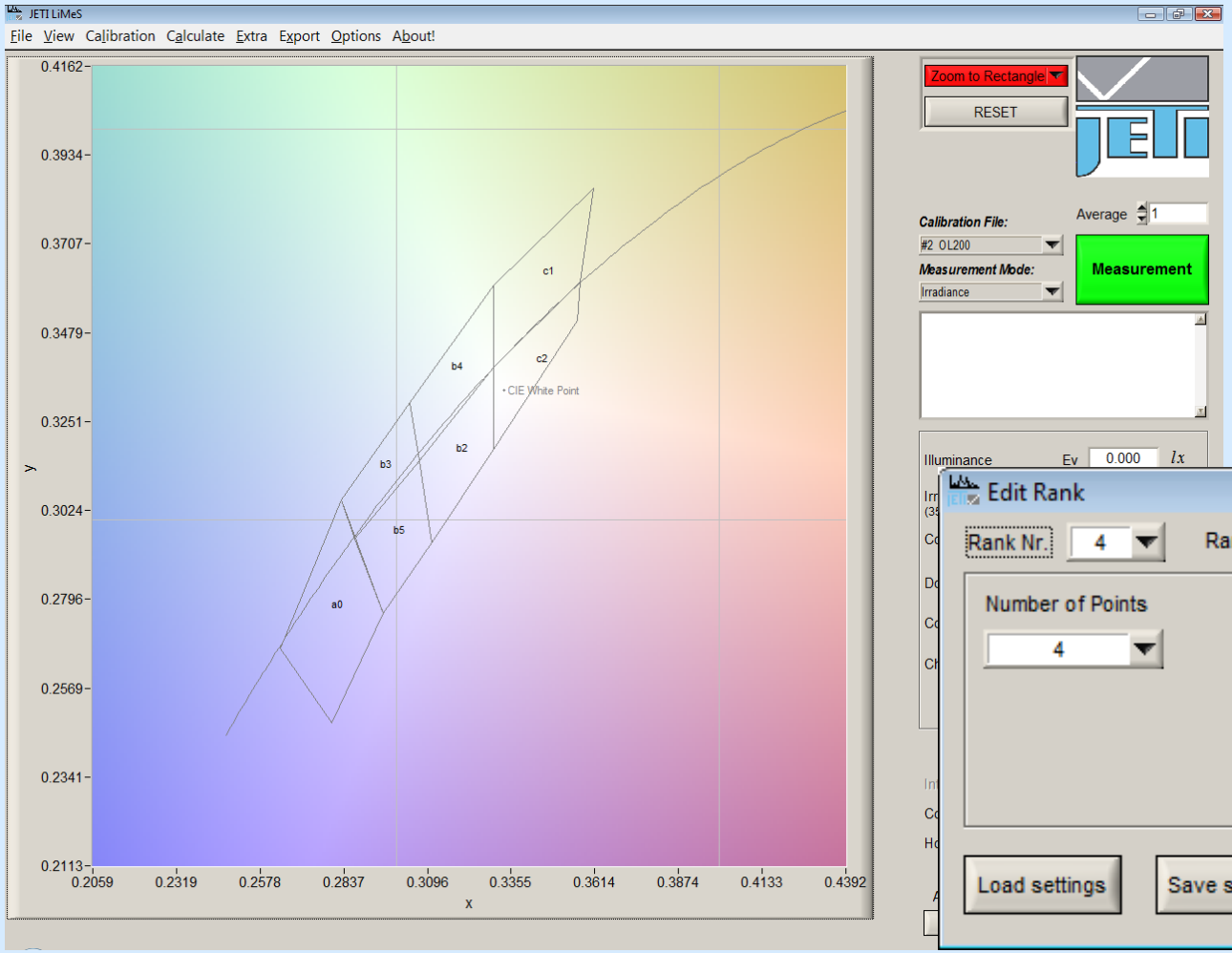
specbos 1301/ 1311 – Luminous flux

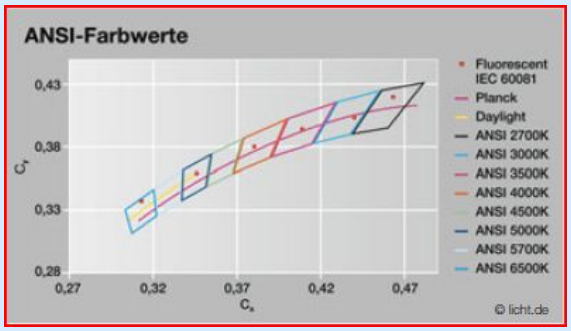
specbos 1401 – CIE 127 averaged intensity

Example: Flux measurement of LED illuminaires

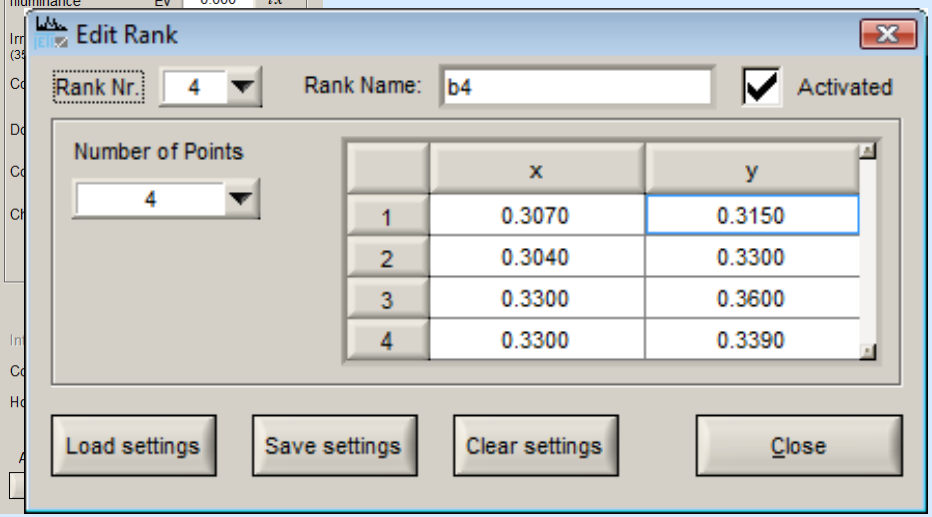


Classification (Definition of Ranks)

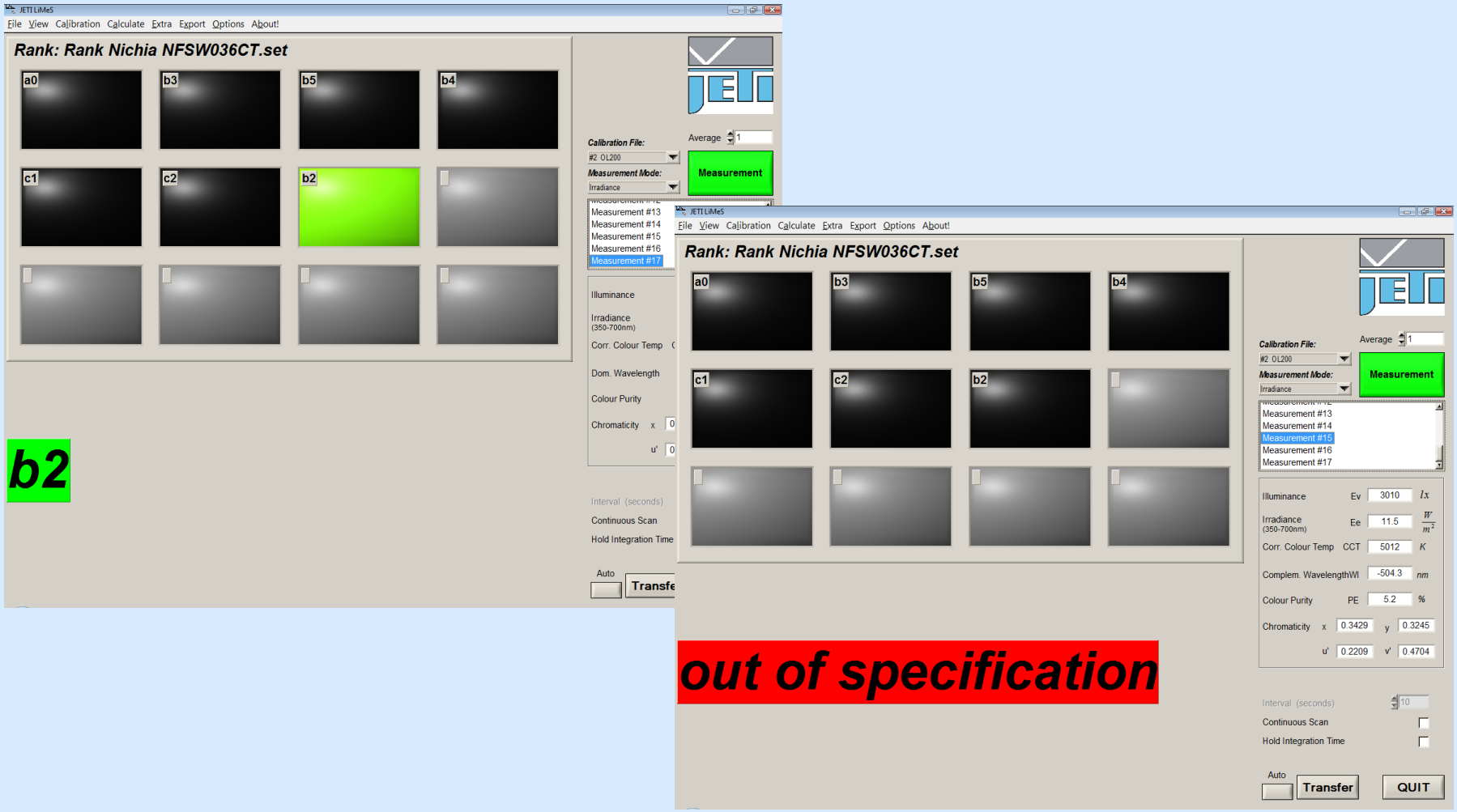




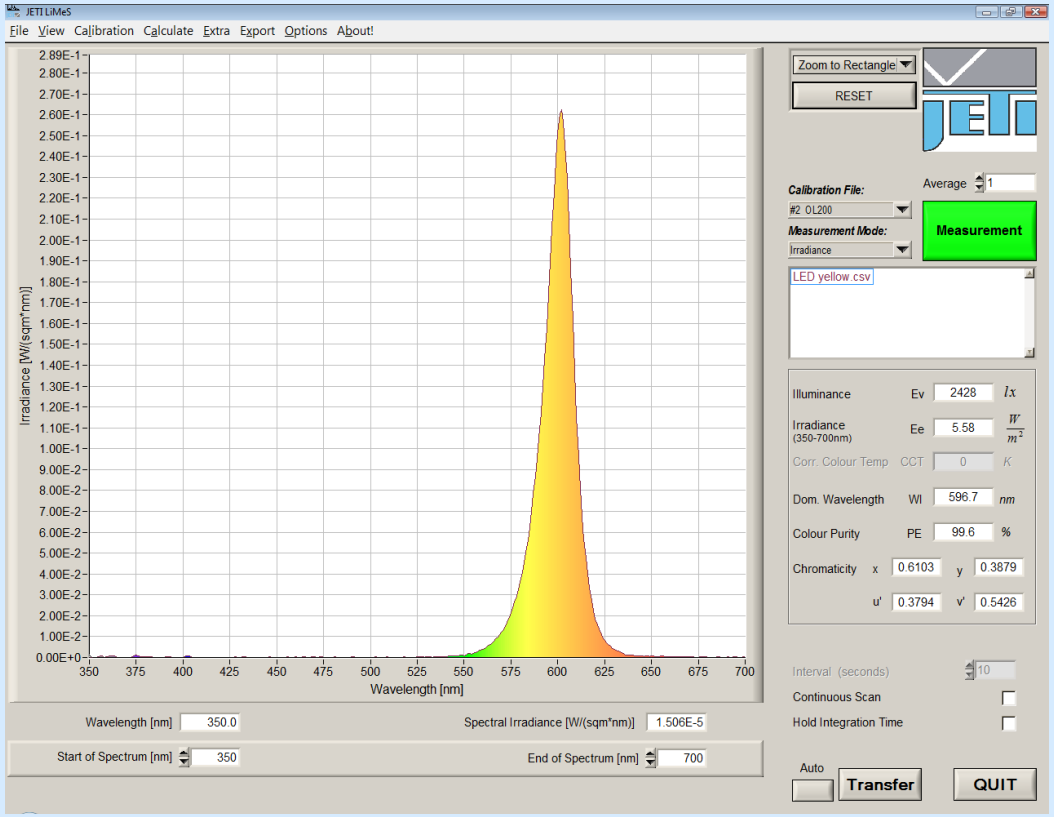
ANSI C78.377-2008

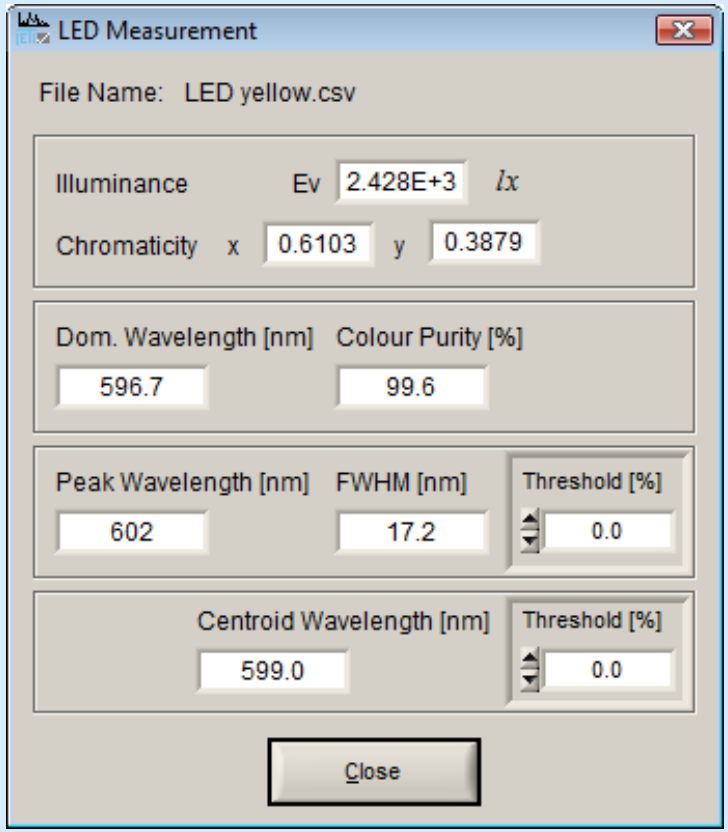


Classification (Results)



LED Values


JETI LiMeS
File View Calibration Calculate Extra Export Options About!
Irradiance [W/(sqm*nm)]
Wavelength [nm]
Zoom to Rectangle
RESET
Calibration File:
#2 OL200
Measurement Mode:
Irradiance
Average 1
Measurement
LED yellow.csv
Illuminance Ev 2428 lx
Irradiance (350-700nm) Ee 5.58 W/m²
Corr. Colour Temp CCT 0 K
Dom. Wavelength WI 596.7 nm
Colour Purity PE 99.6 %
Chromaticity x 0.6103 y 0.3879
u' 0.3794 v' 0.5426
Interval (seconds) 10
Continuous Scan
Hold Integration Time
Wavelength [nm] 350.0
Spectral Irradiance [W/(sqm*nm)] 1.506E-5
Start of Spectrum [nm] 350
End of Spectrum [nm] 700
Auto
Transfer
QUIT


LED Measurement
File Name: LED yellow.csv
Illuminance Ev 2.428E+3 lx
Chromaticity x 0.6103 y 0.3879
Dom. Wavelength [nm] Colour Purity [%]
596.7 99.6
Peak Wavelength [nm] FWHM [nm] Threshold [%]
602 17.2 0.0
Centroid Wavelength [nm] Threshold [%]
599.0 0.0
Close

Light measuring of road lighting

Replacement of Discharge lamps by LED technology

Typical measuring tasks:

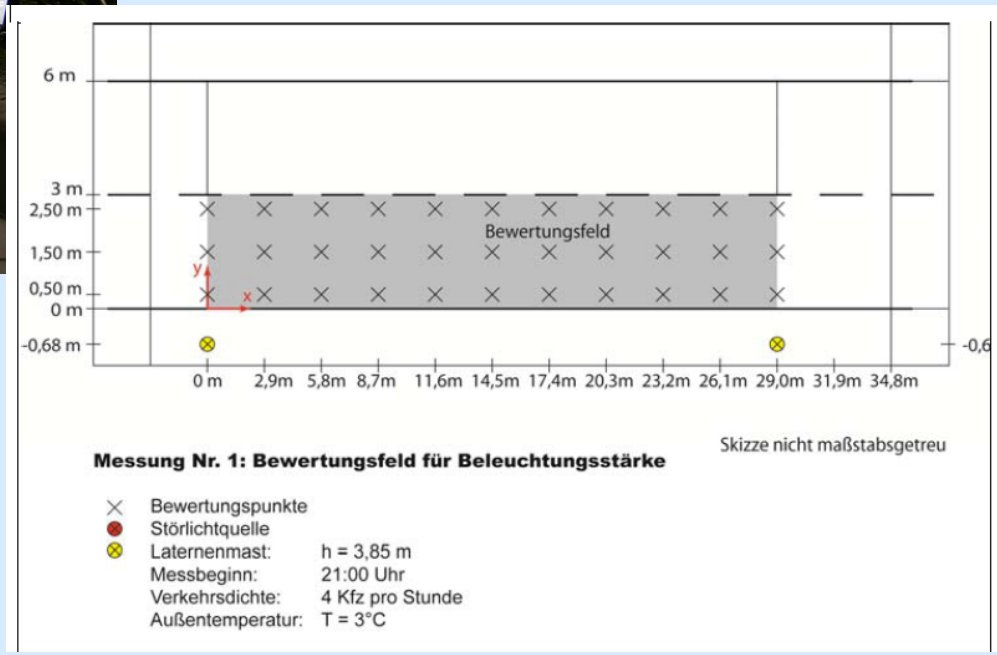
Horizontal illuminance	max. 200 mm above ground
Luminance of road surface	angle 89° to normal of road
Luminance distributions	

Instruments: Luminance camera, e.g. LMK color of Technoteam

Spot meter, e.g. specbos 1211 of JETI

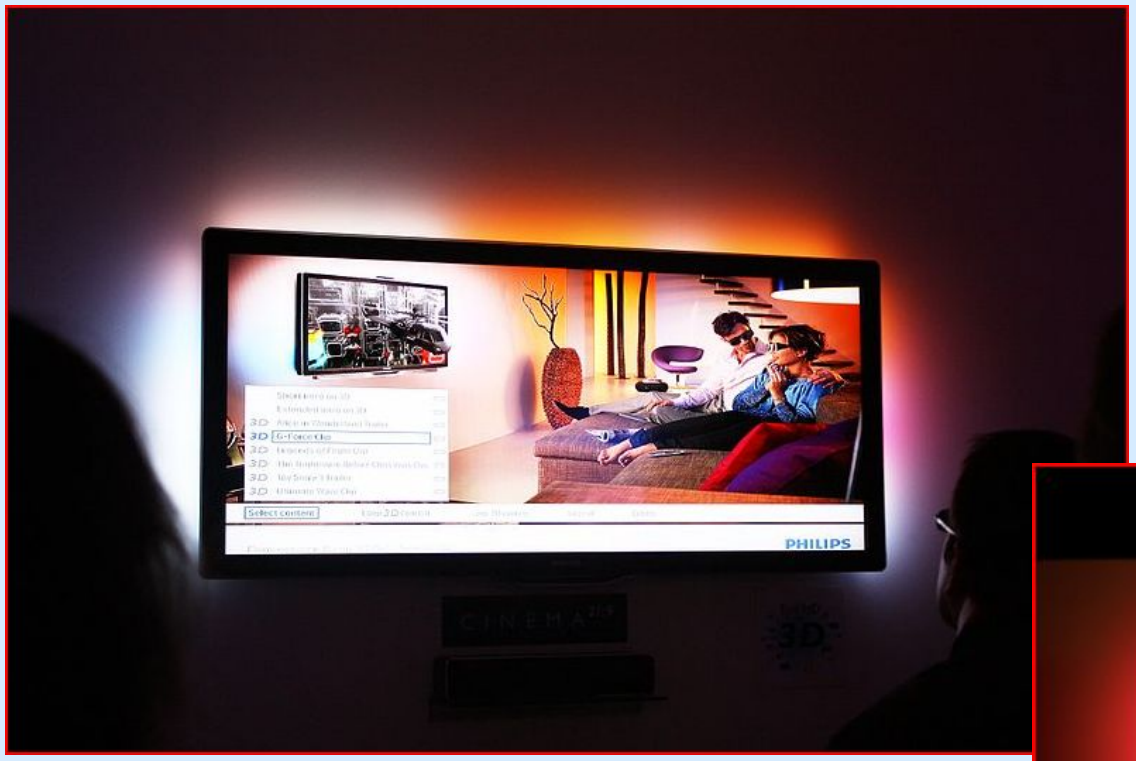
+

Light measuring of road lighting



-> specbos 1211 BT

Philips Ambilight



Content depending LED backward illumination

More relaxed TV consumption

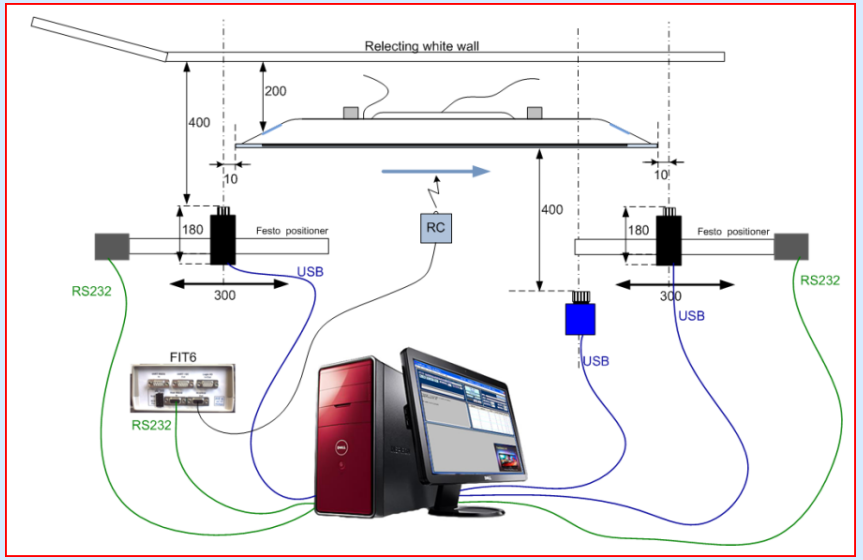
Task: Adjustment of LED driver settings during production

Measurement of Philips Ambilight

- xyY measurement of primaries
- Matrix calculation for LED driver
- Check of primaries and white spectrum

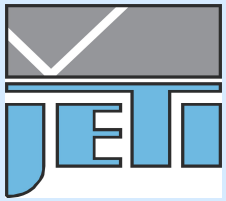
Specification:

- max. 0.5 s per measurement
- moveable -> small dimensions
- continuous operation in production -> robust
- no electromagnetic interference (special EMC test)
- 100% relyable interface (first test with USB, later RS 232 version developed)



Conclusions

- Spectral measurements are prefered for spot measurements
- Photometric and Tristimulus measurements are used for space resolved measurements
- Goniometric measurements are done photometrically, more and more need for spectral measurements
- Photometers and Tristimulus meters can be profiled by a spectroradiometer
- Large number of color measuring instruments for light sources on the market
  (approx. 40 ... 50 spot meters)
- Special care is necessary to measure with uncertainty $u(Y) < 5\ \%$ and $u(x,y) < 0.003$



Thank you for your interest.

Contact: steffen.goerlich@jeti.com