Metrology for Solid State Lighting

EURAMET European Association of National Metrology Institutes

# EMRP-ENG05 Stakeholder Meeting

## Characterised Mesopic Photometer

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coordinator: VSL

CMI · Ministerio de Ciencia e Innovación · CSIC · INRIM Istituto Nazionale di Ricerca Metrologica · Instituto Português da Qualidade · LNE · Schweizerische Eidgenossenschaft / Confédération suisse / Confederazione Svizzera / Confederaziun svizra · MKEH · NPL National Physical Laboratory · PTB · SMU Slovak Institute of Metrology · SP · Helsinki University of Technology Metrology Research Institute · Trescal · Technische Universität Ilmenau · Laplace · La Venaria Reale

Physikalisch-Technische Bundesanstalt PTB

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## Characterised Mesopic Photometer

*contributing partners*

ČMI

LMT®

Aalto University
School of Electrical
Engineering

PTB

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

## Outline

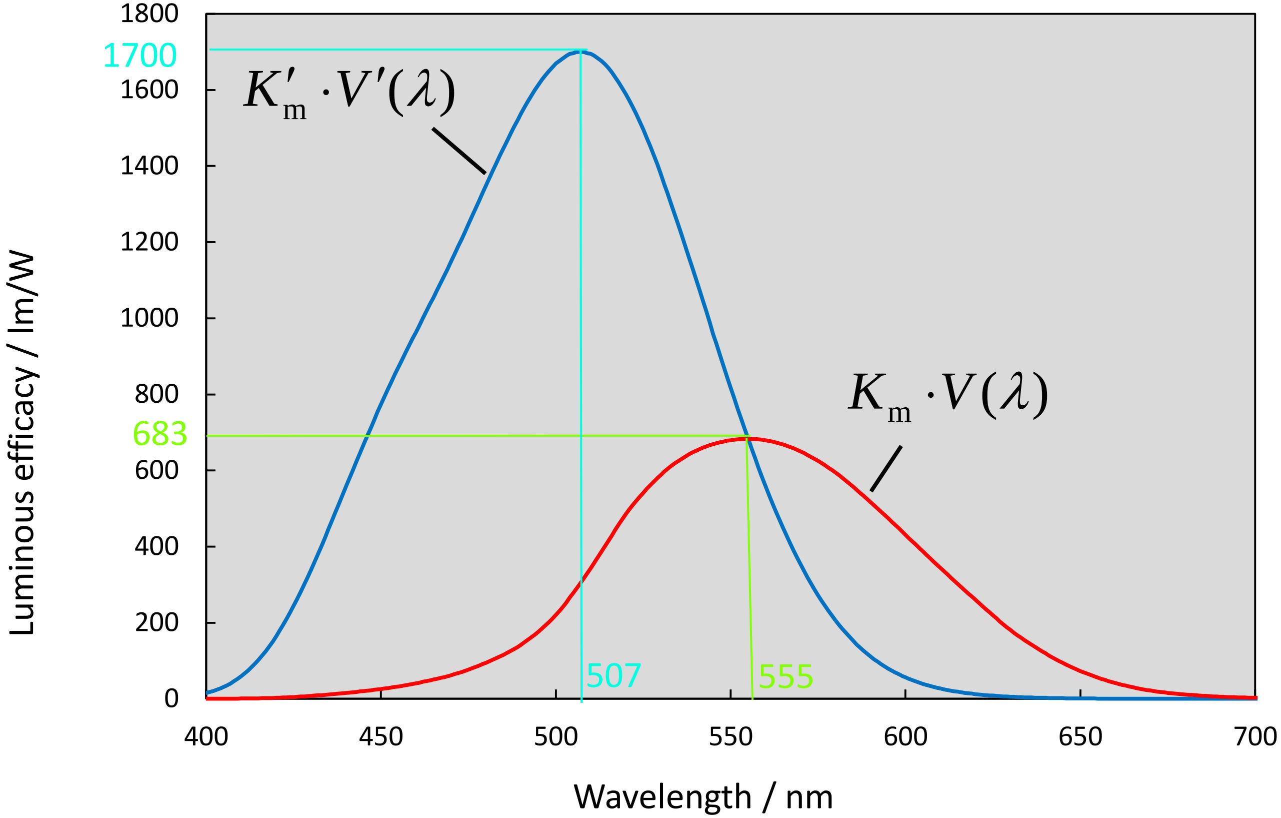
- Goals of the Task
- Background
- Traceability chain for mesopic measurements
- Characterisation of detectors
- Mesopic luminance meter
- Spectral mesopic values
- Conclusion

# Goals

- The aim of this task was to develop reference photometers for traceable optical measurement on SSL sources at low and very low light levels:
  - Development and building a true mesopic luminance meter including the electronics based on a photopic and a mesopic filter radiometers with an target uncertainty of 2 %
  - Mesopic luminance and illuminance measurement using spectroradiometers
  - Traceablility chain for mesopic instruments using characterised photopic and scotopic luminance and illuminance meters

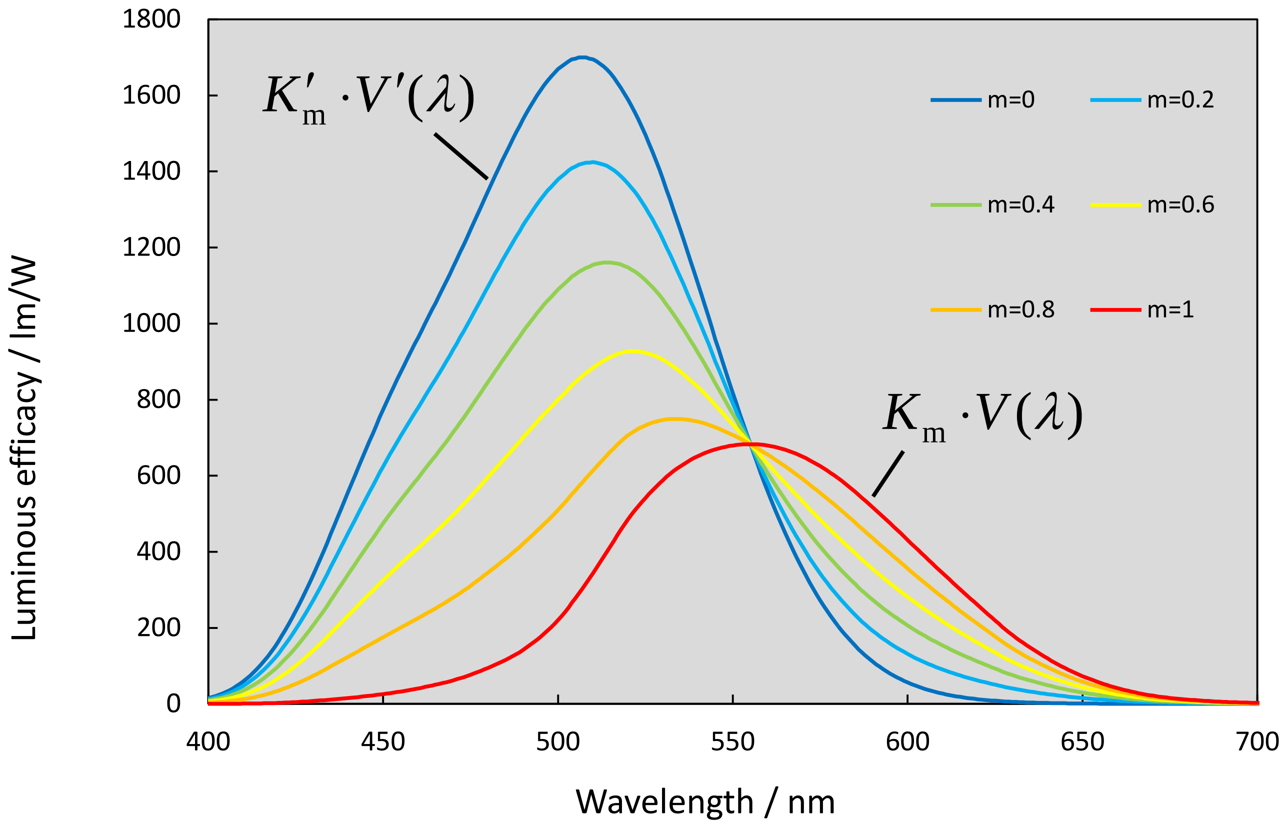
# Background

- Photopic an scotopic luminous efficacy functions as defined by CIE in 1979



# Background

- Mesopic range defined by CIE in 2010 (CIE 191:2010) as a linear combination of the photopic and scotopic luminous efficiency functions
  - dependent on an adaptation level in the range of $(0 \leq m \leq 1)$

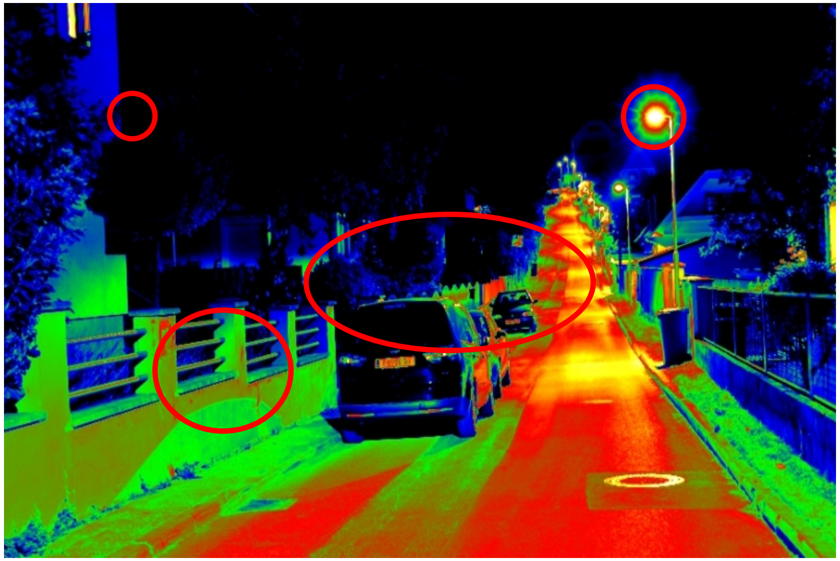



m: adaptation level of observer

# Background

$$V_{\mathrm{mes}}(\lambda) = \frac{1}{M(m)}\left[mV(\lambda) + (1-m)V'(\lambda)\right]$$

- What does “adaptation level” mean



The adaptation level depend on the scenery

- currently investigated by CIE JTC1
- no solution available at the moment

# Traceability chain for mesopic measurements

Photopic path ↓

$I_v(T)$  Luminous intensity standard

↓

$s_v$  Photometer heads

↓

$L_v(T)$  Luminance standard

↓

$c$  Luminance meter

# Traceability chain for mesopic measurements

Photopic path ↓ | Scotopic path ↓

$I_v(T)$  $I'_v(T)$ — Luminous intensity standard

↓

$s_v$  $s'_v$ — Photometer heads

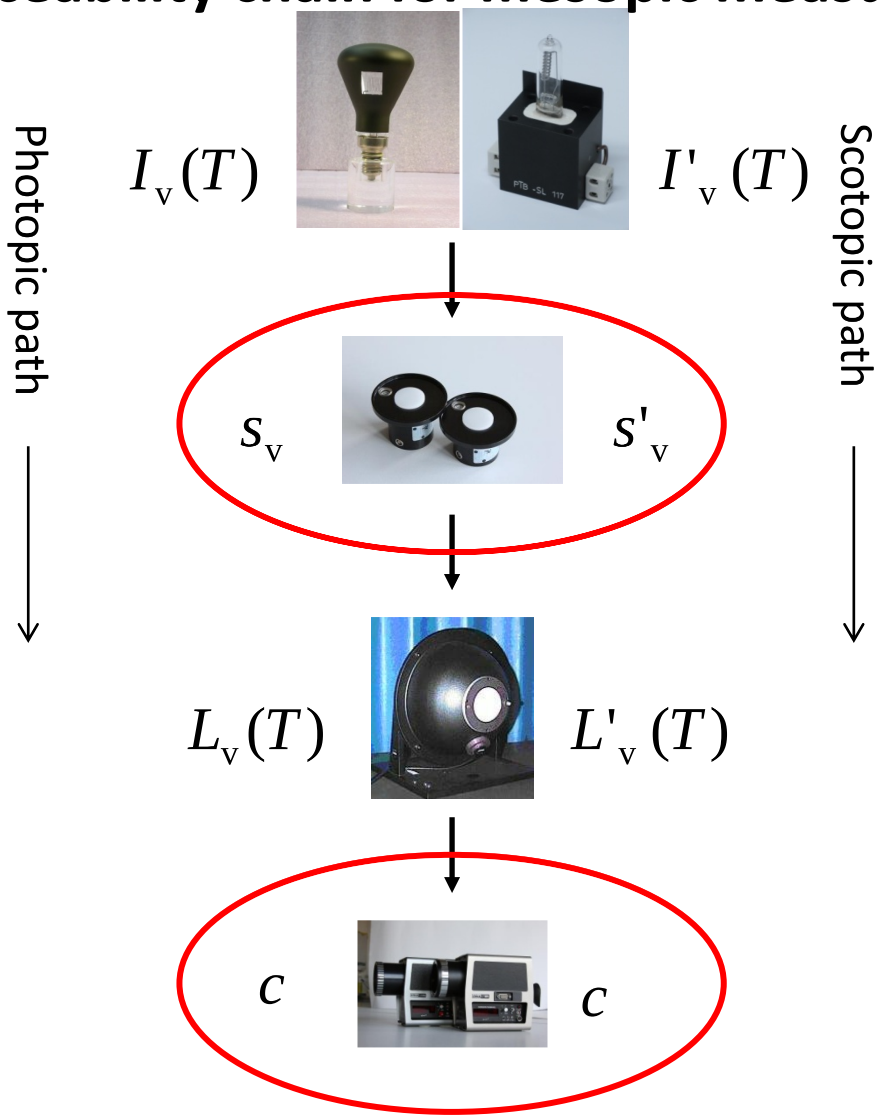
↓

$L_v(T)$  $L'_v(T)$ — Luminance standard

↓

$c$  $c$ — Luminance meter

# Traceability chain for mesopic measurements




Luminous intensity standard

Photometer heads

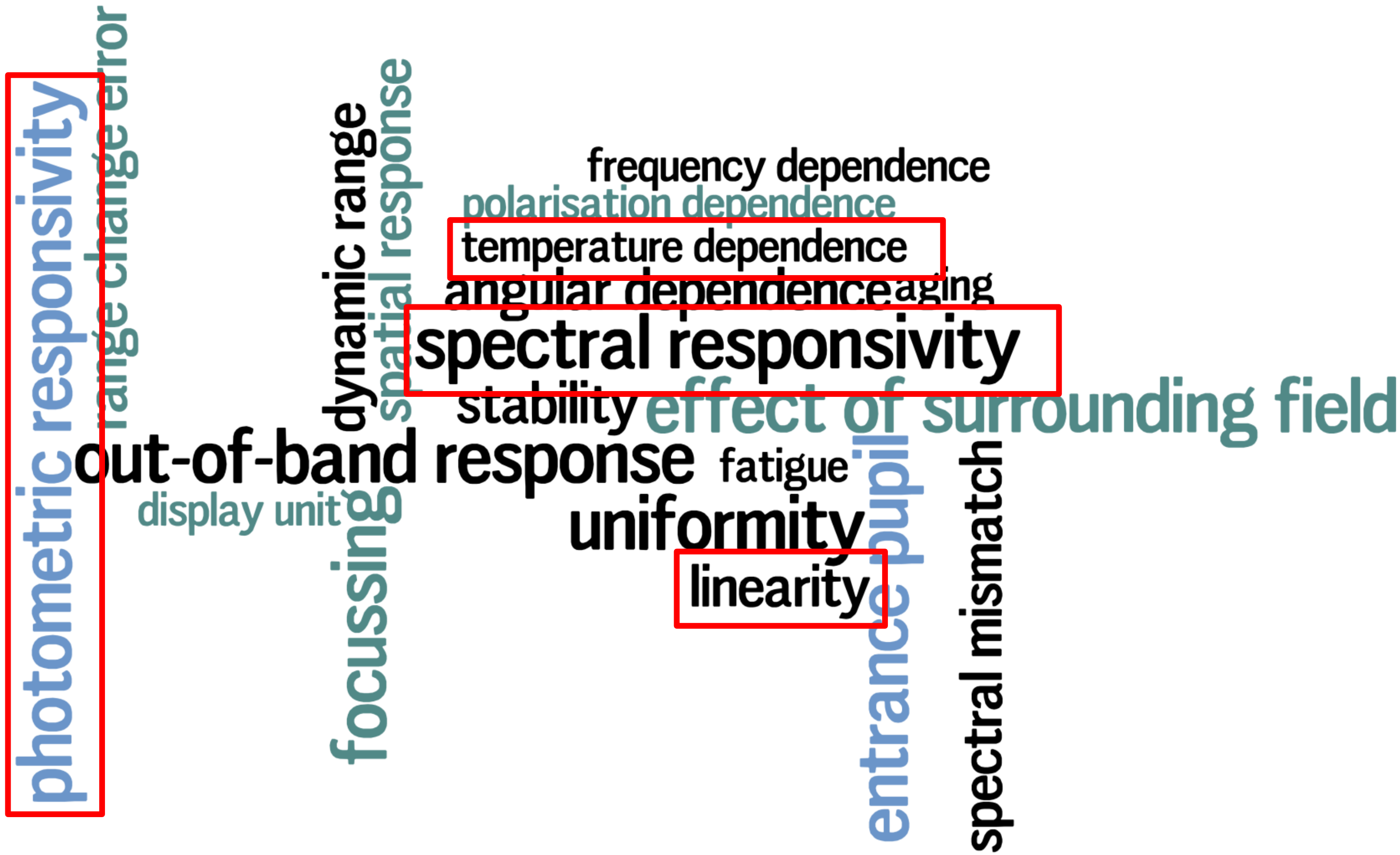
Luminance standard

Luminance meter

# Characterisation of detectors

photometric responsivity
range change error
dynamic range
spatial response
frequency dependence
polarisation dependence
temperature dependence
angular dependence
aging
spectral responsivity
stability
effect of surrounding field
out-of-band response
fatigue
display unit
focussing
uniformity
linearity
entrance pupil
spectral mismatch

# Characterisation of detectors



# Characterisation of detectors

P30SCT Scotopic illuminance meter

P30SCT Photopic illuminance meter

- Activ area: 30 mm diameter
- $V(\lambda)$ and $V'(\lambda)$
- Mosaic  filters
- Cosine corrected
- Temperature stabilized at approx. 35 °C

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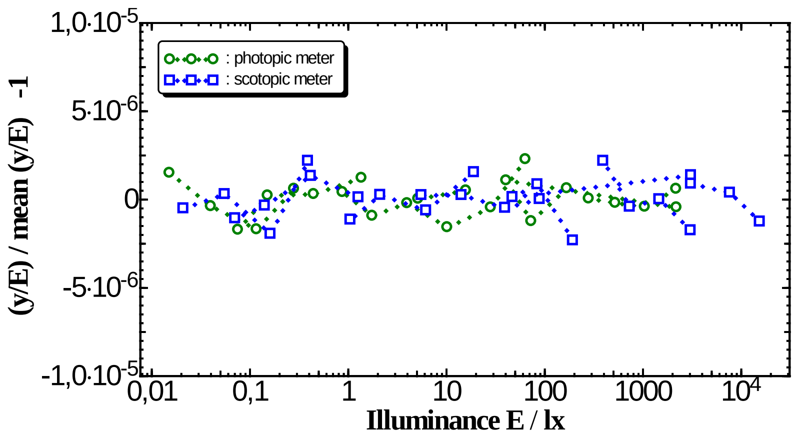
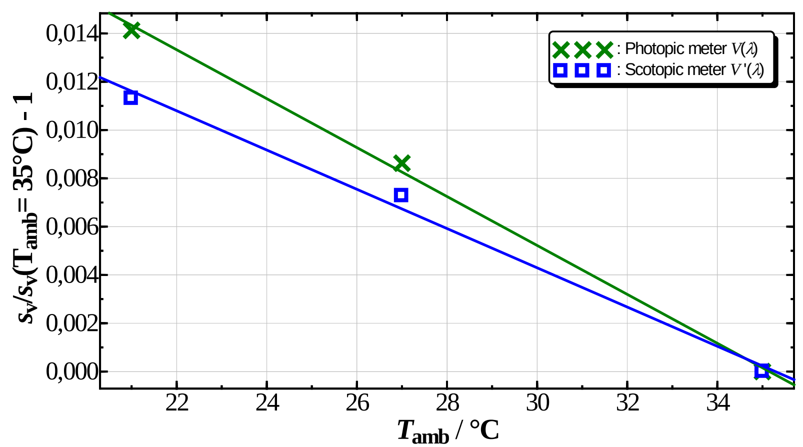
# Characterisation of detectors

## Linearity and temperature dependence of photometer heads:

Linearity




Temperature dependence



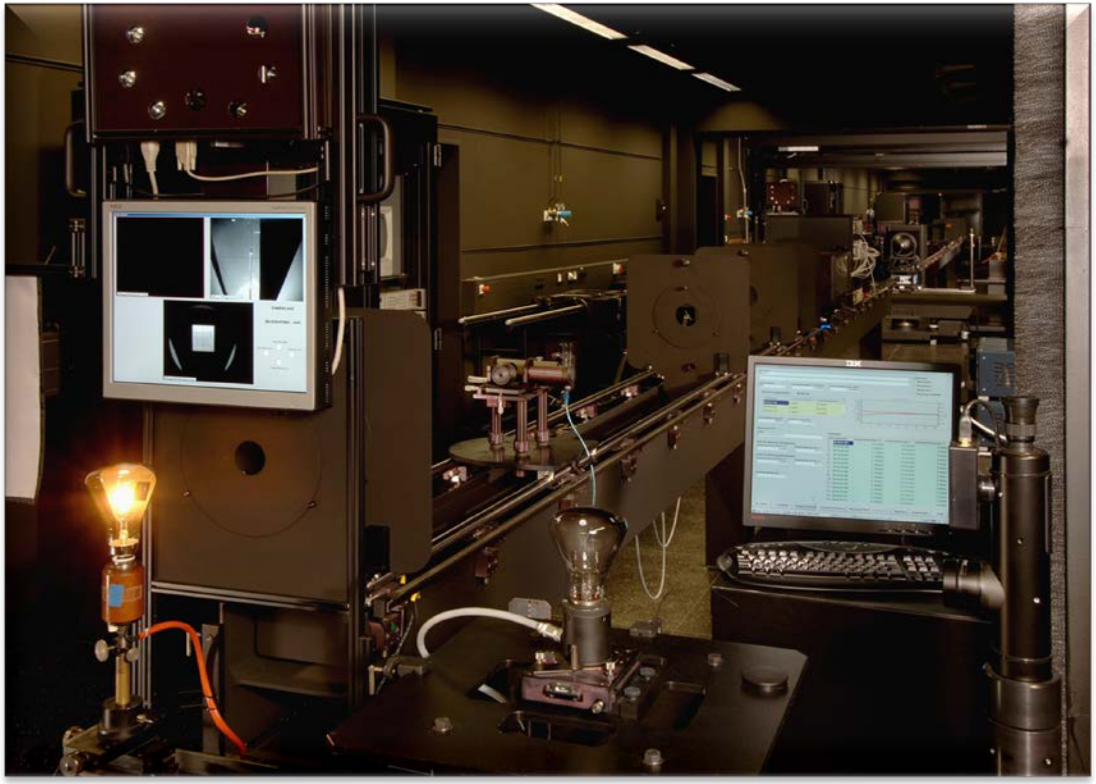

Photopic meter:

$\alpha_0$ = -0,1 %/K

Scotopic meter:

$\alpha_0$ = -0,08 %/K

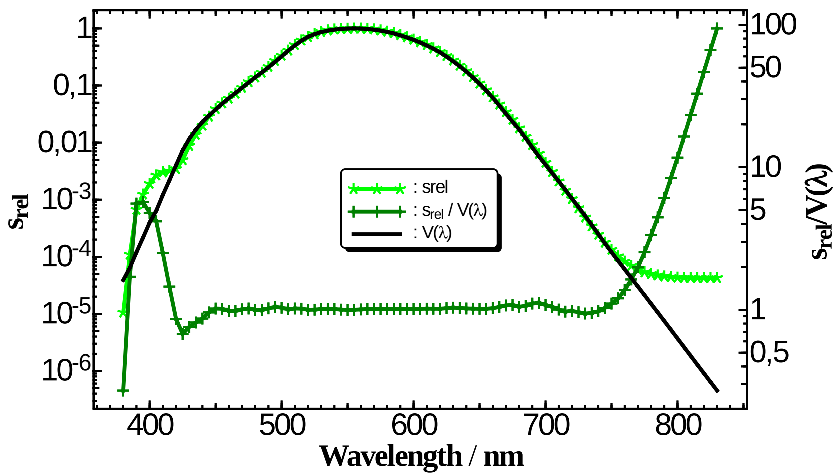
# Characterisation of detectors

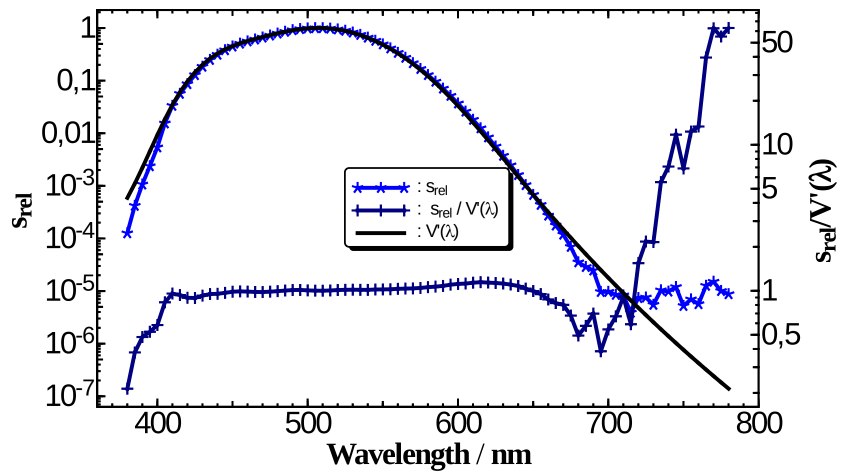


- Lamp holder that allows independent alignment of 6 degrees of freedom on cross bench
- maximum distance to source >40m
- Measurement carriage with 6 places for measurement devices on rail system
- Detectors inside mounted on carousel
- Different lamps like luminous intensity standard Wi41/G and high power lamps for linearity measurements

# Characterisation of detectors

- Photopic detector
- Scotopic detector




$s_v$ = 19,081 nA/lx
m = 0,002

$s'_v$ = 6,581 nA/lx
m' = 0,015

# Characterisation of detectors


- Wavelength range 230 nm to 1600 nm
- Output power up to 100 mW/nm
- Power stabilisation better than 0,1 %
- Bandpass limitation down to 0,1 nm

- Measurement against reference trap detector in substitution
- trap calibrated against cryogenic radiometer

- Treatment of speckle, polarisation and interferences
- Determination of uniform radiation field through integrating sphere or holographic diffusers
- Uniformity in measurement plane better than 0,1 %
- Mounting of the detectors on 3-axis translation stage with positioning better than 0,1 mm

# Characterisation of detectors

P30SCT Scotopic illuminance meter

P30SCT Photopic illuminance meter

- Activ area: 30 mm diameter
- $V(\lambda)$ and $V'(\lambda)$
- Mosaic  filters
- Cosine corrected
- Temperature stabilized at approx. 35 °C

LMT®

**On customer request, these detectors are now also implemented in goniophotometer systems from LMT  suitable for the determination of the S/P ratio of lamps and luminaires.**

# Characterisation of detectors

L1009 Photopic luminance meters

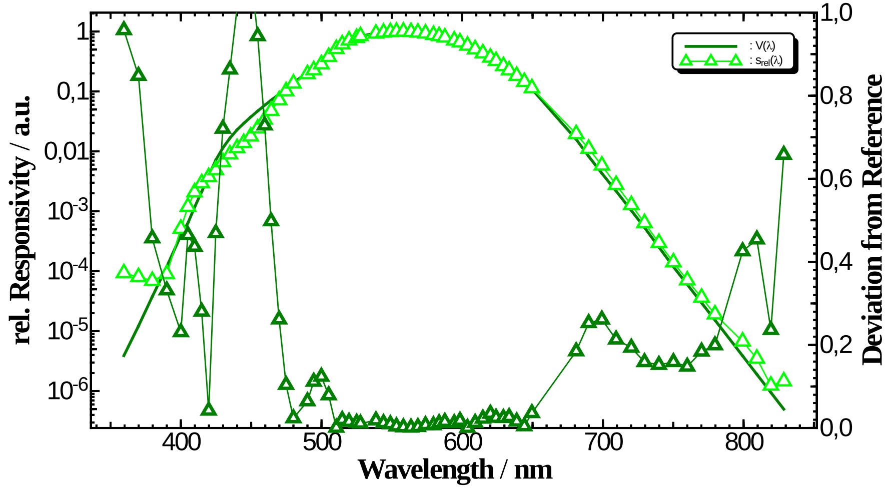
L1009 Scotopic luminance meters

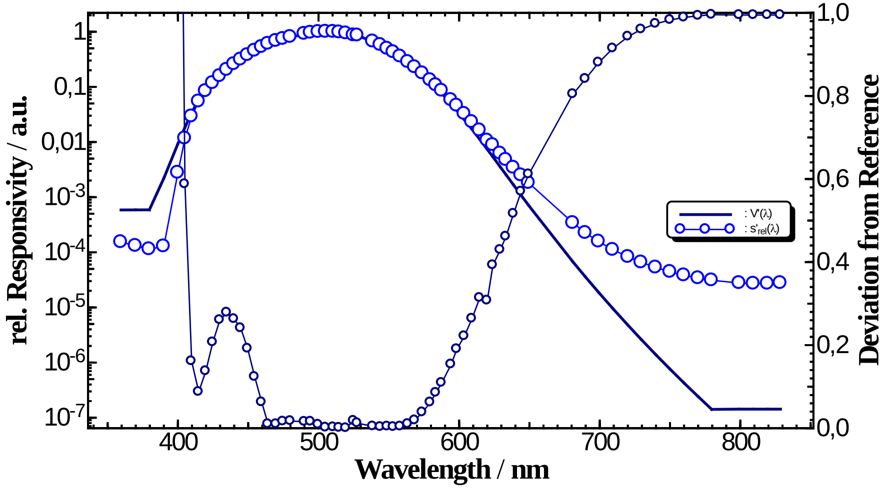

- Field of view: 3°, 1°, 20‘, 6‘
- $V(\lambda)$ and $V'(\lambda)$
- full filters
- no temperature stabilisation

# Characterisation of detectors

## Responsivity of luminance meters:

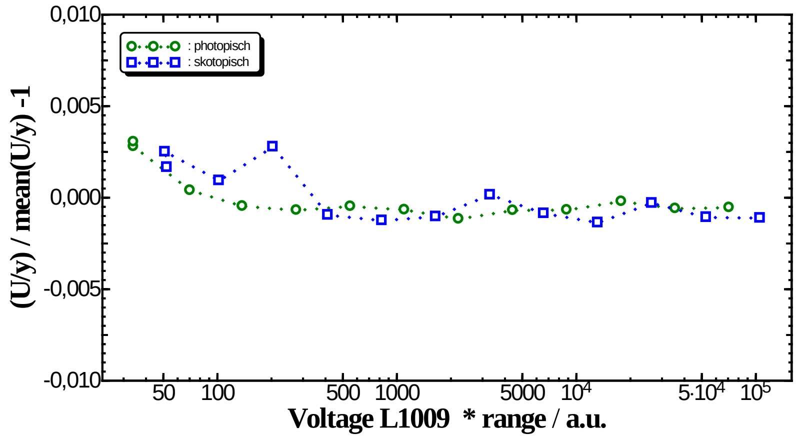
- Photopic detector
- Scotopic detector

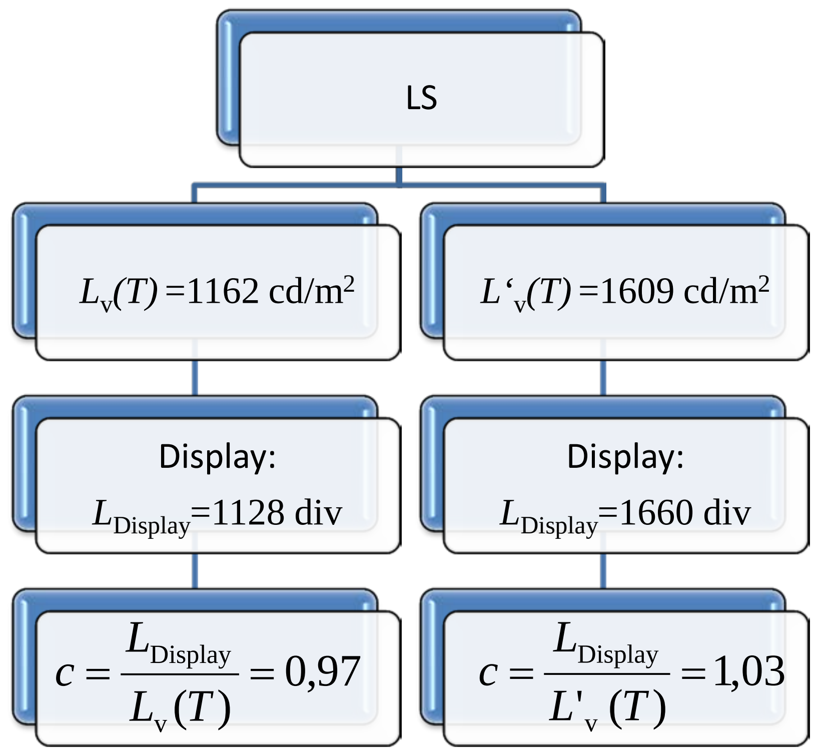


# Characterisation of detectors

## Linearity and calibration factor of luminance meter:



# Traceability chain for mesopic measurements

Photopic path ↓ — Scotopic path ↓

$I_v(T)$


$I'_v(T)$

Luminous intensity standard

↓

$s_v$

$s'_v$

Photometer heads

↓

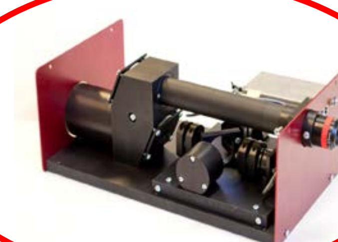
$L_v(T)$

$L'_v(T)$

Luminance standard

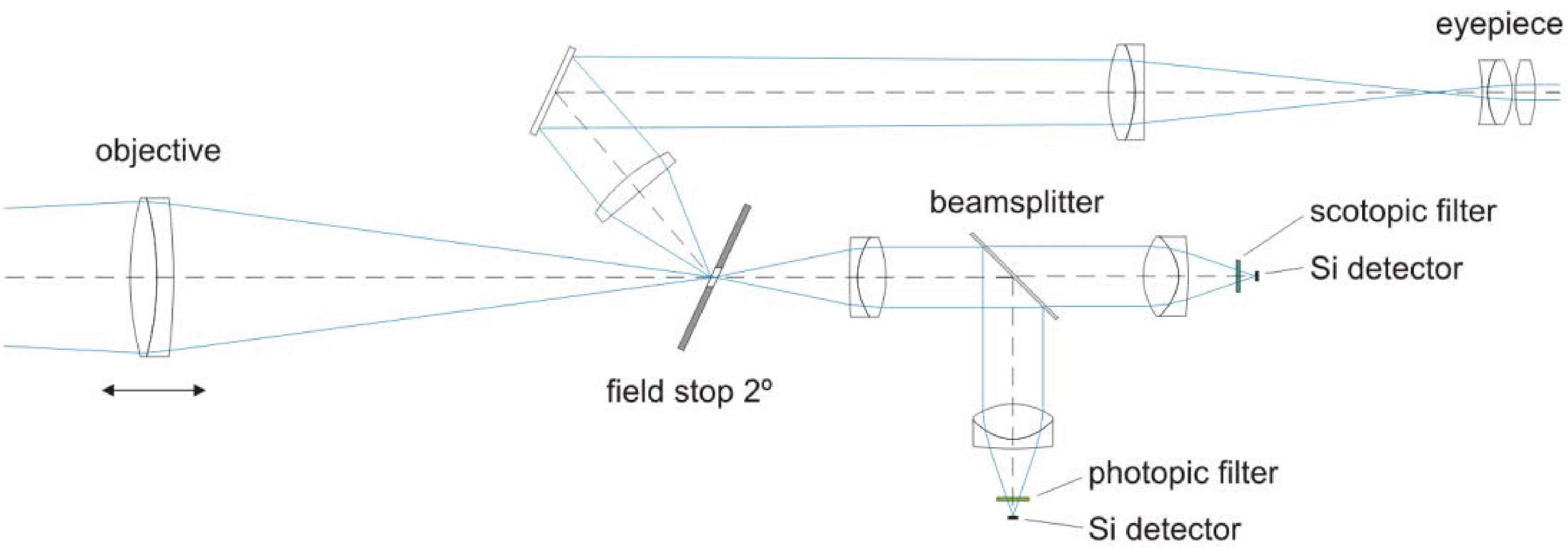
$c$

$c$ ↔



Luminance meter

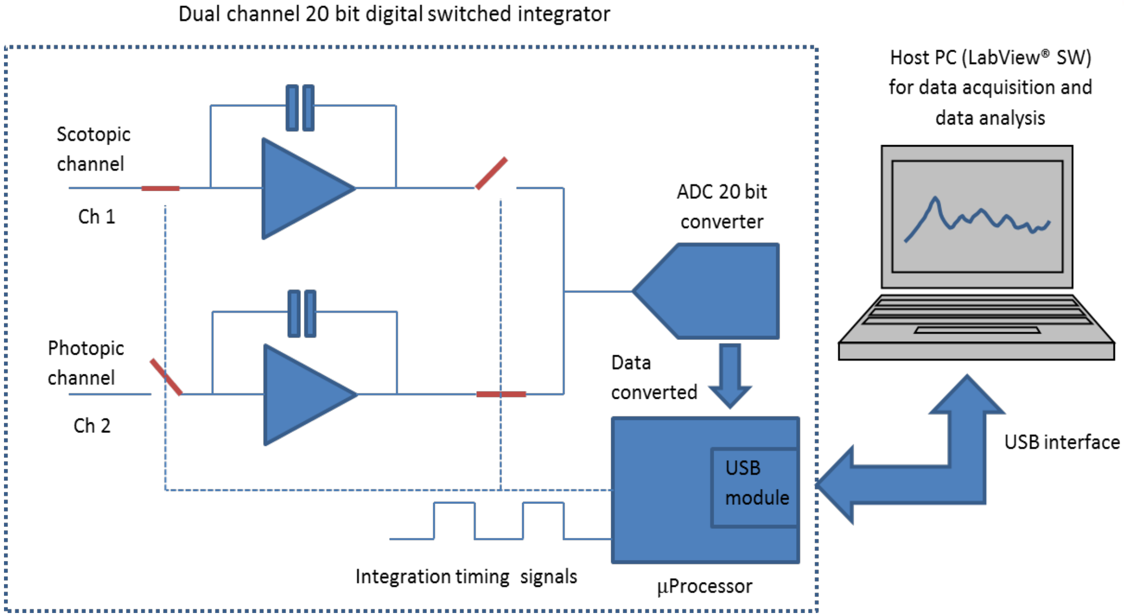
# Mesopic luminance meter



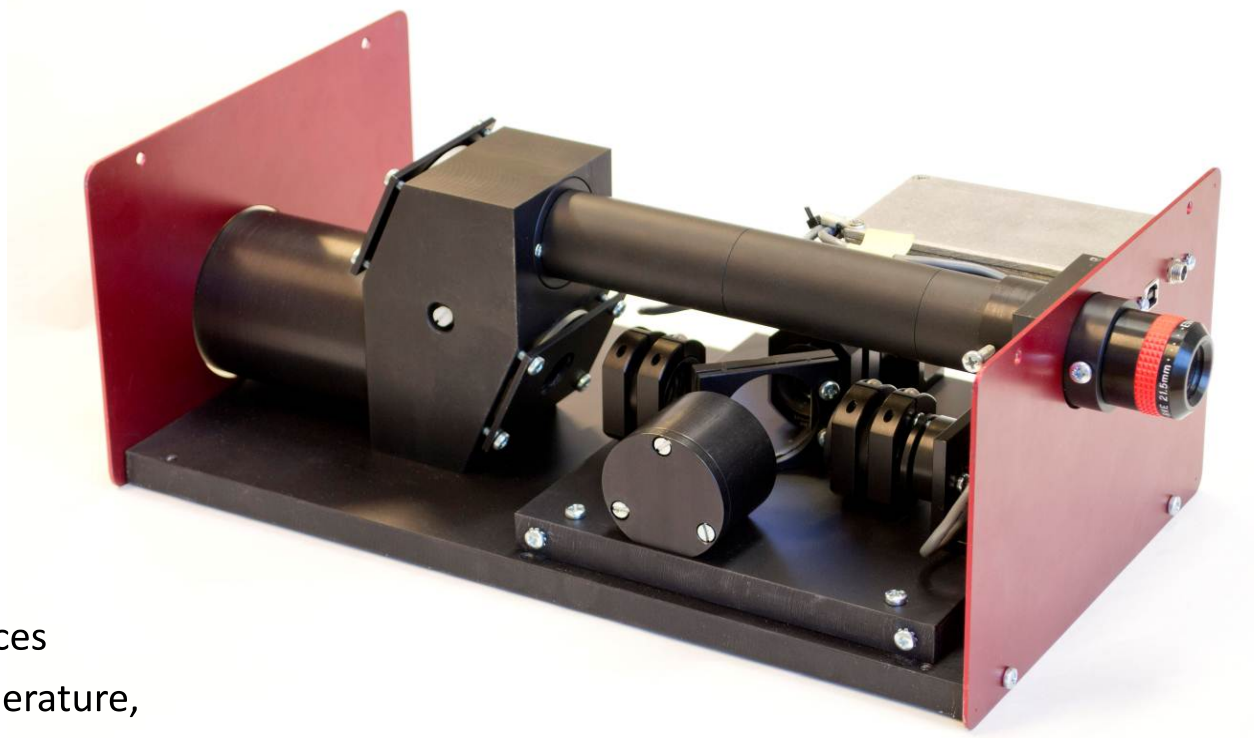

- Off-the-shelf optical components
- 2 detection channels, weighted by $V(\lambda)$ and $V'(\lambda)$ respectively
- Lowest measured luminance level: 0,005 cd/m$^2$
- Standard deviation of the mean: 1 % with <2 s of integration
- Estimated $f'_1$ for photopic: 3,6 %; scotopic: 6 %

# Mesopic luminance meter

- 2-channel switched integrator amplifier with 20 bit ADC
- Amplifier is based on a Burr-Brown ACF2101 integrated circuit
- Controlled by LabVIEW via USB
- 5 decades dynamic range




# Mesopic luminance meter



- Spectral sensitivity
- Linearity
- Effects of out-of-field sources
- Environment effects (temperature, humidity)
- Response to modulated luminance
- Polarization
- …

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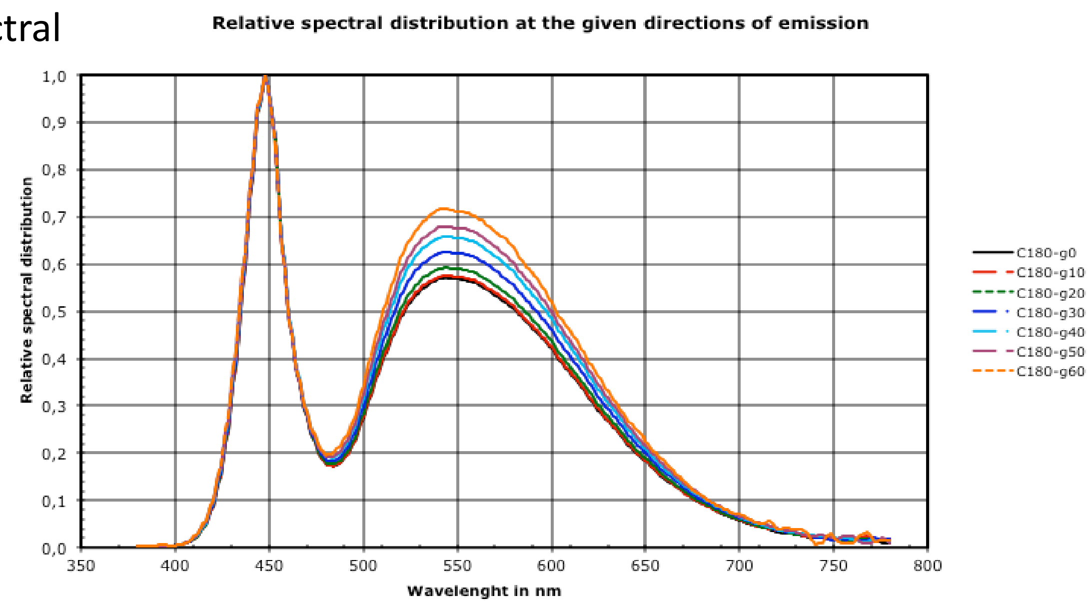
# Spectral mesopic value

- Characterisation of luminaires
- Measurements of luminous flux, luminous intensity distribution and luminous efficacy necessary to characterise luminaires according to existing standards.
- With LED used in street lighting additional measurements needed regarding spectral intensity distribution



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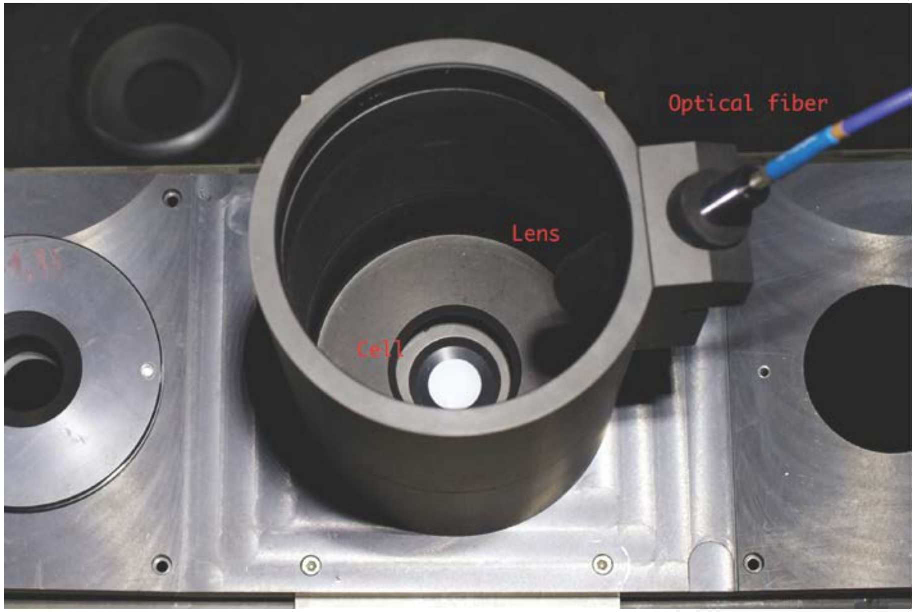
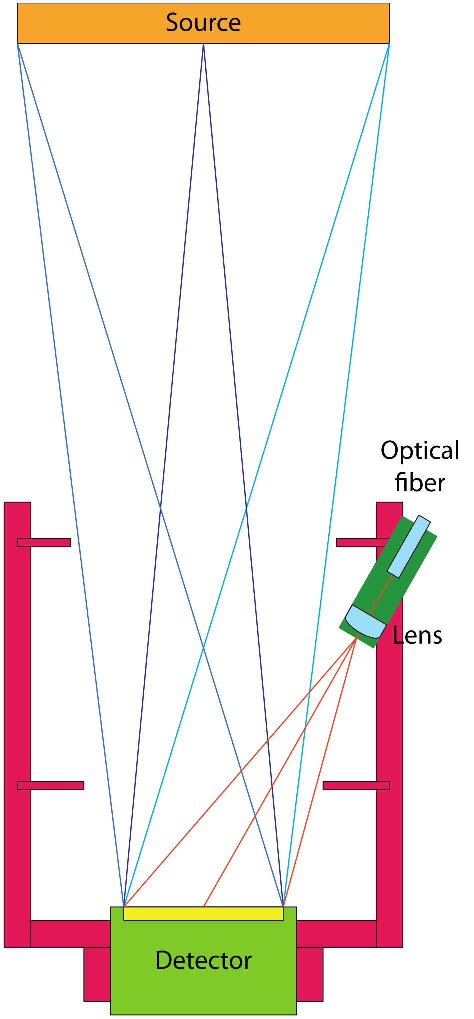
# Spectral mesopic value

- Photopic characterisation of luminaires in goniophotometers and for applications where spectral mesopic luminance values are determined using the spectral reflection coefficient of surfaces.

$$L = \frac{\rho}{\pi} \cdot E \quad \Rightarrow \quad L(\lambda) = \frac{\rho(\lambda)}{\pi} \cdot E(\lambda)$$



# Conclusion

- Development of a photopic and a scotopic traceability chain to allow calibrations in the mesopic range according to CIE191:2010
- Development of a mesopic luminance meter with appropriate low noise electronics
- Development of a detector system for the spectral characterisation of lamps and luminaires to determine mesopic luminance values in road lighting
- Comprehensive characterisation of selected detectors and measurement systems for suitability and uncertainty analysis

- Determination of adaptation level up to now not implemente

## Substitution methods …

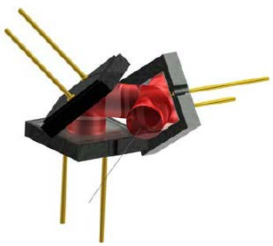
Detector

Source

Cryogenic radiometer

Spectrally tunable source

Trap detector



Spectrally tunable source

Si-Trap detector + aperture

Spectrally tunable source

Filtered radiometer

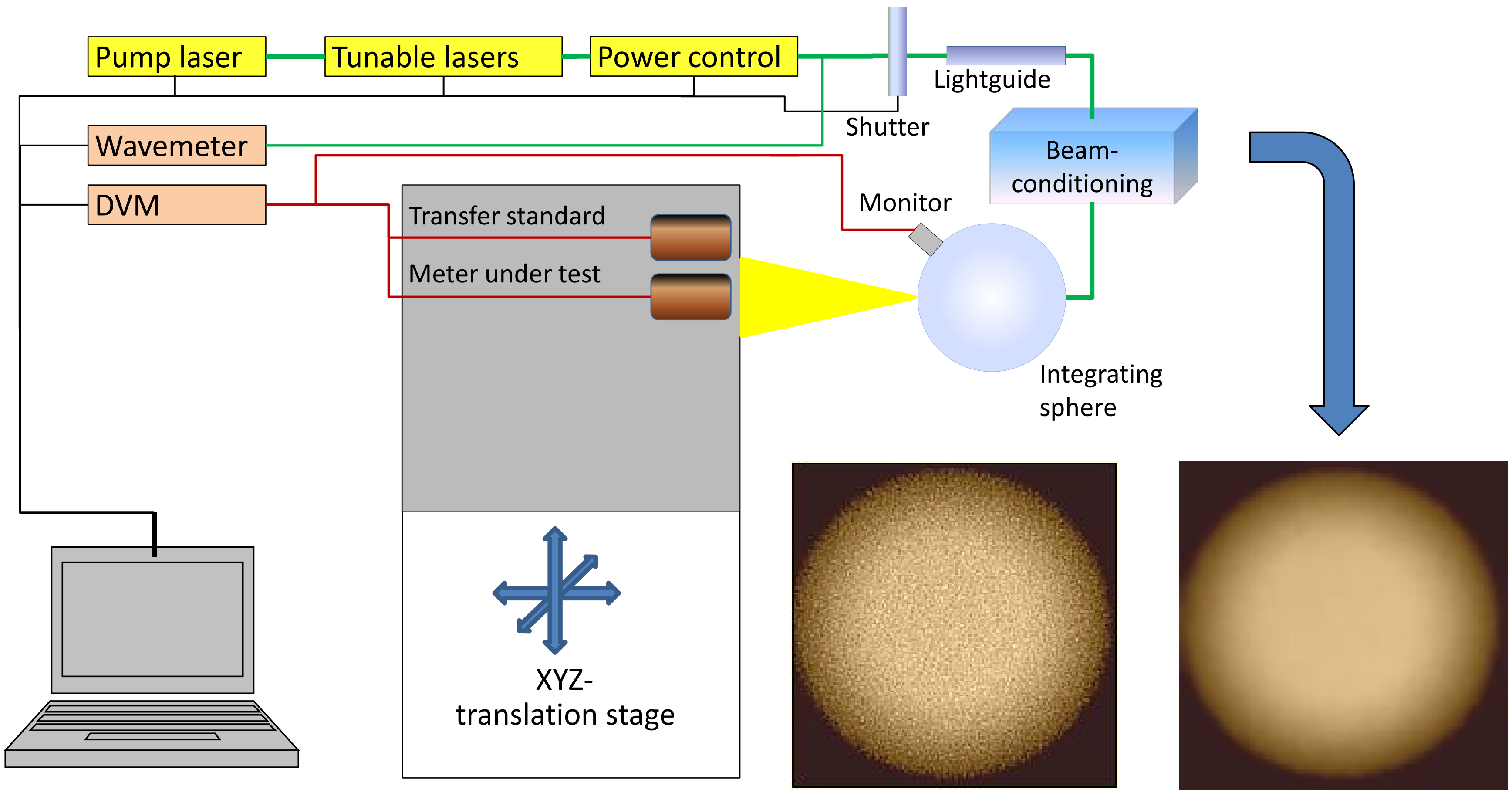
Broad-band source

Photometer

**… to minimize uncertainty**

# Characterisation of detectors

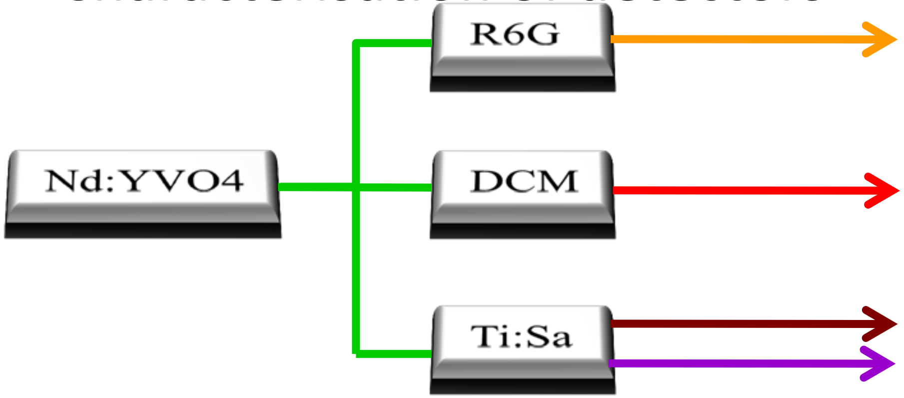
## TULIP setup at PTB

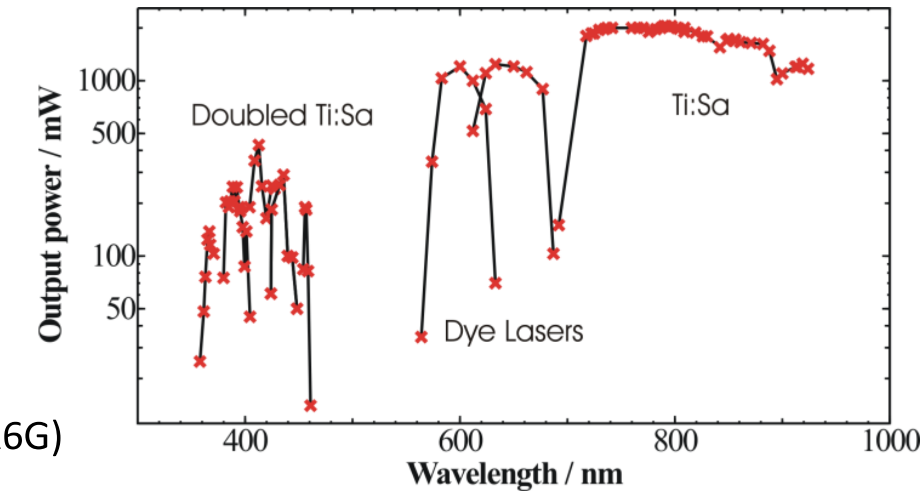



*V. E. Anderson et al, Applied Optics, Vol. 31, No. 4, 1992*

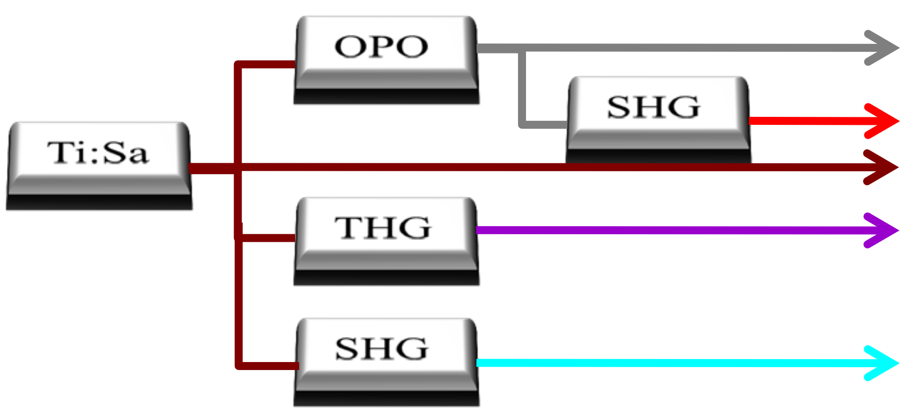
*S. Brown et al; Applied Optics, Vol. 45, No32, 2006*

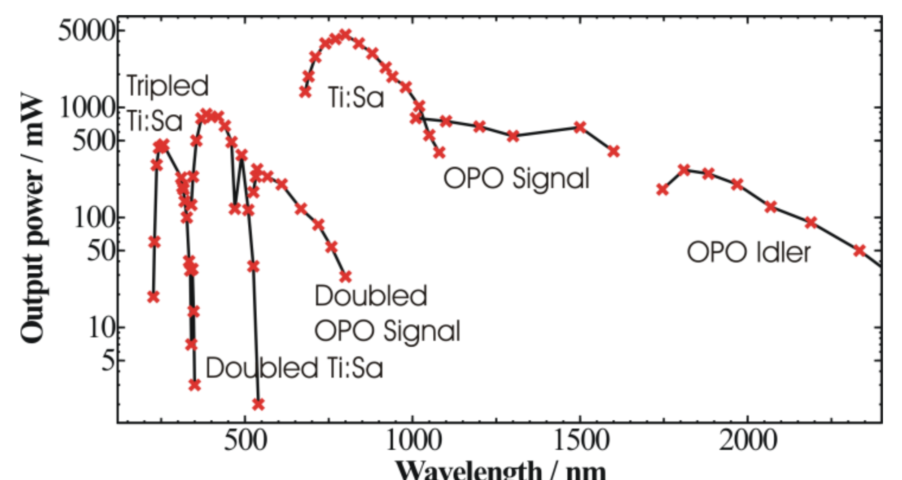
# Characterisation of detectors



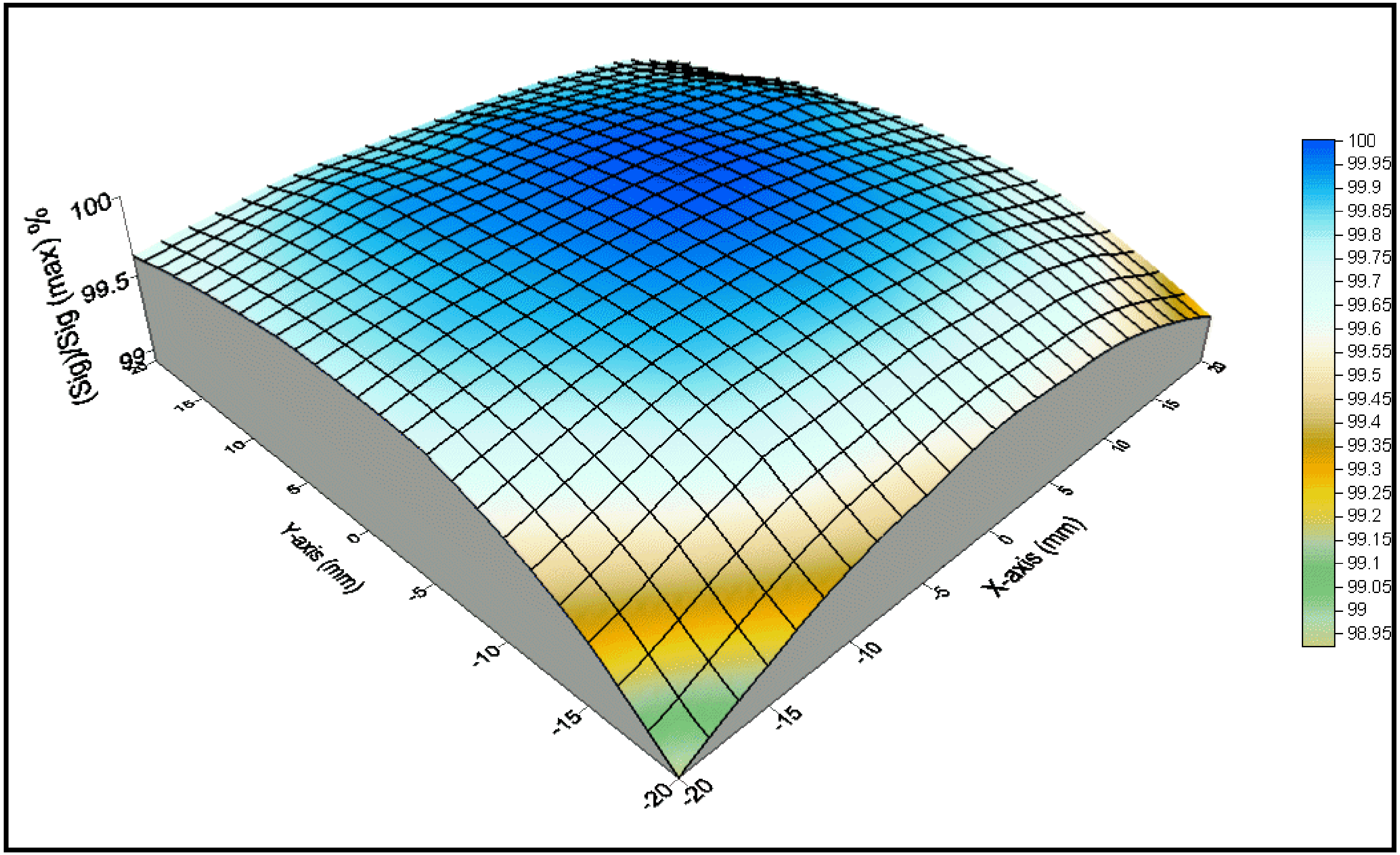

Continous wave setup with Ti:Sa, Dye lasers (DCM, R6G) and intracavity doubling of the Ti:Sa laser




Quasi-cw setup with high repetition femtosecond Ti:Sa laser, optical parametric oscillator, and external doubling and tripling of Ti:Sa and OPO

# Characterisation of detectors




Uniformity of the irradiation field in a distance of 70 cm from the sphere source

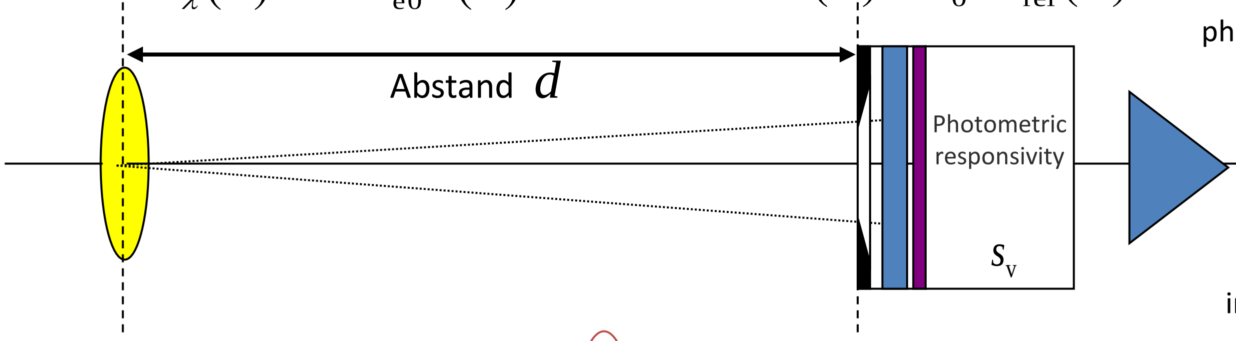
# Characterisation of detectors

spectr. radiant power density

$$\Delta\Phi_\lambda(\lambda) = \Delta\Phi_{e0} S(\lambda)$$

spectral responsivity

$$s(\lambda) = s_0 \cdot s_{\rm rel}(\lambda)$$




photocurrent

$$y = \frac{\Delta\Phi_{e0}}{\Delta A_2} s_0 \int_0^\infty S(\lambda)\, s_{\rm rel}(\lambda) \mathrm{d}\lambda$$

$$E_{\rm v} = \frac{\Delta\Phi_{e0}}{\Delta A_2} K_{\rm m} \int_0^\infty S(\lambda)\, V(\lambda) \mathrm{d}\lambda$$

irradiance

photometric responsivity (for illuminant A)

$$\frac{1}{s_{\rm v}} \overset{\rm DEF}{=} \frac{K_{\rm m}}{s_0} \frac{\int_0^\infty P(\lambda, T_{\rm A})\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty P(\lambda, T_{\rm A})\, s_{\rm rel}(\lambda) \mathrm{d}\lambda}$$

$y = E_{\rm v} \cdot s_{\rm v}$

$$E_{\rm v} = y \cdot \frac{K_{\rm m}}{s_0} \frac{\int_0^\infty S(\lambda)\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty S(\lambda)\, s_{\rm rel}(\lambda) \mathrm{d}\lambda}$$

luminous intensity tungsten filament lamp

$$I_{\rm v}(T) = \frac{d^2}{\Omega_0} E_{\rm v} = y \frac{d^2}{\Omega_0} \frac{1}{s_{\rm v}} F(T)$$

approximation

mismatch correction factor for planckian radiator

$$F(T) = \frac{\int_0^\infty P(\lambda, T)\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty P(\lambda, T)\, s_{\rm rel}(\lambda) \mathrm{d}\lambda} \Bigg/ \frac{\int_0^\infty P(\lambda, T_{\rm A})\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty P(\lambda, T_{\rm A})\, s_{\rm rel}(\lambda) \mathrm{d}\lambda} \approx \left(\frac{T}{T_{\rm A}}\right)^m$$

mismatch correction factor for arbitrary radiators

$$ccf = \frac{\int_0^\infty S(\lambda)\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty S(\lambda)\, s_{\rm rel}(\lambda) \mathrm{d}\lambda} \Bigg/ \frac{\int_0^\infty P(\lambda, T_{\rm A})\, V(\lambda) \mathrm{d}\lambda}{\int_0^\infty P(\lambda, T_{\rm A})\, s_{\rm rel}(\lambda) \mathrm{d}\lambda}$$