PTB

Tunable Lasers at PTB for Photometry and Radiometry

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Federal Ministry
of Economics
and Technology

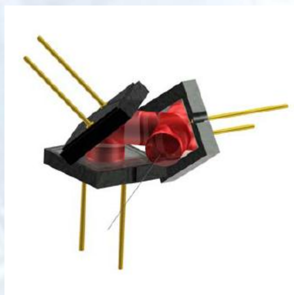
Calibration chains, e.g. photometric responsivity

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

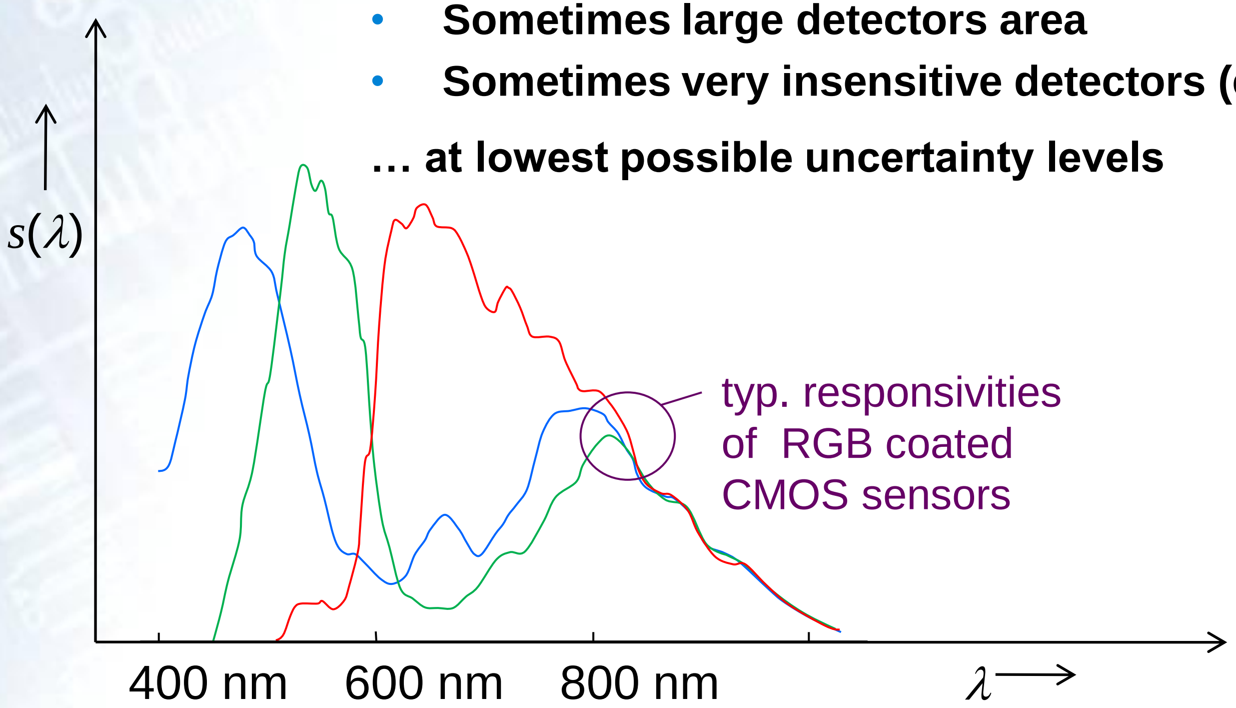
… to minimize uncertainty

Challange

Science and industry are asking for more precise and most versatile optical measurement instruments to be calibrated.

- **High dynamic range of spectral responsivity**
- **Not spectrally flat detector responsivity**
- **Spatially non-uniform detector systems**
- **Sometimes large detectors area**
- **Sometimes very insensitive detectors (e.g. UV-meters)**

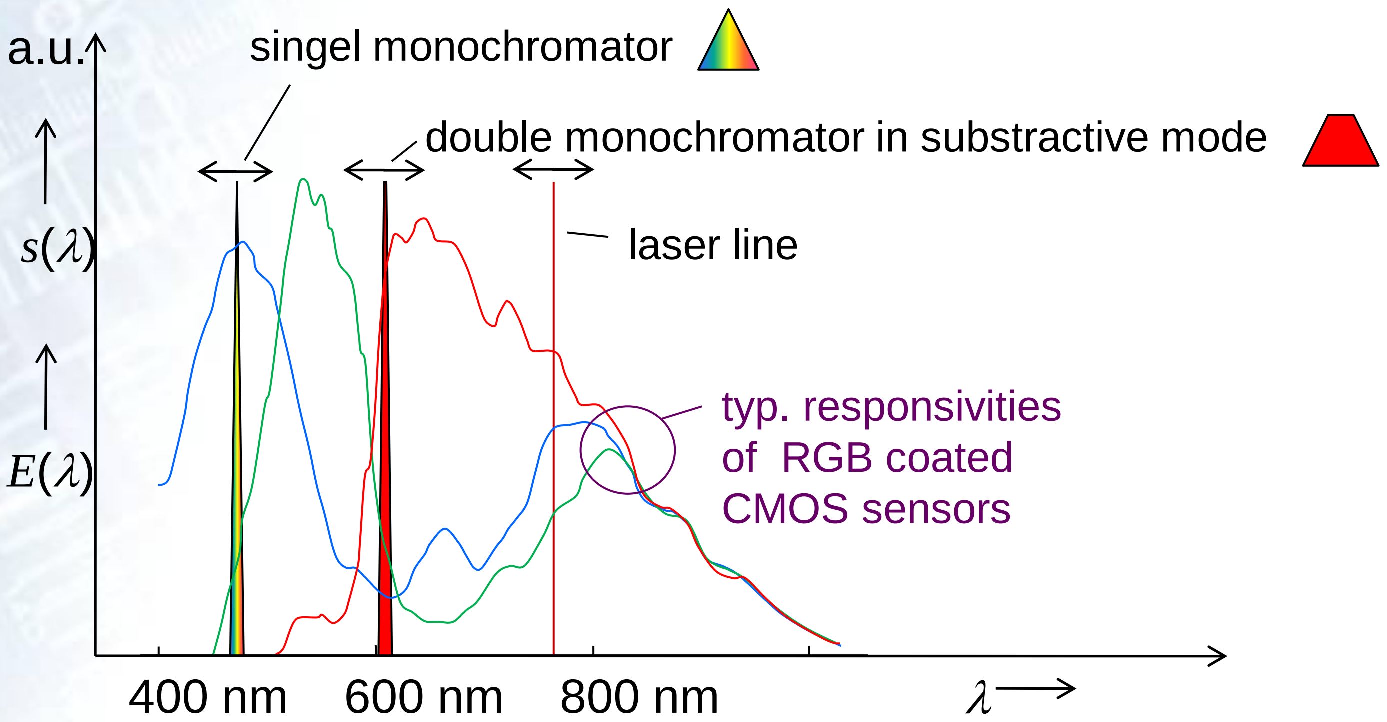
… at lowest possible uncertainty levels



Challange

Drawbacks of classical monochromator based spectrally tunabel sources:

- **Reduction of bandwidth means reduction of output power**
- **Spectral uniformity only with double-monochromator in subtractive mode**
- **Often deconvolution necessary**



Advantage Laser

Benefit of laser aided measurements:

- Nearly monochromatic source => no deconvolution
- High power => spatially uniform radiant source for large area irradiation at high irradiance levels

Ideal for characterisation and calibration of:

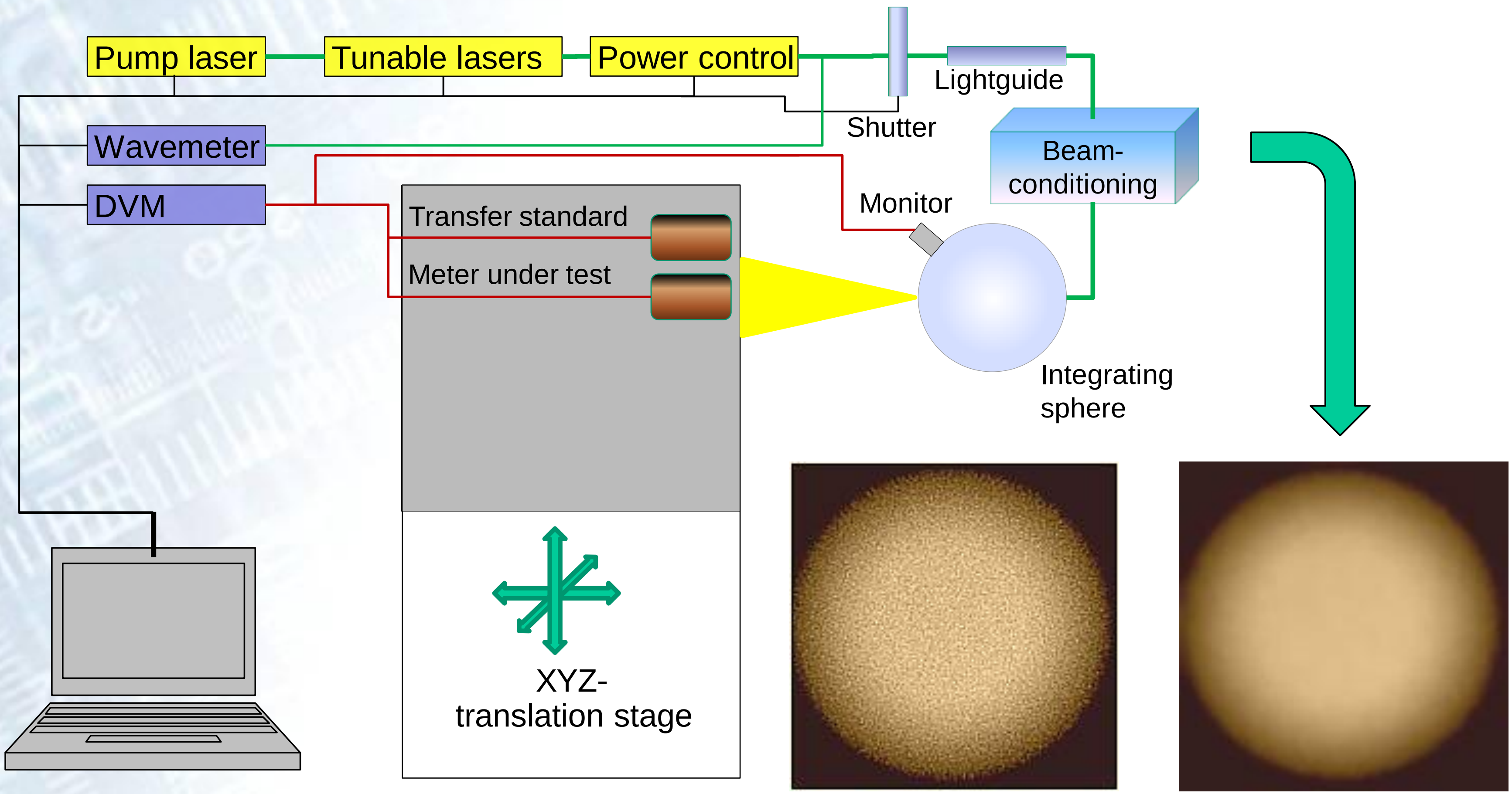
- Broad-band detectors
- Spectroradiometers
- Imaging luminance/radiance measuring devices
- Hyperspectral imagers
- Source calibration with direct traceability to cryogenic radiometer

Challenges:

- Coherence effects

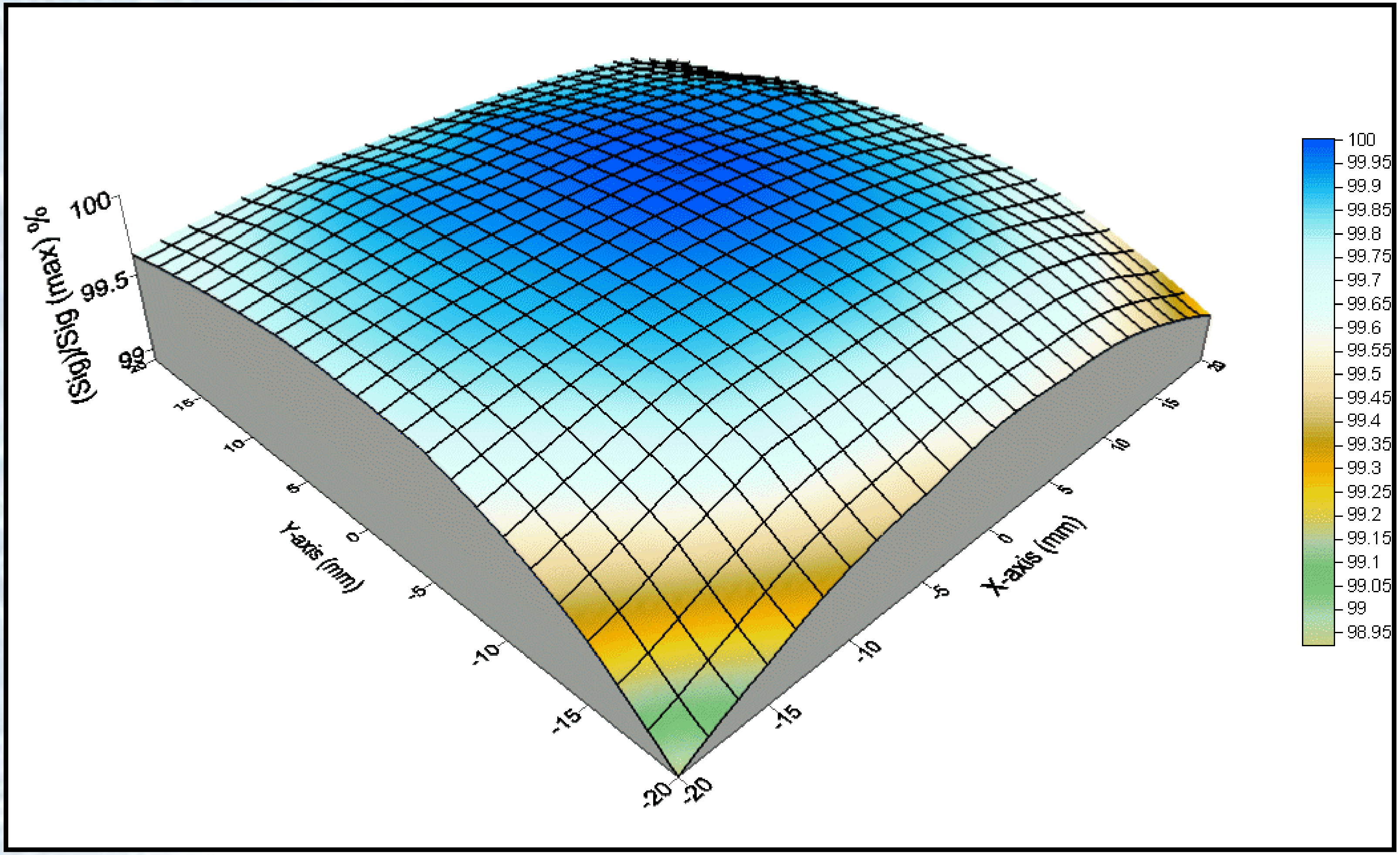
Principle setup for responsivity calibration

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

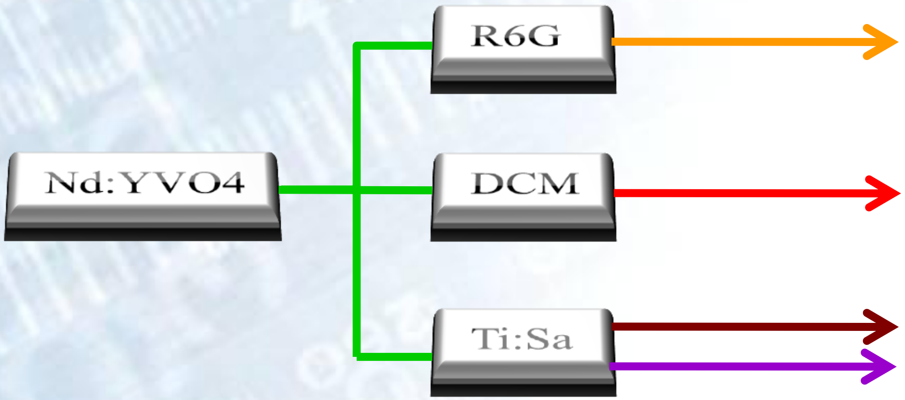
Uniformity

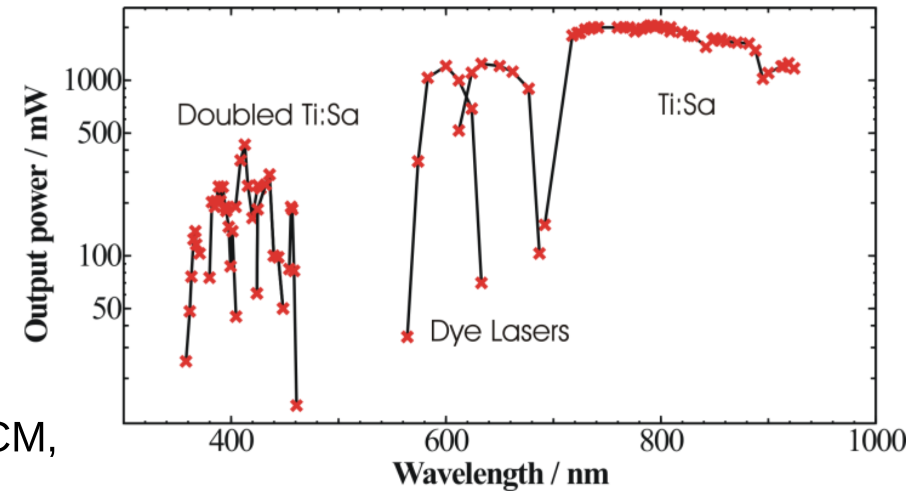


Uniformity of the irradiation field in a distance of 70 cm from the sphere source

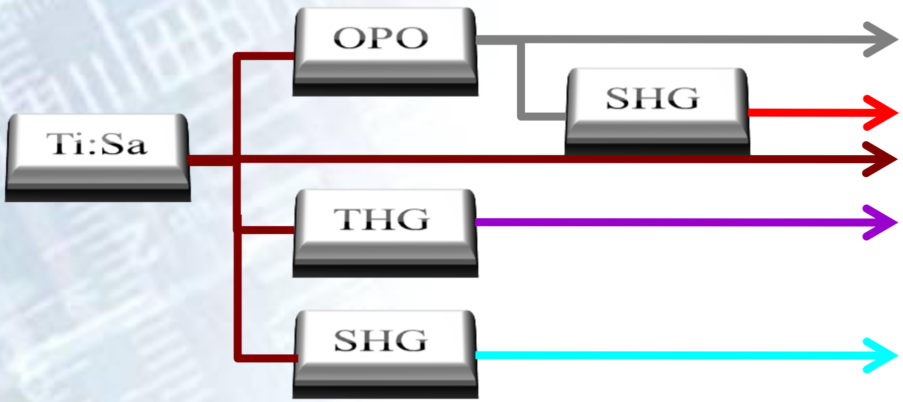
Available spectral ranges at the TULIP setup of PTB

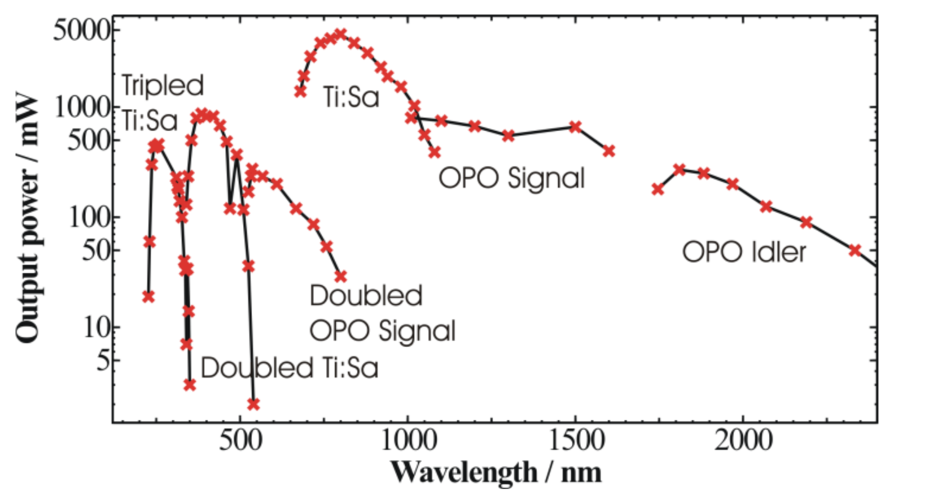
PTB





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

Available spectral ranges at the TULIP setup of PTB

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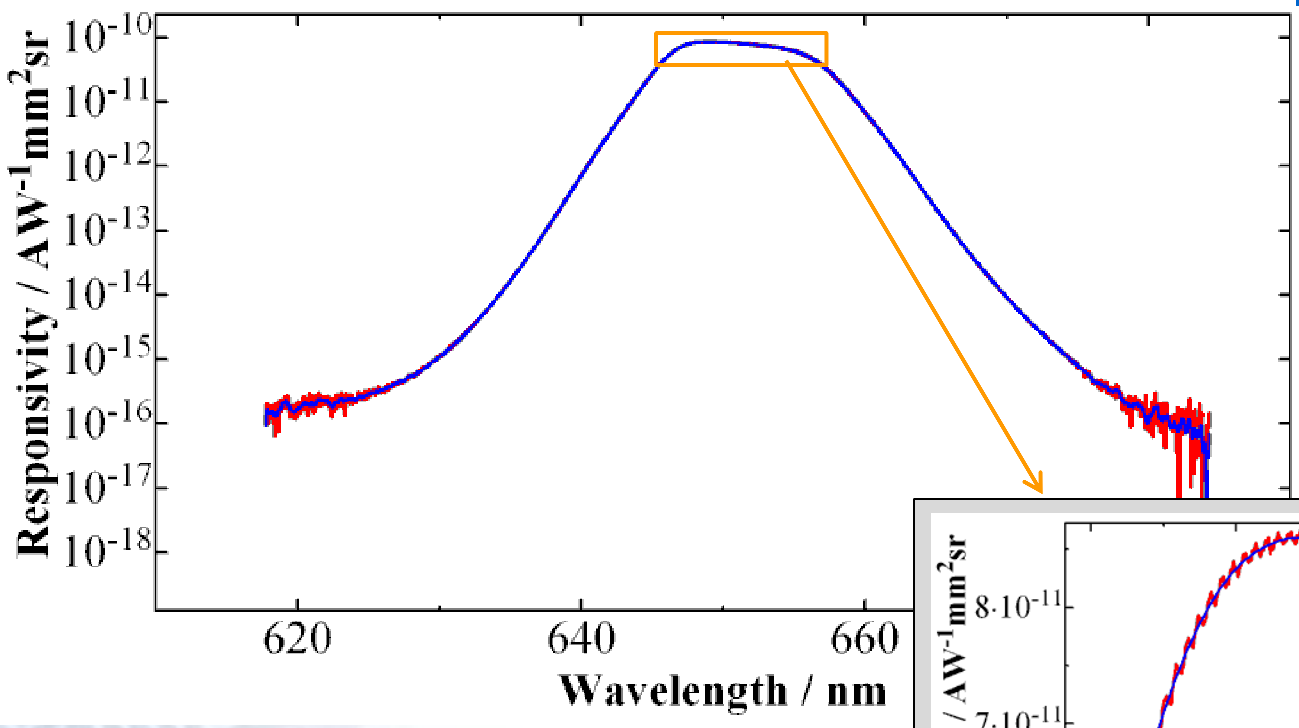
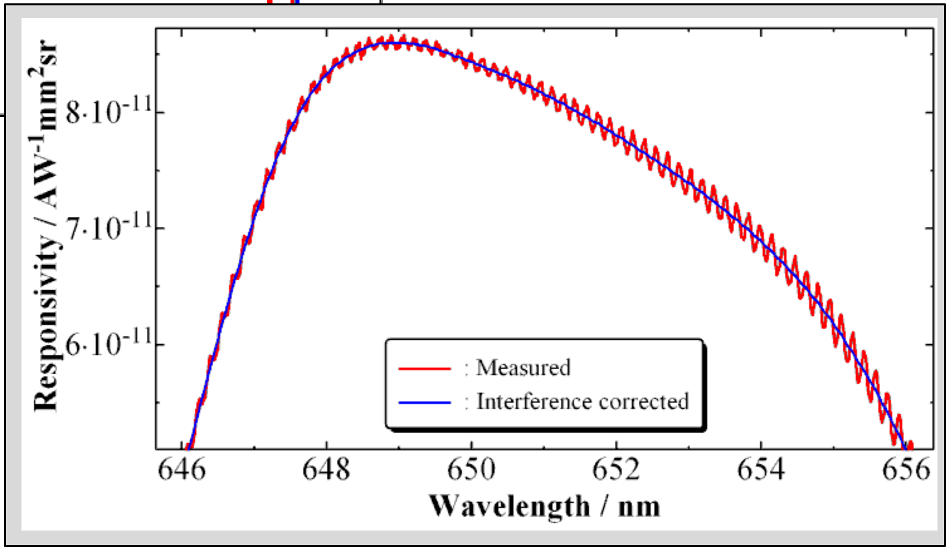
Results of TULIP





- interference fringes in no diffuser in front of detector
- Not necessarily disturbing for broadband application

Digital filtering to remove interference fringes

Input Signal

↓

Discrete fourier transformation

↓

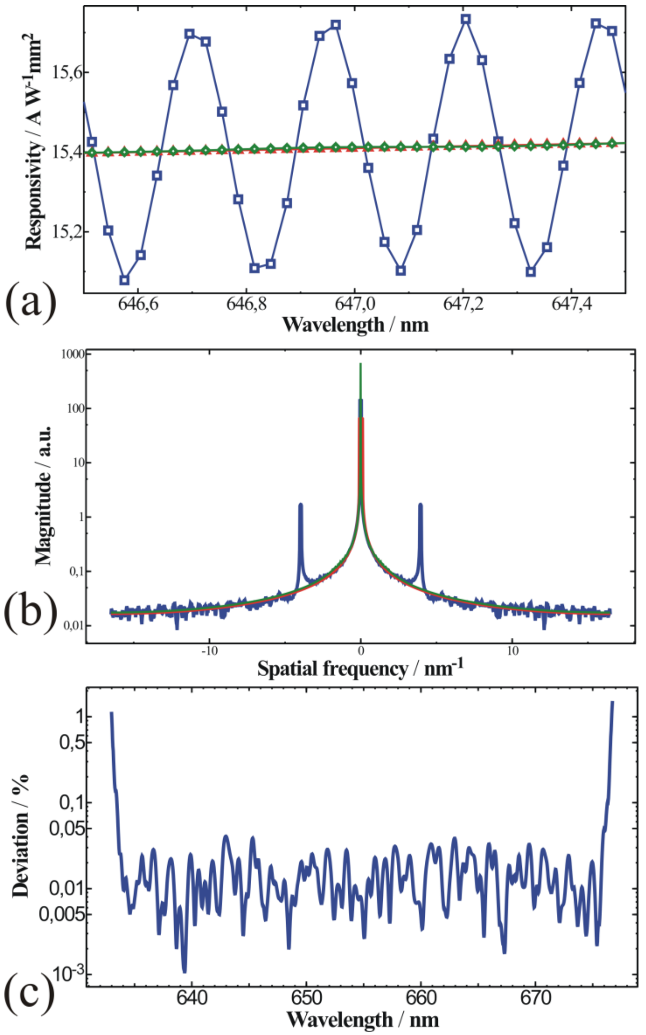
Peak detection and noise damping

↓

Inverse fourier transformation

↓

Output signal



Digital filtering to remove interference fringes

Input Signal

Discrete fourier transformation

Peak detection and noise damping

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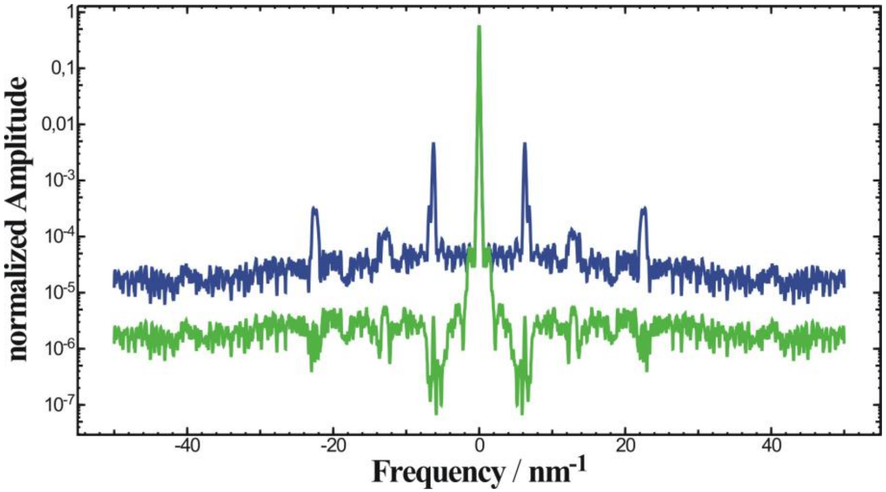
Output signal



Digital filtering to remove interference fringes

PTB

Input Signal

↓

Discrete fourier transformation

↓

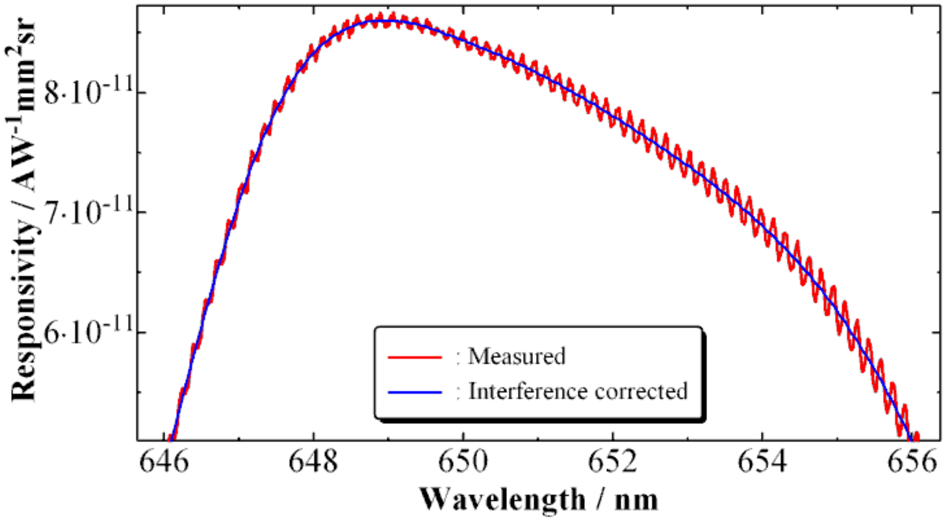
Peak detection and noise damping

↓

Inverse fourier transformation

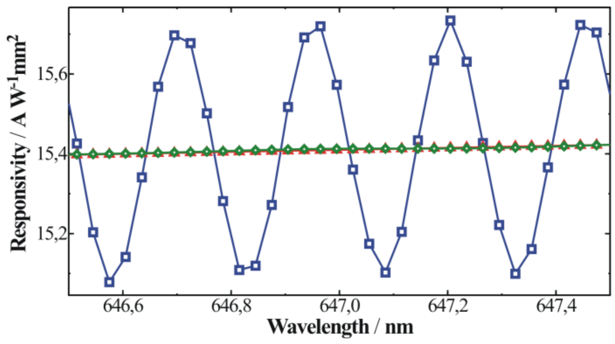
↓

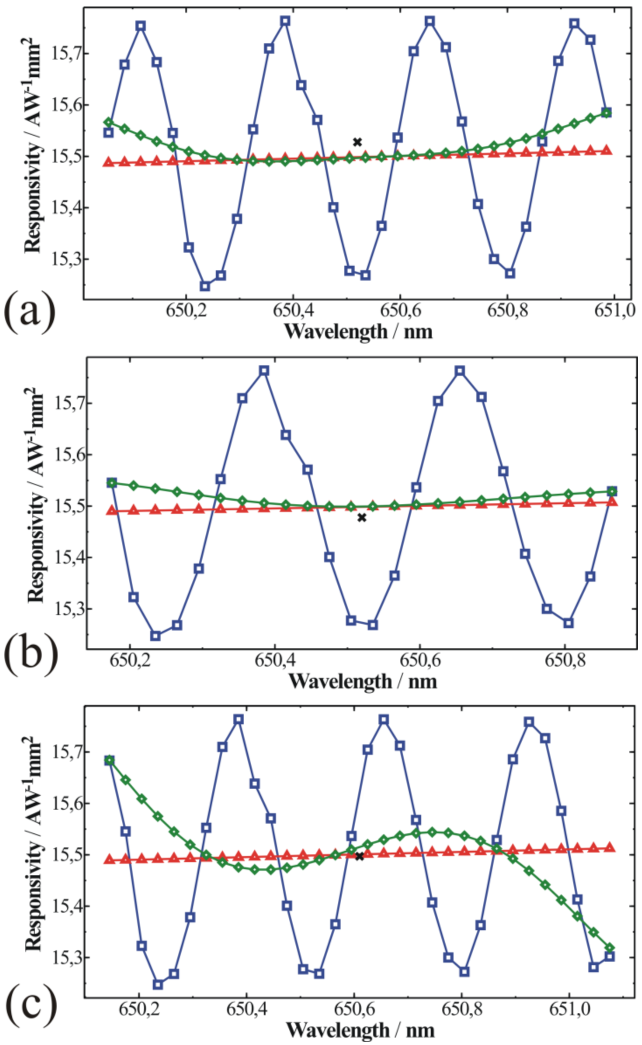
Output signal



Poster DBR_PO_017: Michaela Schuster et. al.
Correction algorithm for interference-affected measurement data

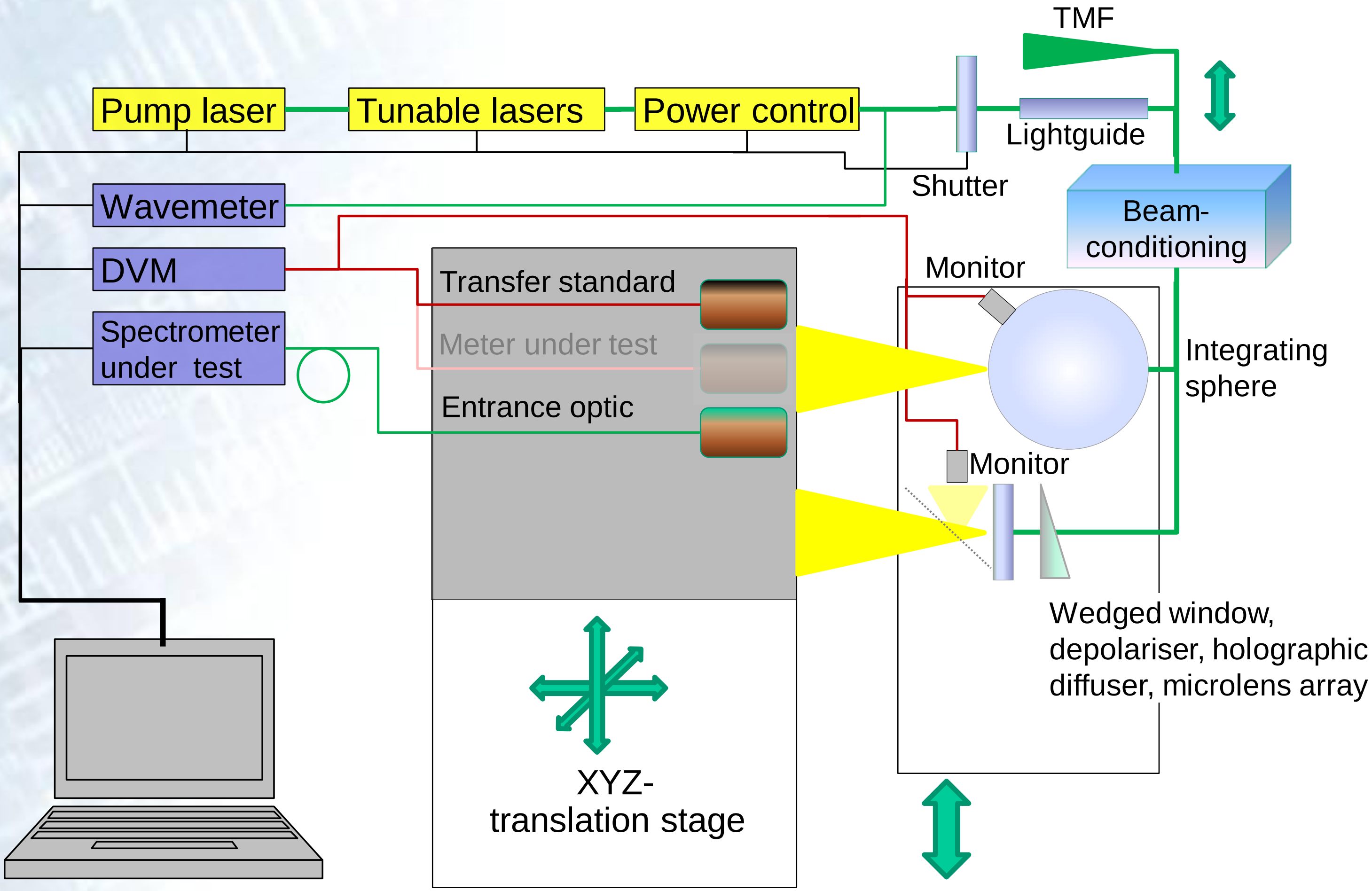
Increasing measurement speed





- Stepsize about 0.03 nm
- i.e. 3500 Measurement point for the spectral range of 100nm
- For as single responsivity value only about two interference periods necessary
- In our case: only 500 measurement points for accurate responsivity values at 5 nm step size over 100 nm

Characterisation of spectroradiometers



Basic idea

Instrument Matrix

Measured Spectrum

Source spectrum

$$\mathbf{X} = \mathbf{A}\mathbf{Y}$$

$$\mathbf{Y} = \mathbf{A}^{-1}\mathbf{X}$$

Regularisation

Y. Zong

Tikhonov

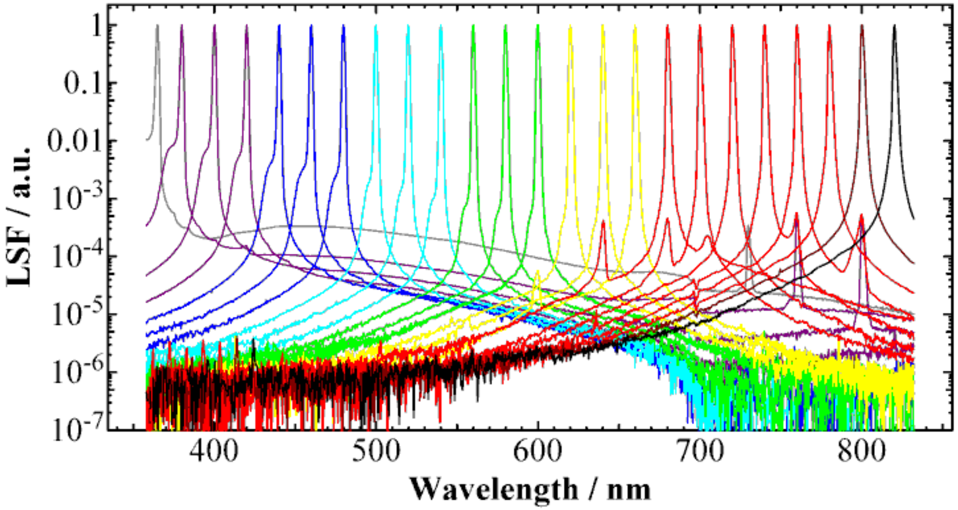
$$\mathbf{Y} = \mathbf{C}_{corr}\mathbf{X}$$

Stray-light correction only

$$\mathbf{Y}_\alpha = \underbrace{\left(\mathbf{A}^T\mathbf{A} + \alpha^2\mathbf{I}\right)^{-1}\mathbf{A}^T}_{\mathbf{C}_{corr}}\mathbf{X}$$

Stray-light and band-pass correction

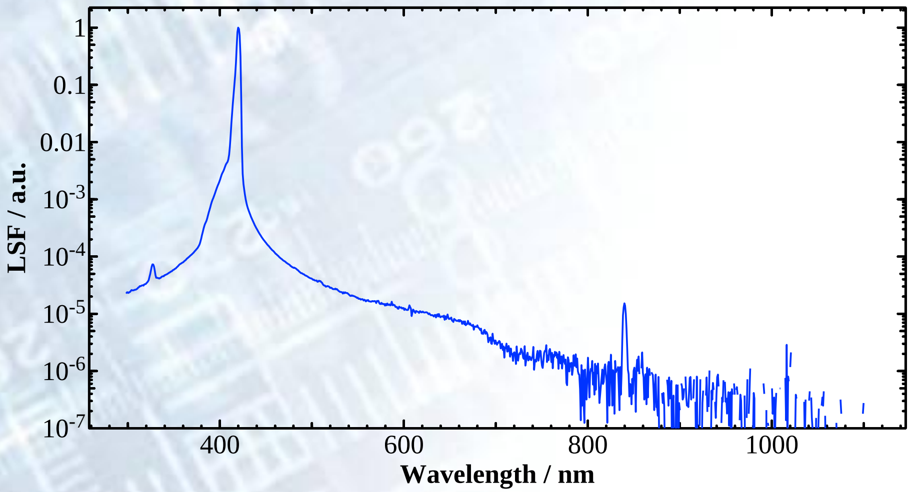
Typical series of line spread functions of array spectroradiometer



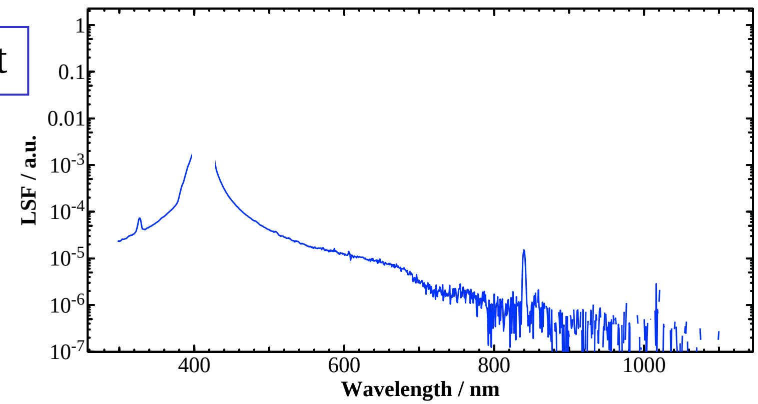
Poster SBR_OR_007: Saulius Nevas et. al.
Simultanious Correction of Bandpass and Stray Light Effects in Array Spectroradiometer

Basic idea

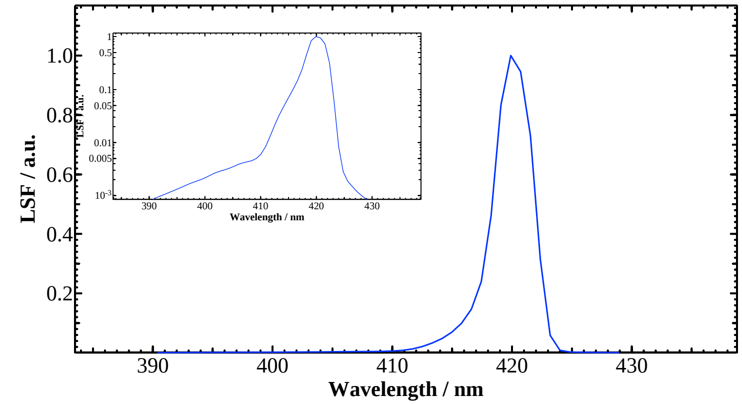
- Spectral deconvolution problematic because of ill-conditioned data
- Existing correction techniques typically deal separately with either the bandpass or the stray light correction



Stray light

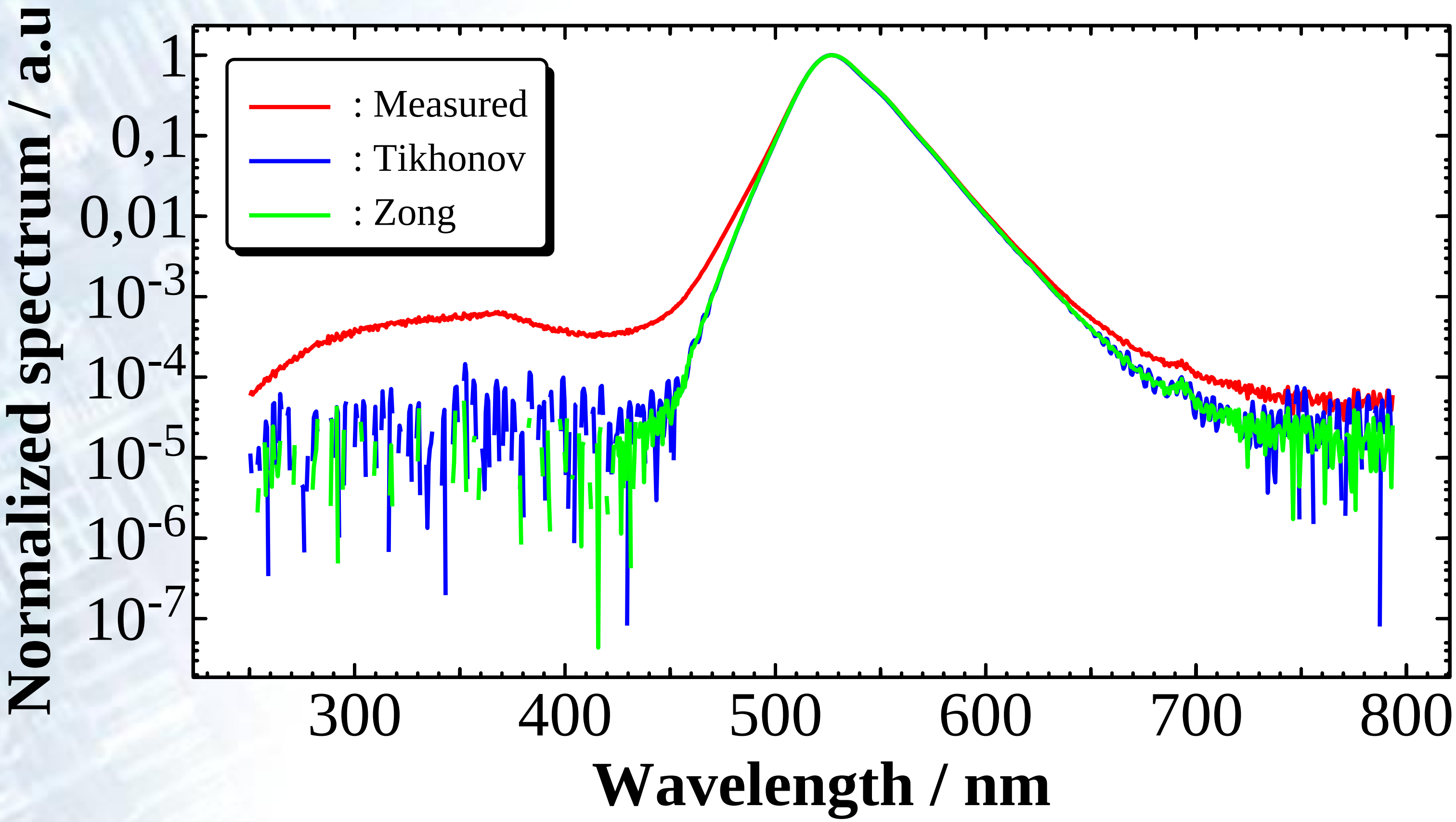


Bandpass



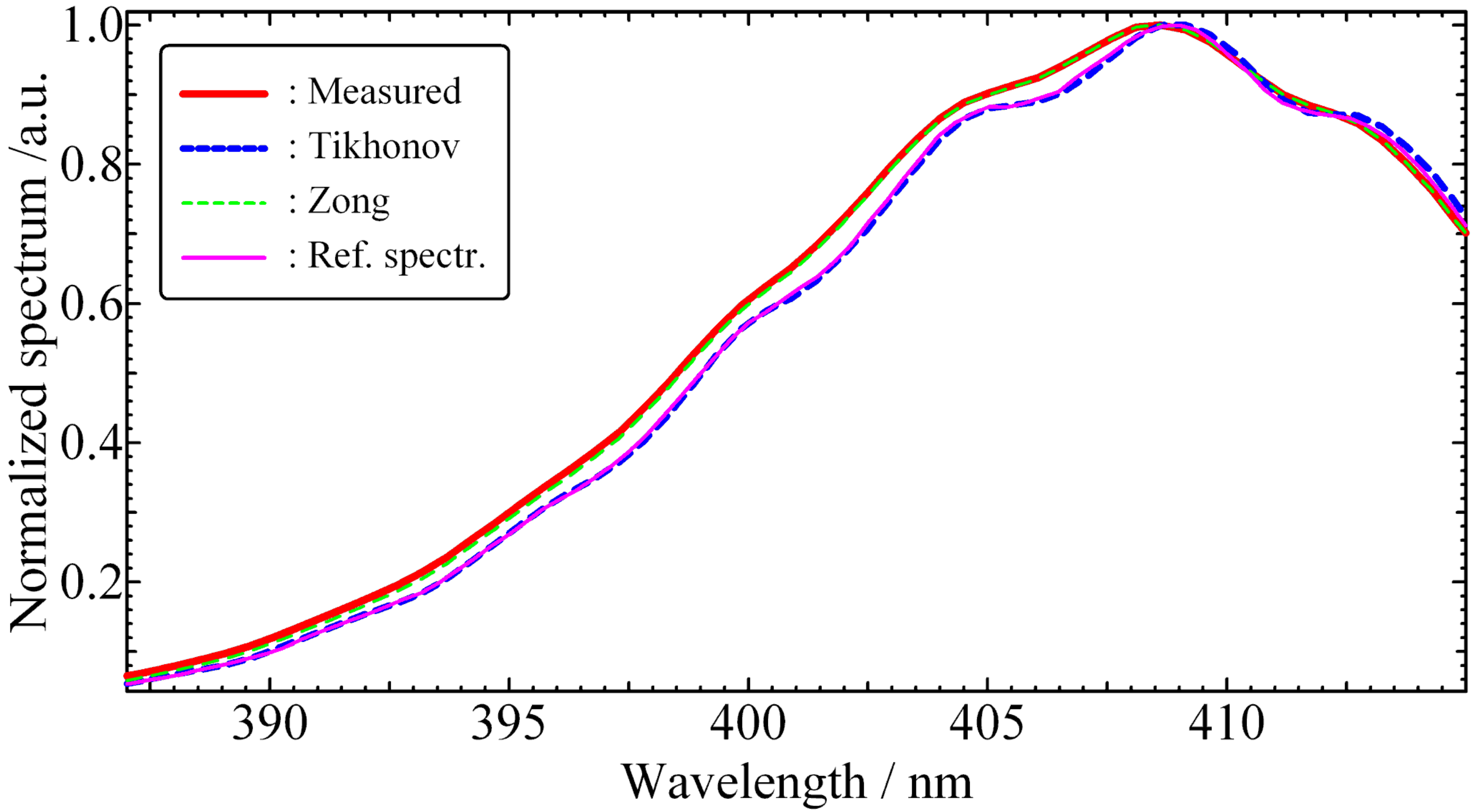
- The border between the bandpass and stray light level?

Results



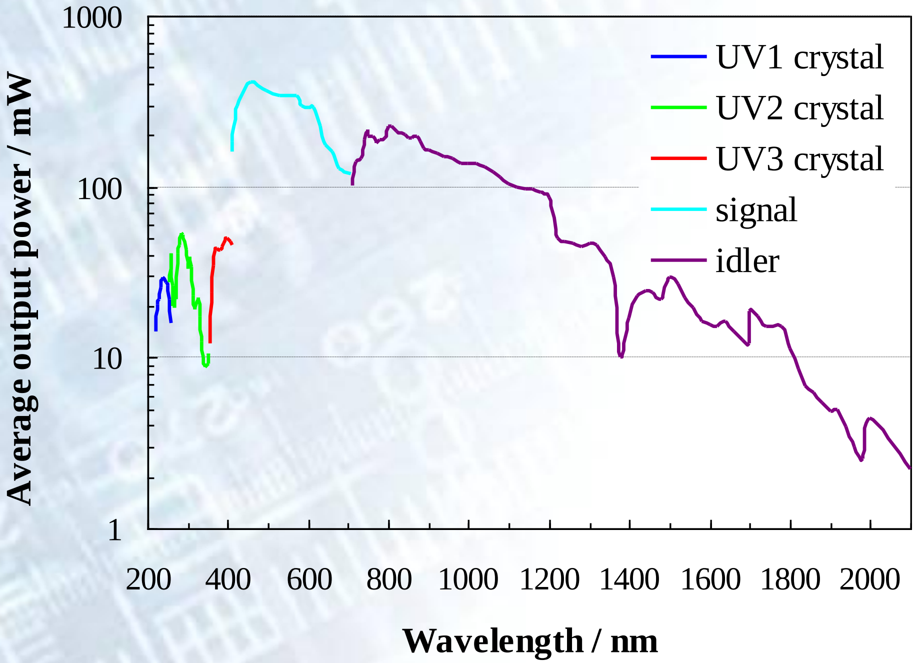
: Measured
: Tikhonov
: Zong
Normalized spectrum / a.u
1
0,1
0,01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
300
400
500
600
700
800
Wavelength / nm

Results



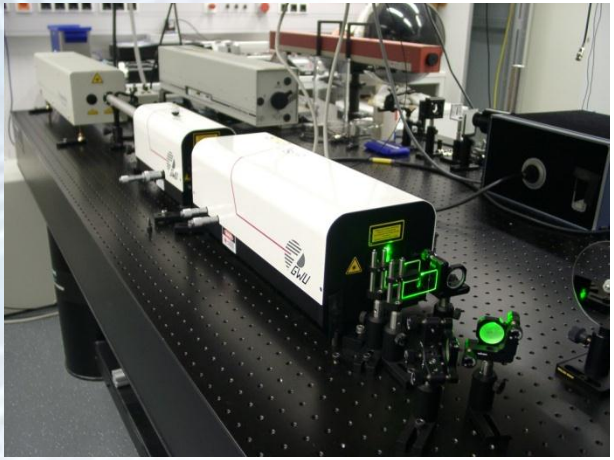
1.0
0.8
0.6
0.4
0.2
Normalized spectrum /a.u.
: Measured
: Tikhonov
: Zong
: Ref. spectr.
390
395
400
405
410
Wavelength / nm

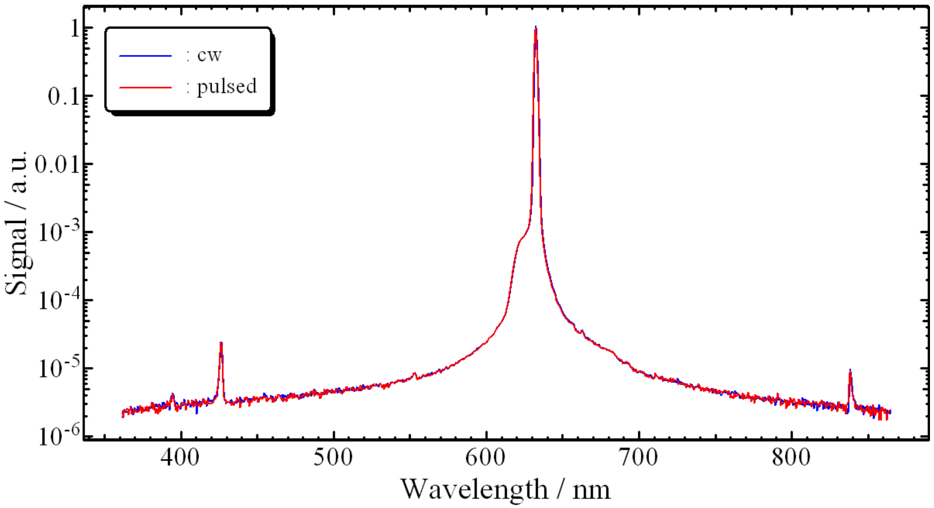
PTB



Pusled laser system with OPO and SHG:

- Easy to handle
- low cost
- Large spectral range (220 nm – 2.4 µm)
- low repetition rate (20 Hz)





Characterisation of imaging cameras

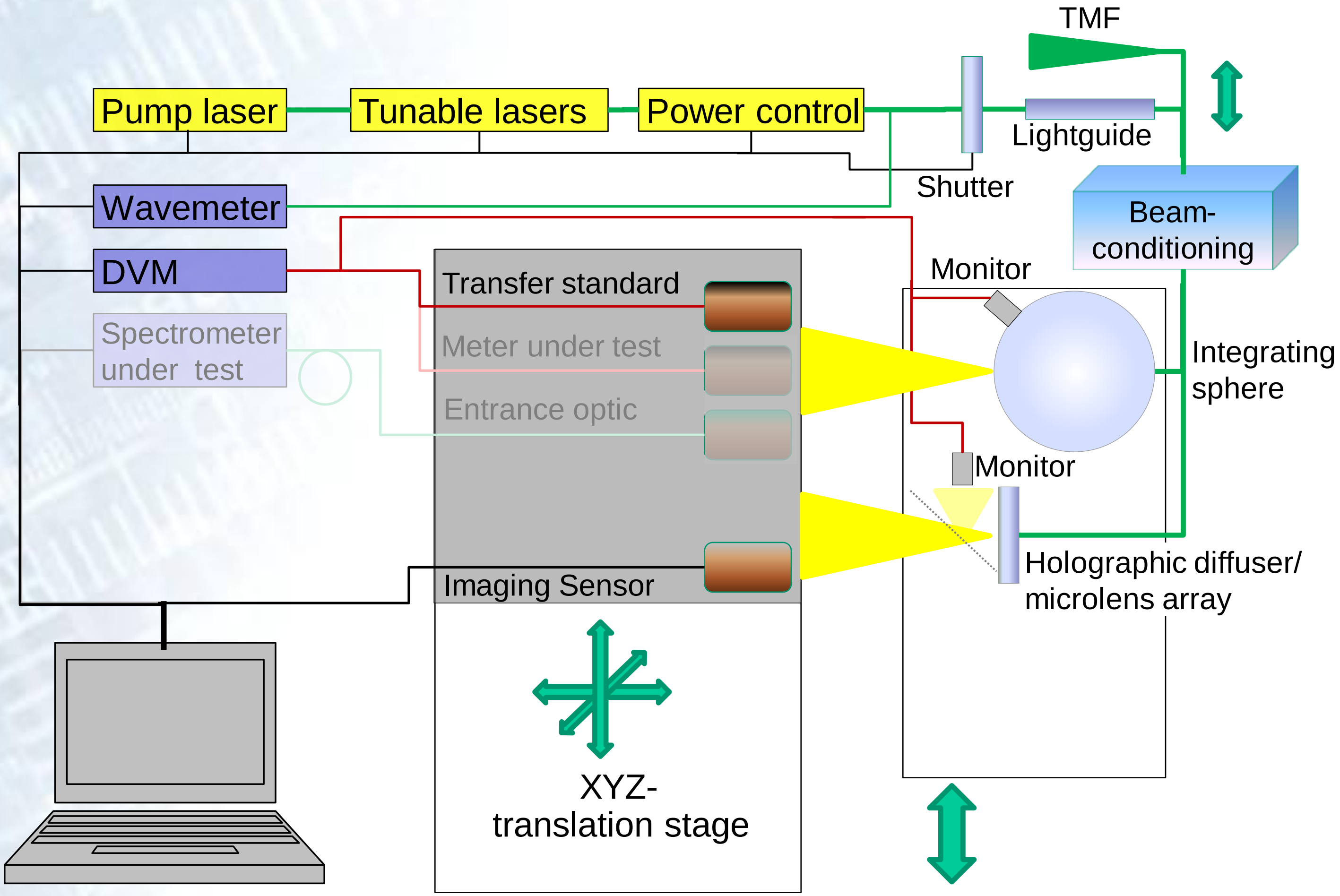
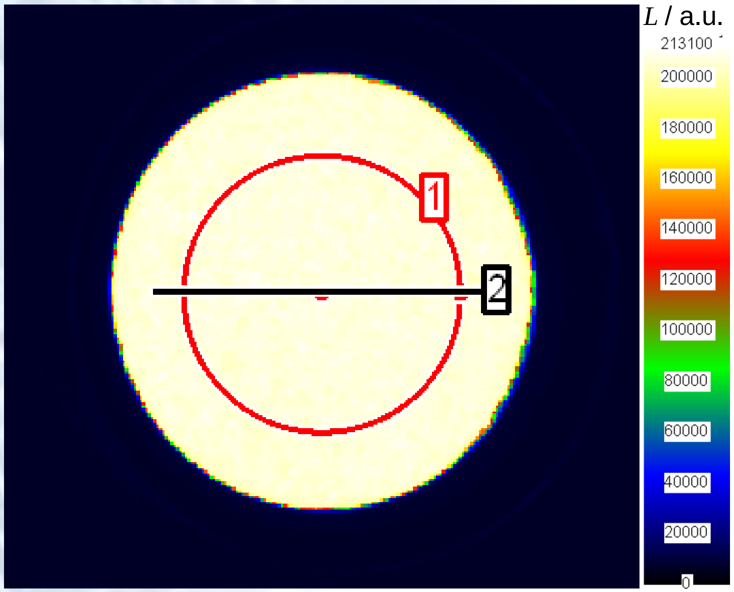
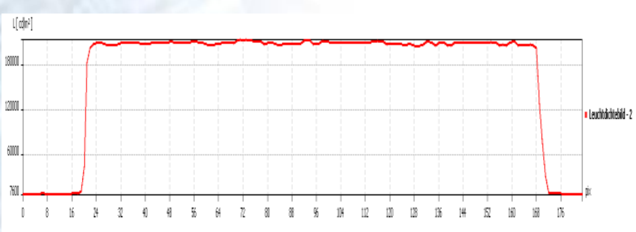


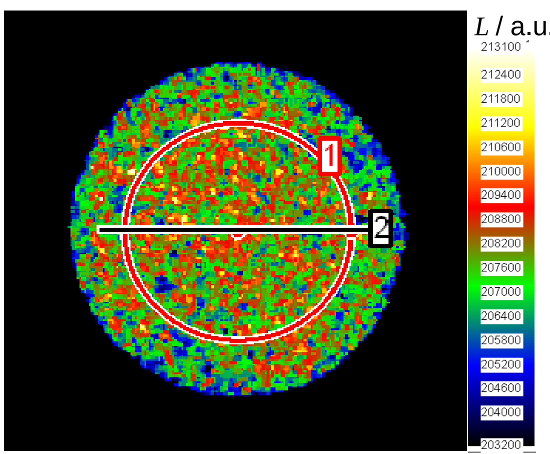
Image of sphere port



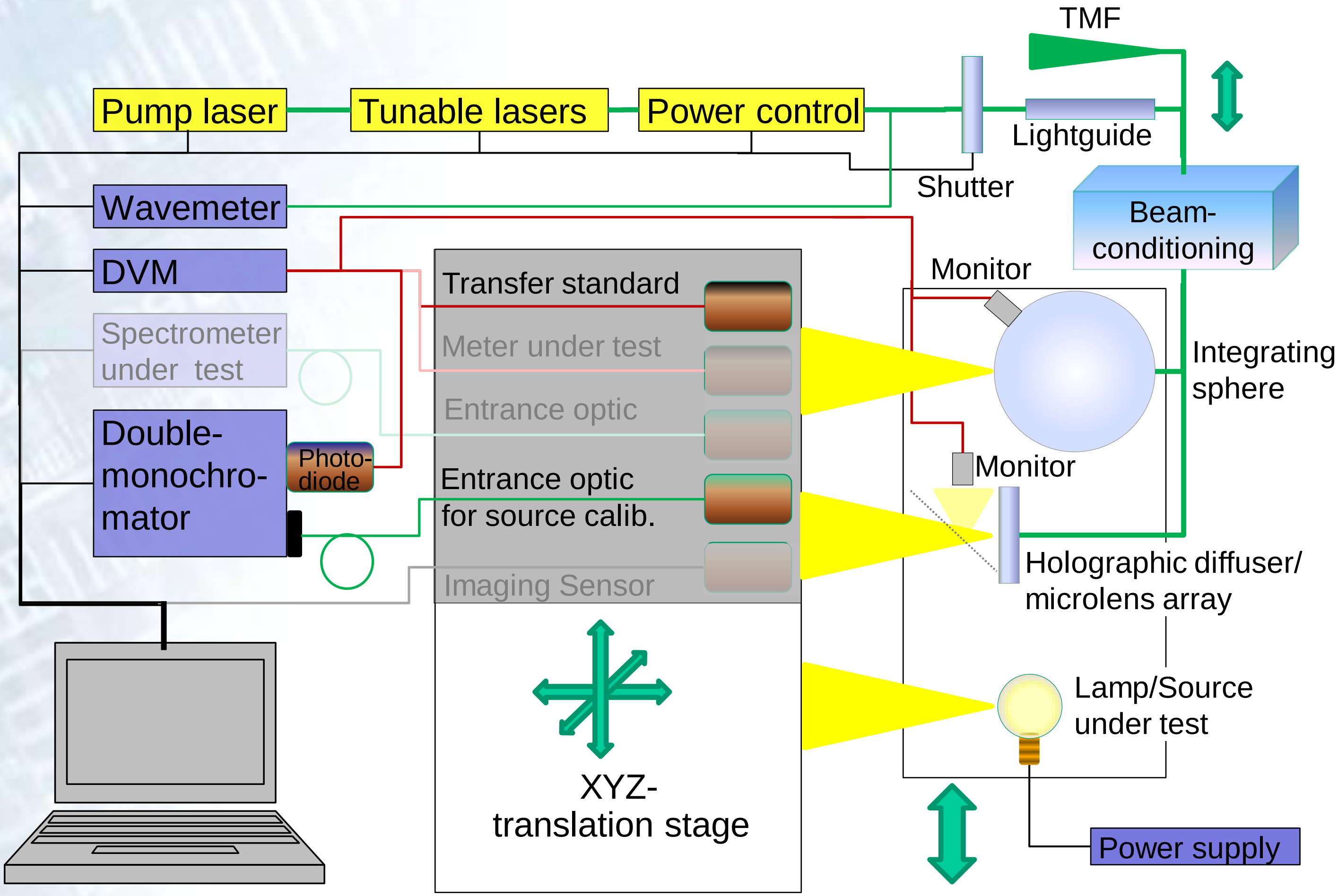


- Characterisation of nonlinearity
- Spectral characterisation
- Radiance responsivity calibration
- Spatial characterisation
- Stray-light characterisation

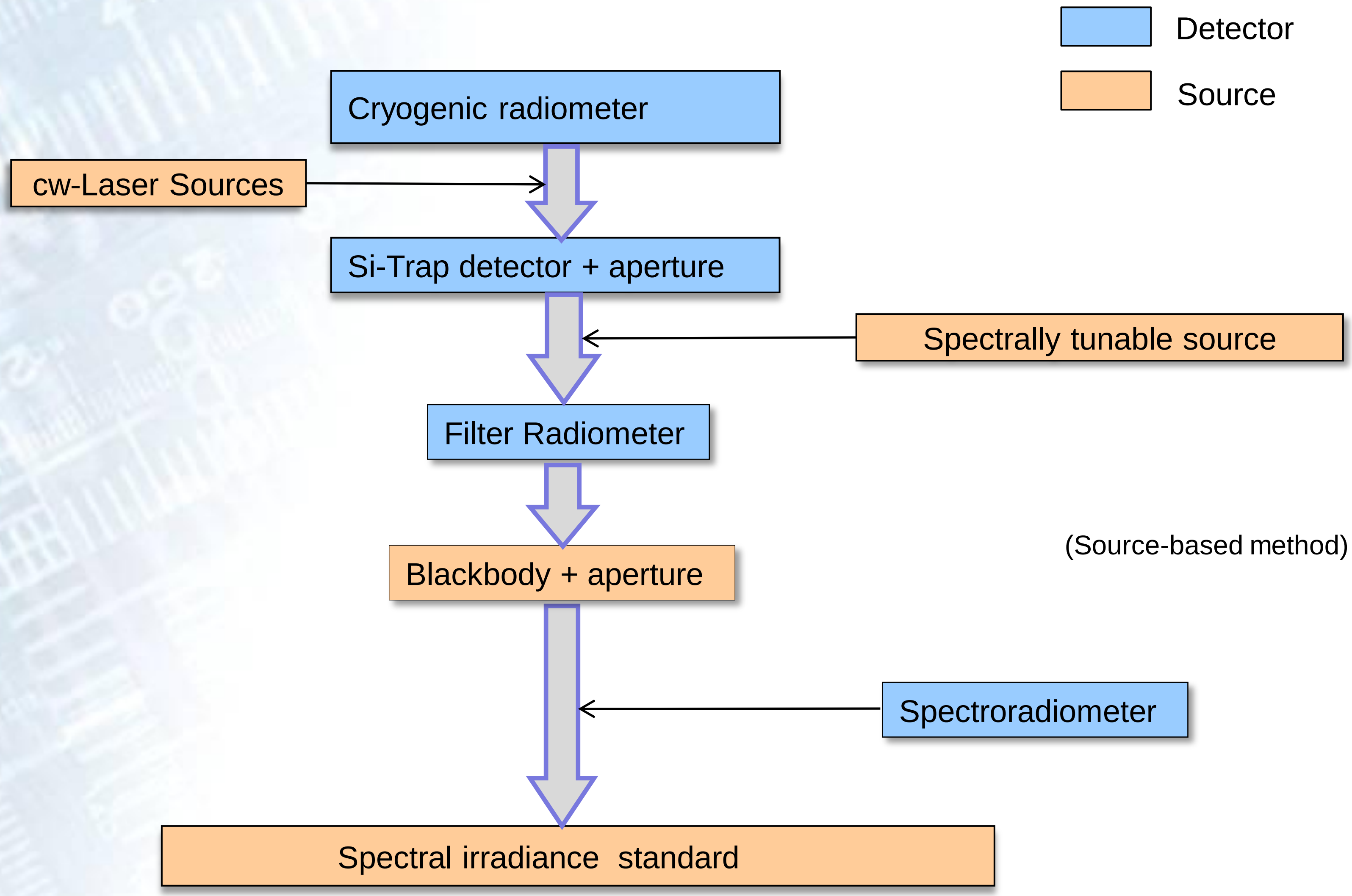
Uniformity and propper reduction of speckle effects is getting essential



Detector based source calibration

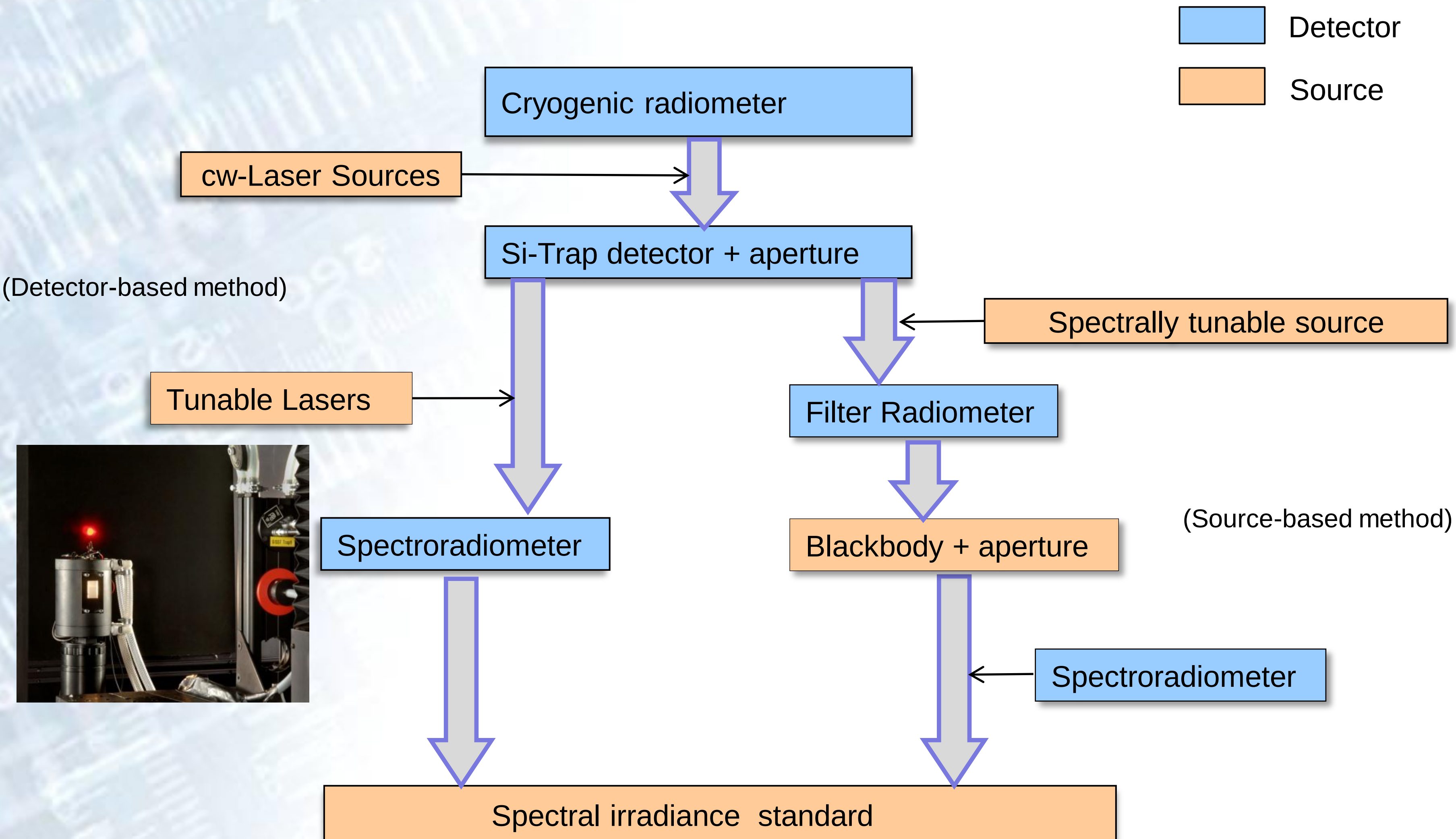


Source calibration chain

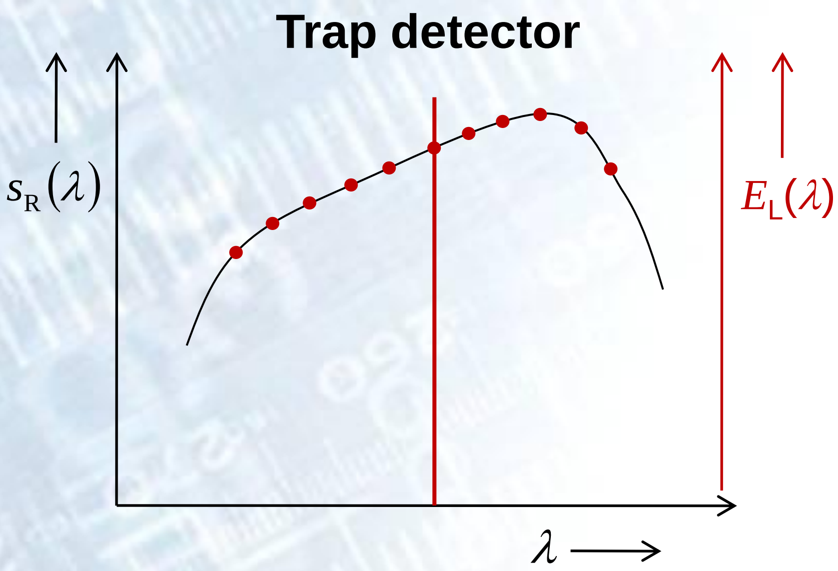


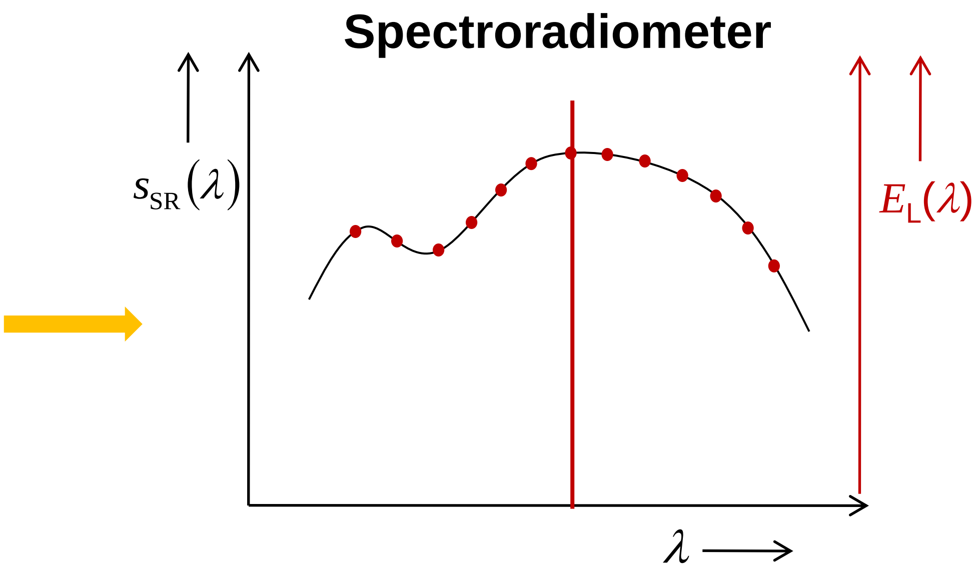
(Source-based method)

Source calibration chain



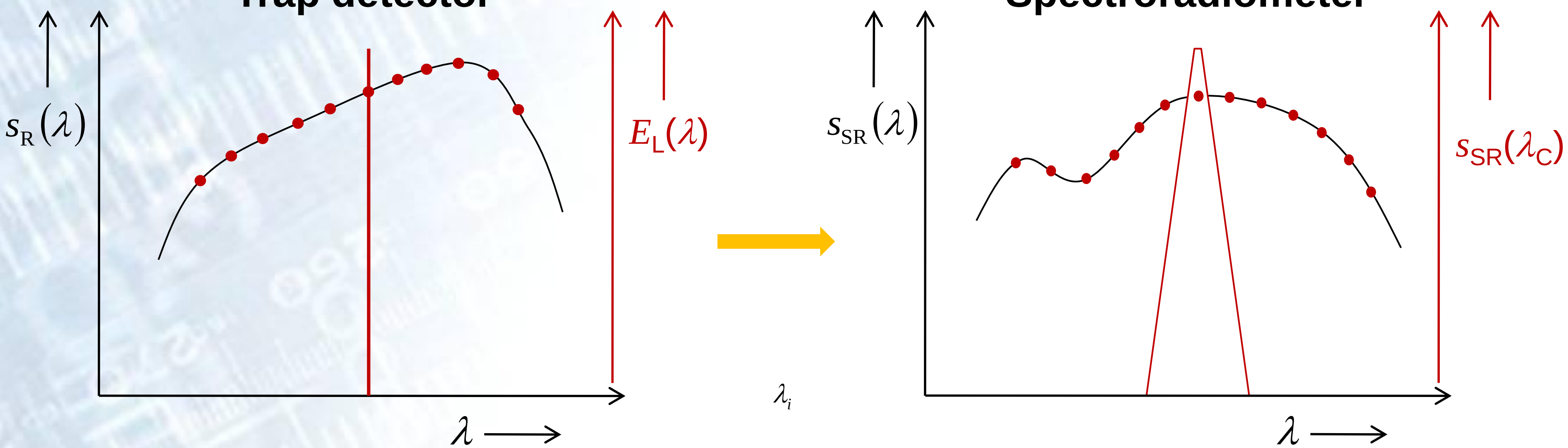
Basic idea


Trap detector
$s_R(\lambda)$
$E_L(\lambda)$
λ

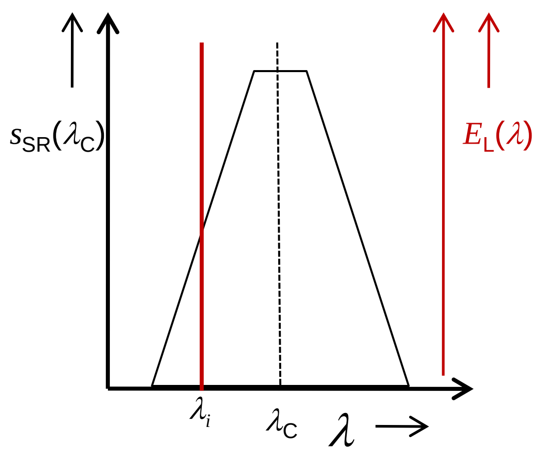

Spectroradiometer
$s_{SR}(\lambda)$
$E_L(\lambda)$
λ

1. Step: Calibration of the Spectroradiometer

Trap detector — **Spectroradiometer**



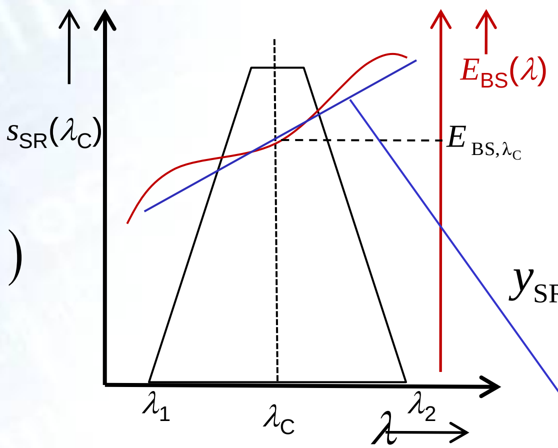
$$\Rightarrow \quad E_L(\lambda_L) = \frac{y_R(\lambda_L)}{s_R(\lambda_L)}$$



$$s_{SR,\lambda_C}(\lambda_i) = \frac{y_{SR,\lambda_C}(\lambda_i)}{y_R(\lambda_i)} \cdot s_R(\lambda_i)$$

2. Step: Calibration of the unknown source

PTB



$$s_{SR,\lambda_C}(\lambda_i) = \frac{y_{SR,\lambda_C}(\lambda_i)}{y_R(\lambda_i)} \cdot s_R(\lambda_i)$$

$$y_{SR,\lambda_C} = E_{BS,\lambda_C} \cdot \int_{\lambda_1}^{\lambda_2} s_{SR,\lambda_C}(\lambda) \cdot (1 + \Delta E_{rel,\lambda_C}(\lambda)) d\lambda$$

$$\Rightarrow E_{BS.\lambda_C} = \frac{y_{SR,\lambda_C}}{\int_{\lambda_1}^{\lambda_2} s_{SR,\lambda_C}(\lambda) d\lambda + \underbrace{\int_{\lambda_1}^{\lambda_2} s_{SR,\lambda_C}(\lambda) \cdot \Delta E_{rel,\lambda_C}(\lambda) d\lambda}_{\approx 0}}$$

$$E_{BS,\lambda_C} = \frac{y_{SR,\lambda_C} \cdot y_R(\lambda_C)}{y_{SR,\lambda_C}(\lambda_C) \cdot s_R(\lambda_C)} \cdot \frac{1}{\Delta\lambda} + \text{corr}$$

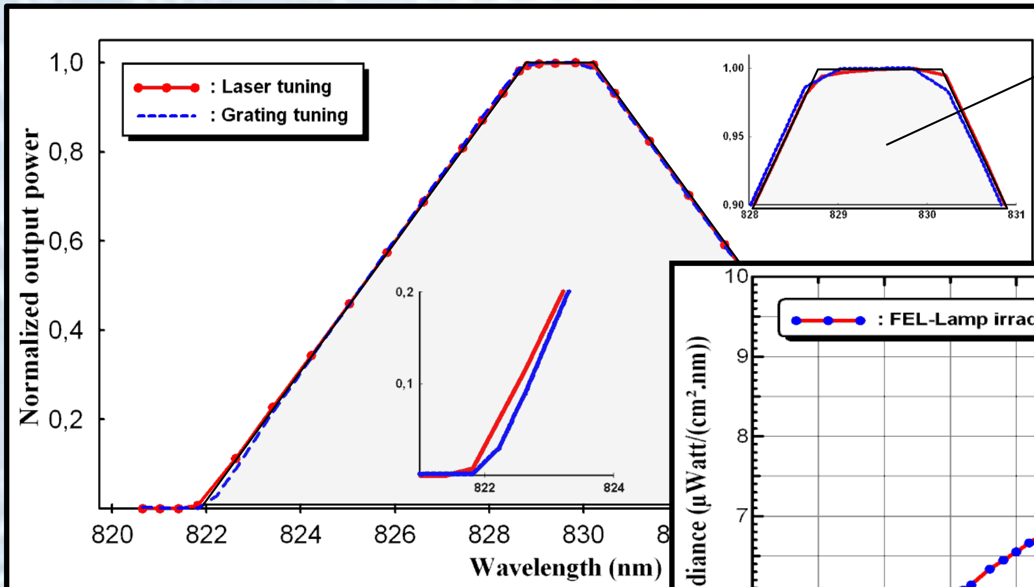
- For ideally trapezoidially slit-function
- For linear spectral irradiance

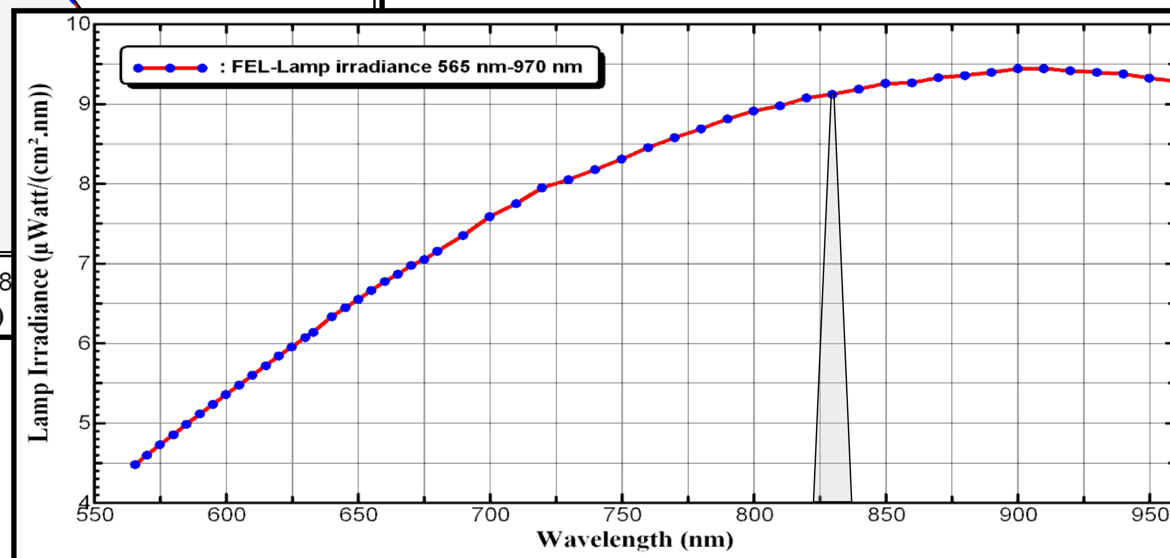
$$u\left(\int_{\lambda_1}^{\lambda_2} s_{SR,\lambda_C}(\lambda) \cdot \Delta E_{rel,\lambda_C}(\lambda) d\lambda\right) \neq 0$$

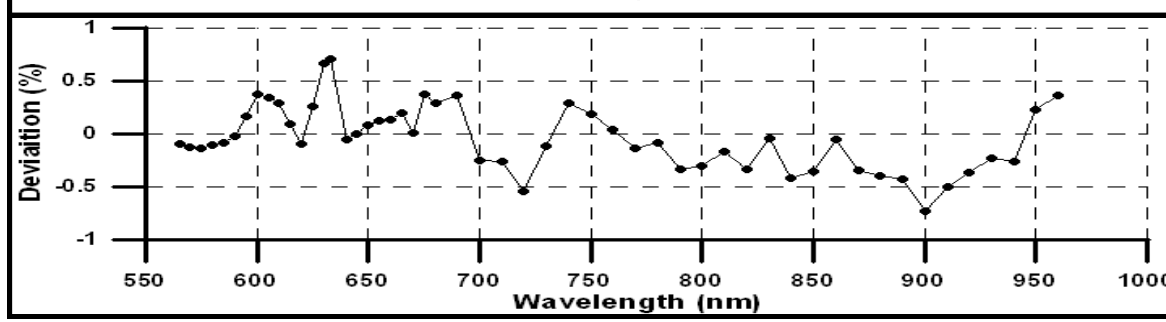
To be estimated from the slope of the result of the measured spectral irradiance

Detector based calibration of a 1000 W FEL lamp

PTB

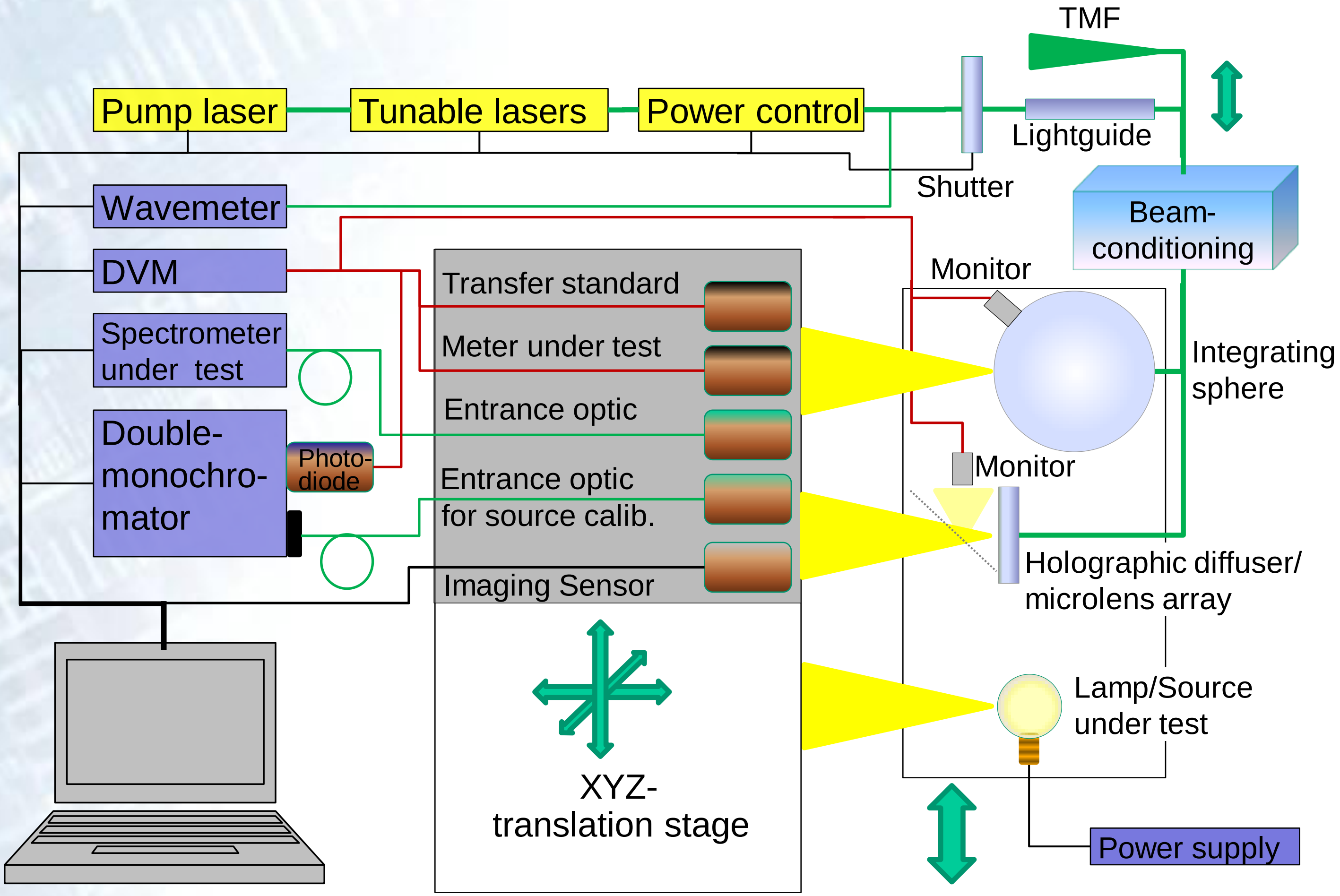






S. Winter, A. Abd-Elmageed, et.al, "Detector based traceability chain for spectral irradiance using tunable lasers", Proceedings of the 27 th International Commission on Illumination (CIE) conference, Sun City, South Africa, 10-15 July (2011)

Summary



Sketch of the TULIP setup with its various beam geometries depending on the measurement task and the spectral range used

Summary cont.

PTB

- CW-laser deliver highly accurate wavelength scale for calibration
- Pulsed laser span the total spectral range from 200 nm up to 4 µm for radiometric purpose as turnkey ready solutions
- Ideal sources for radiance and irradiance responsivity calibrations
- Tunable laser can be used for detector based source calibration
- It is planed to use tunable laser at PTBs next generation calibration setup for reference solar cells (see poster and oral presentation DBR_OR_018)