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Automated calibration of optical sensors using a low-cost kHz OPO laser system

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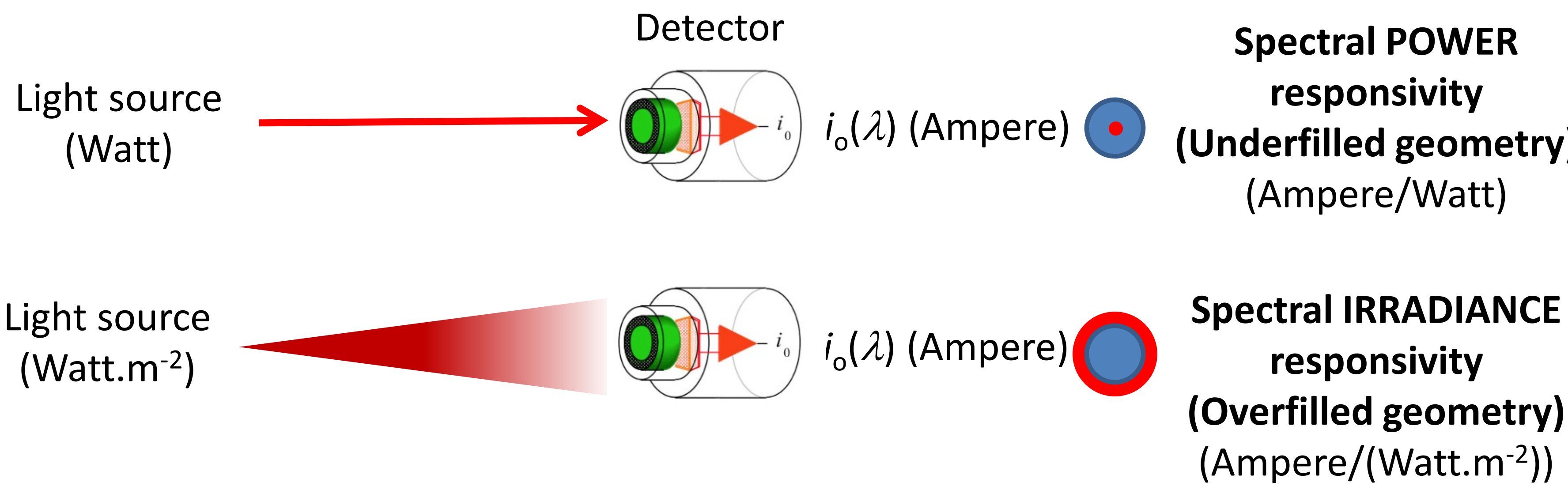
Overview

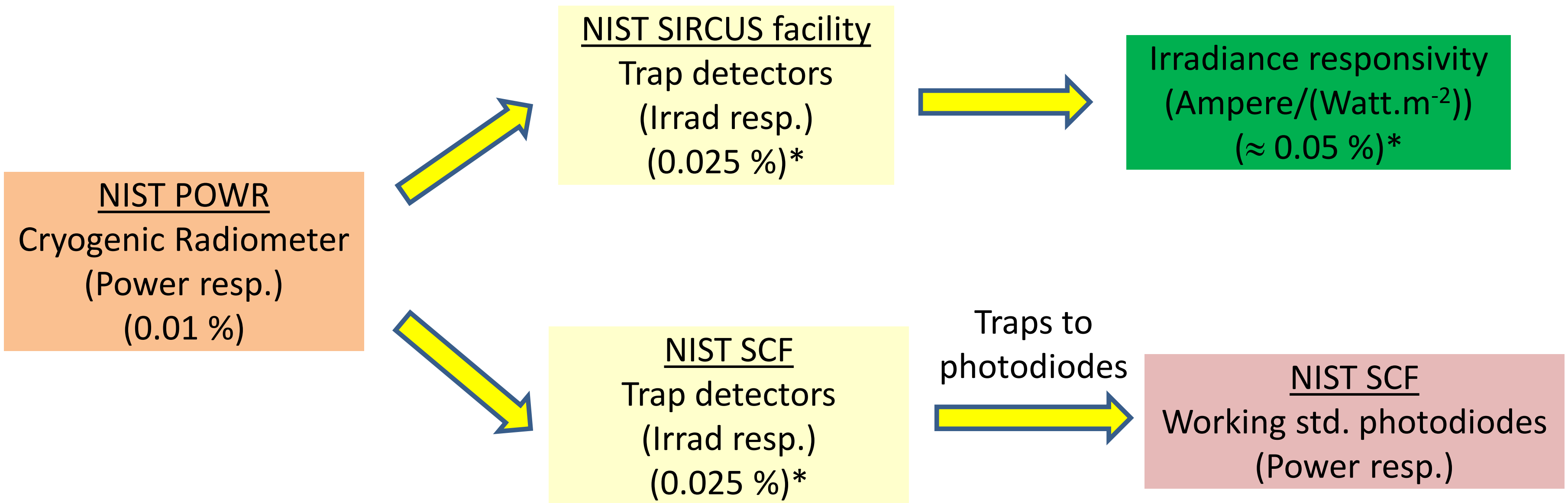
- Introduction
- Existing spectral calibration methods
- New 1 kHz optical parametric oscillator (OPO) based calibration system
- Stray-light correction using kHz OPO
- Summary

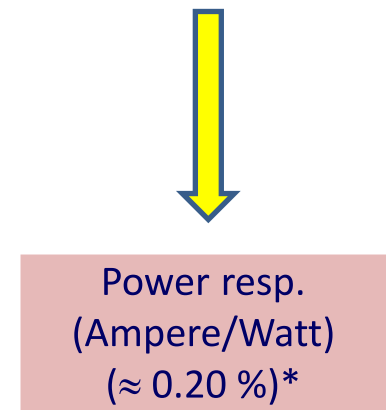
Spectral calibration of optical sensors



- SI base unit -luminous intensity: candela
- SI base unit –radiance temperature: Kelvin
- Spectral irradiance scale (FEL lamps)
- Remote sensing
- Colorimetry and radiometry
- …

Existing spectral calibration facilities at NIST





* BEST expanded uncertainty (*k*=2)

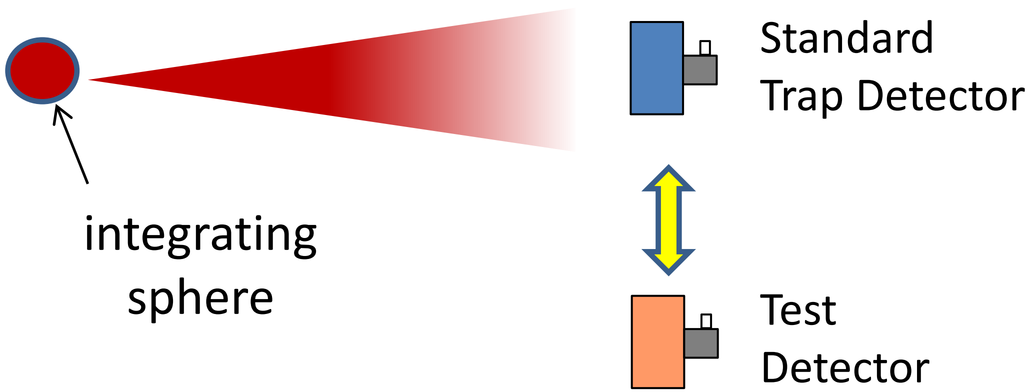
<u>POWR: p</u>rimary optical watt radiometer

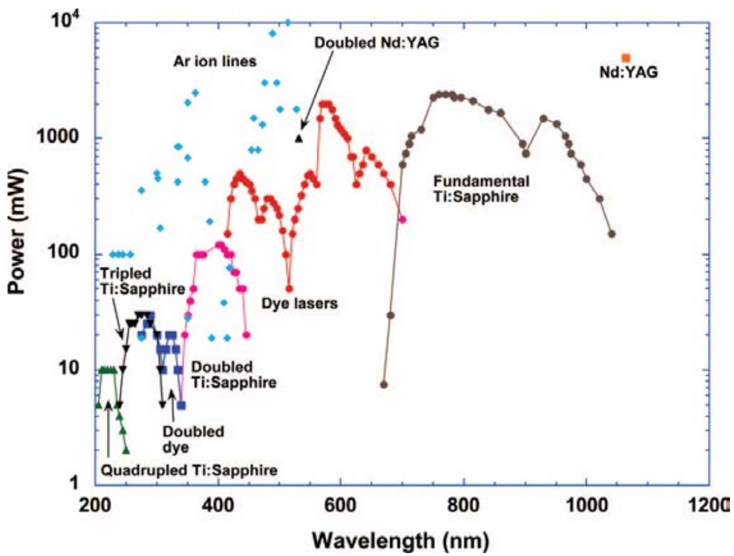
<u>SIRCUS:</u> Spectral irradiance and radiance responsivity calibrations using uniform sources

<u>SCF:</u> Spectral comparator facility

<u>Trap detector:</u> specially configured, multi-element silicon photodiodes detector with high performance.

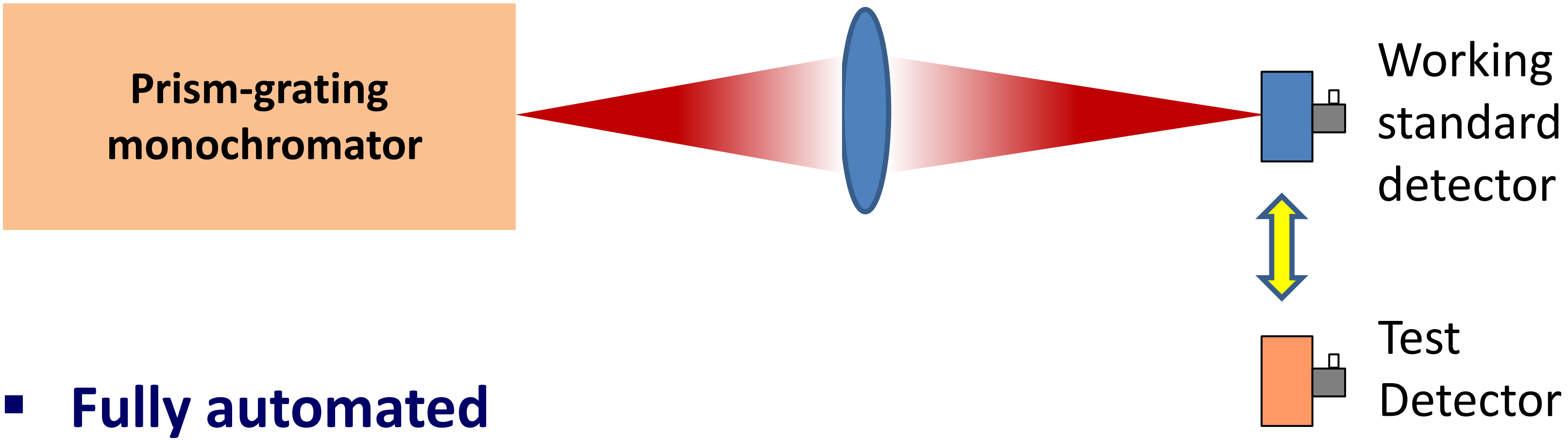
The NIST SIRCUS facility





- Continuous spectral coverage from UV to NIR
- Continuous wave (CW) or quasi–CW tunable lasers based research facility
- high power (e.g., 100 mW), narrow bandwidth (<0.01 nm)
- Used for realization of SI base units: Kelvin and candela
- Provide calibrations for primary radiometric standards and for remote sensing instruments …
- Difficult to automate & high-cost

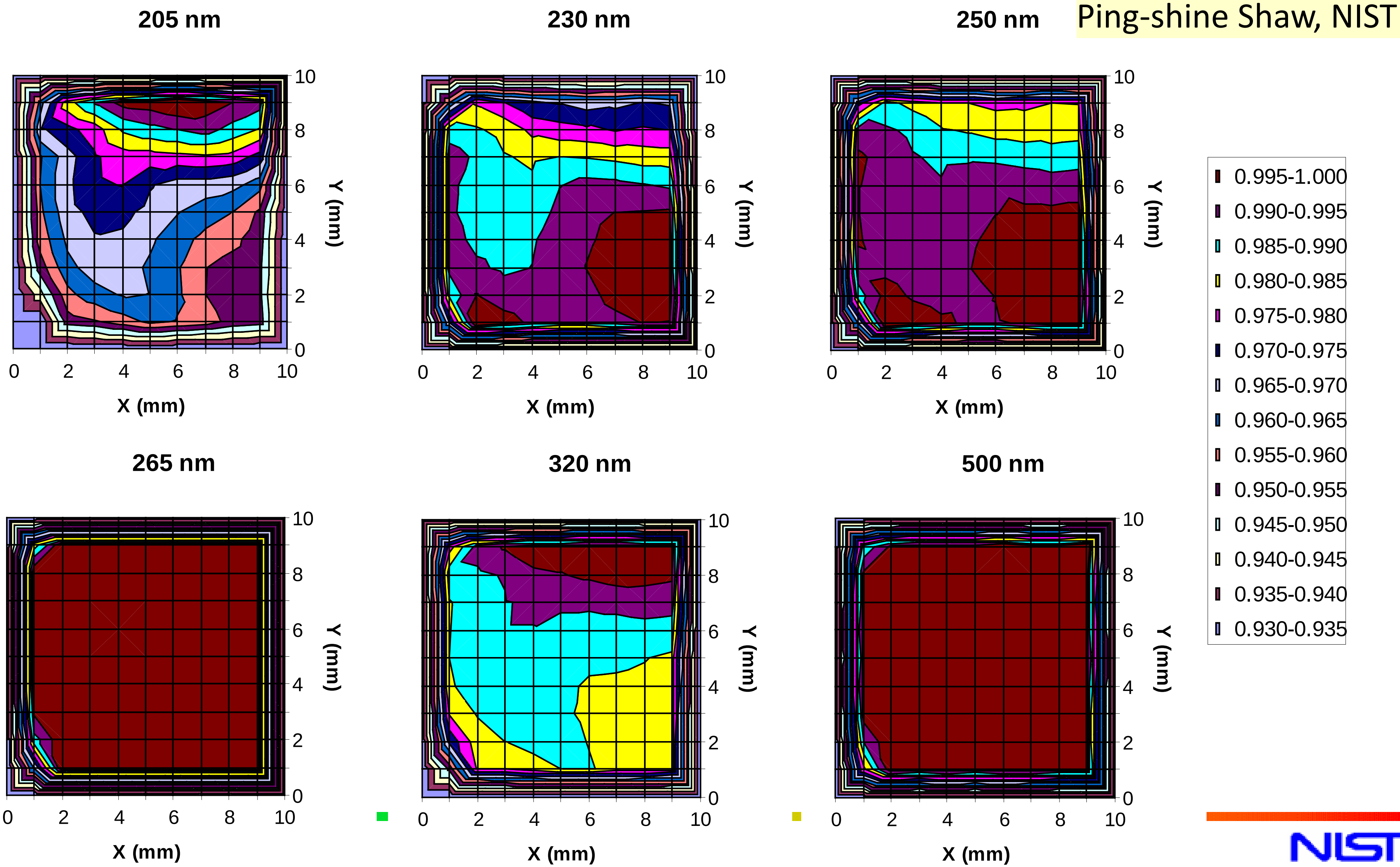
NIST SCF



- **Fully automated**
- Lamp-monochromator based calibration facility, no fringe problem
- Main facility to disseminate NIST Scale to industry
- Low radiant power (μW level), broad bandwidth (4 nm)
- Designed for power responsivity
- Large uncertainties to acquire irradiance responsivities (mapping method does not work well!)

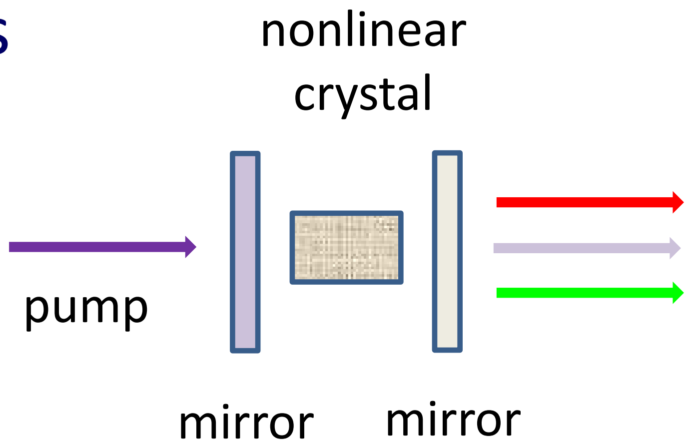
Spatial uniformity of a Si photodiode

Acknowledgement to
Ping-shine Shaw, NIST



Fully automated tunable OPO-based laser sources

- OPO: optical parametric oscillators
- Fully automated
- Large tunable range
- Portable
- Much lower cost



- Low repetition rate (10 Hz to 1000 Hz)
- Narrow pulse width, extremely low duty cycle (e.g., 10^{-6})
- Pulse to pulse variation and difficult to stabilize
- Trans-impedence amplifiers don't work well

Have not been used as calibration source yet

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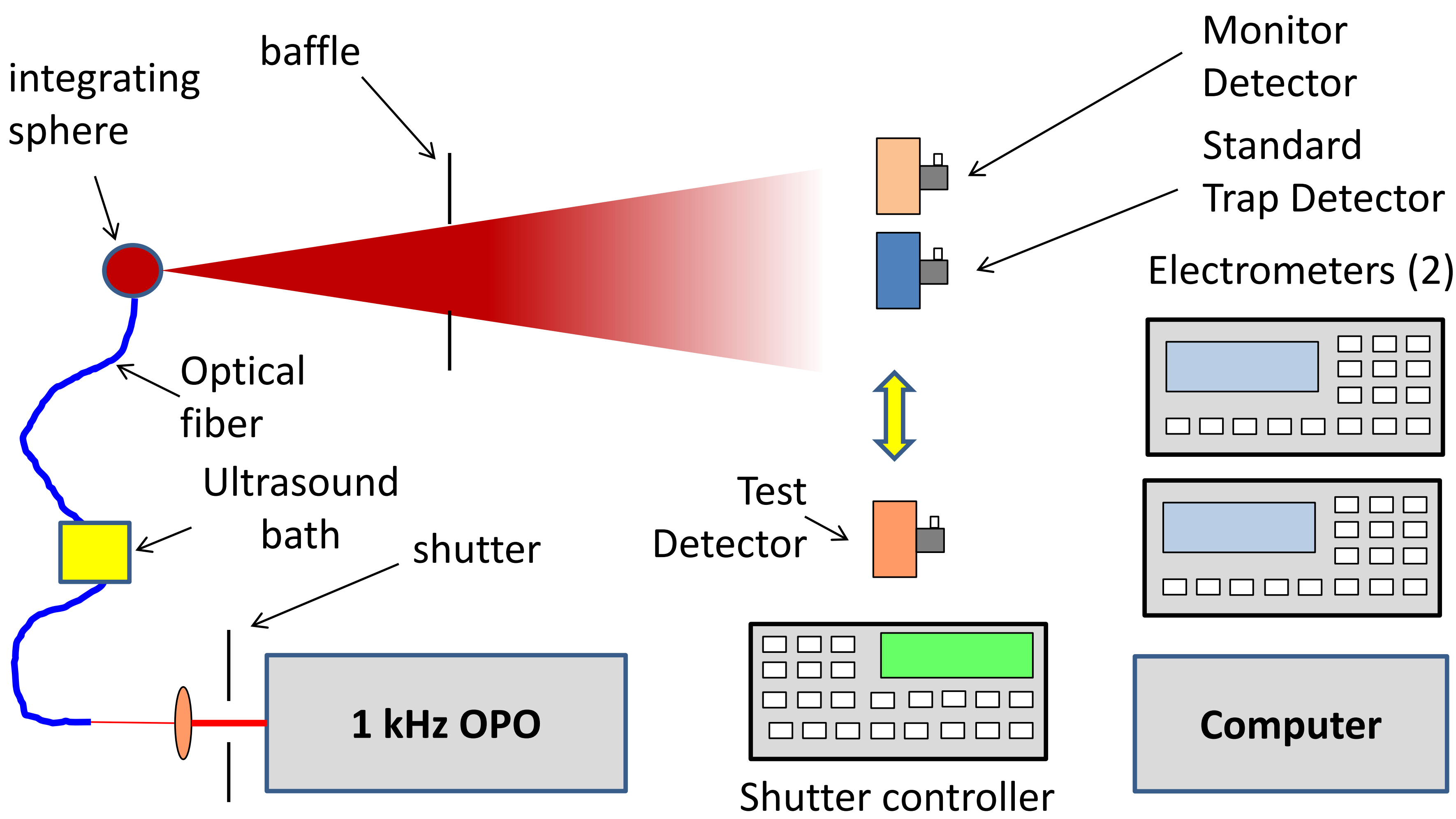
Key questions

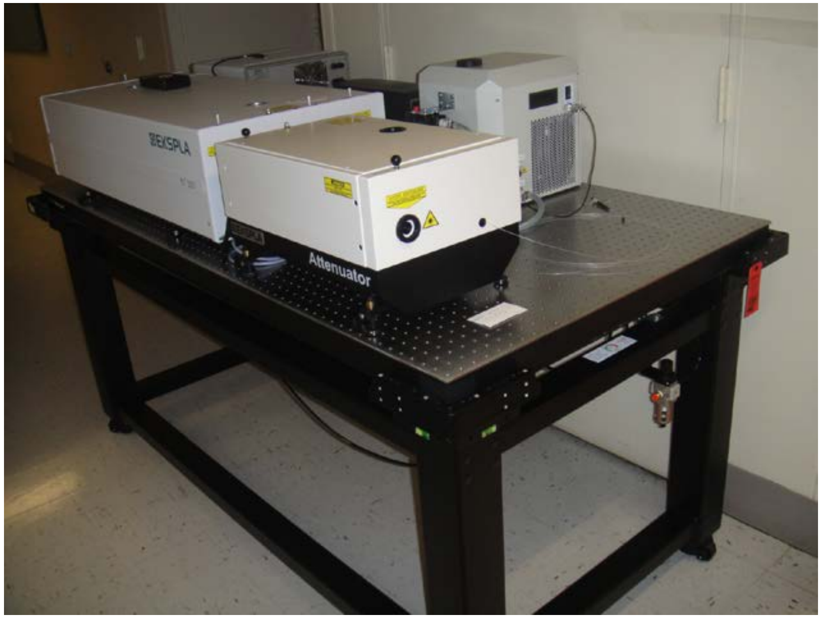
- Can pulse lasers be used for calibration of detectors with small uncertainties?
- How to overcome fluctuation of a pulsed laser and obtain repeatable results?
- Will detectors be saturated?
- Is a pulse laser equivalent to a CW laser for detector calibrations?

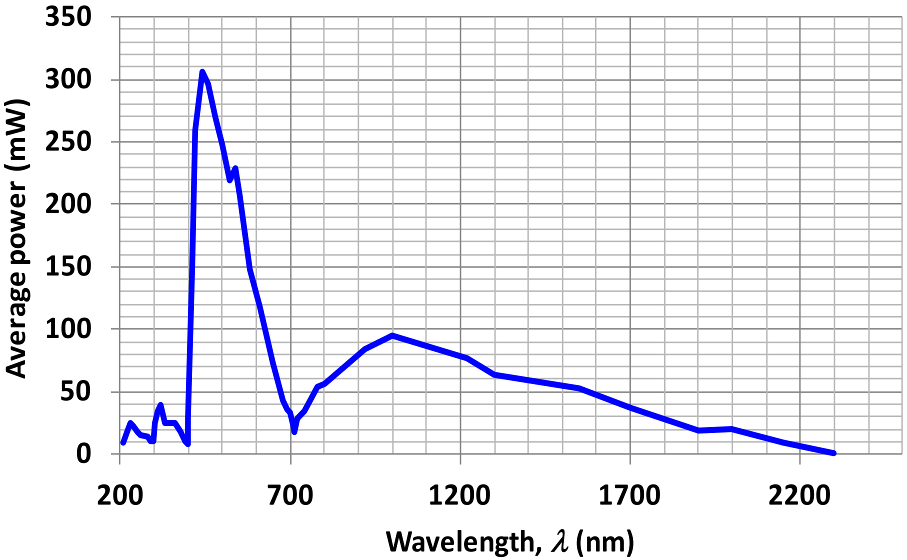
Schematic of the new automated calibration system



$$R_{test}(\lambda) = R_{\text{standard}}(\lambda) \times Q^{\text{M}}_{\text{test}}(\lambda) / Q^{\text{M}}_{\text{standard}}(\lambda)$$

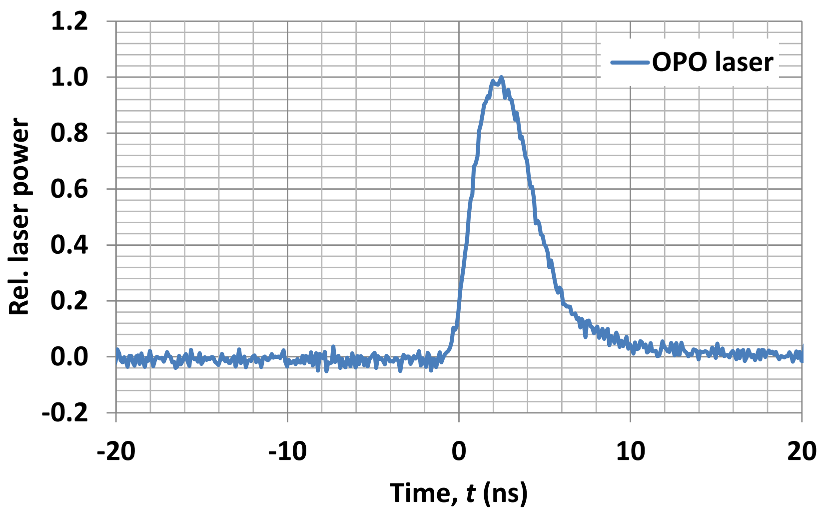
The automated OPO system

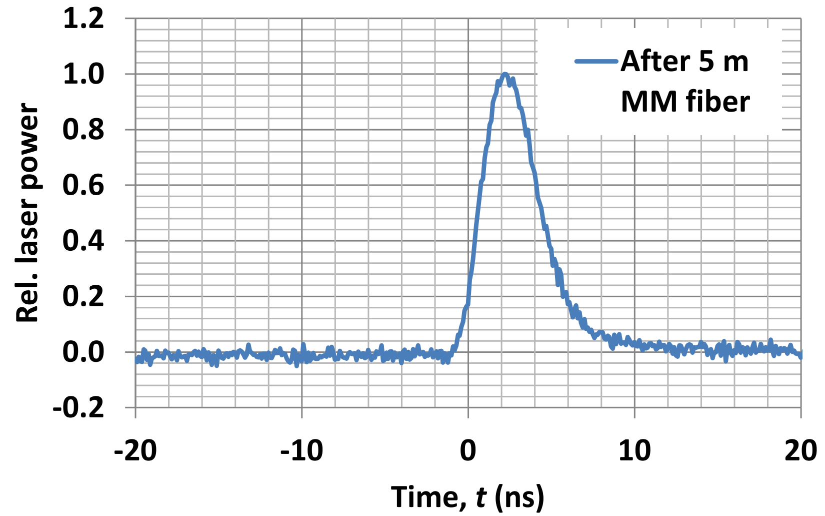


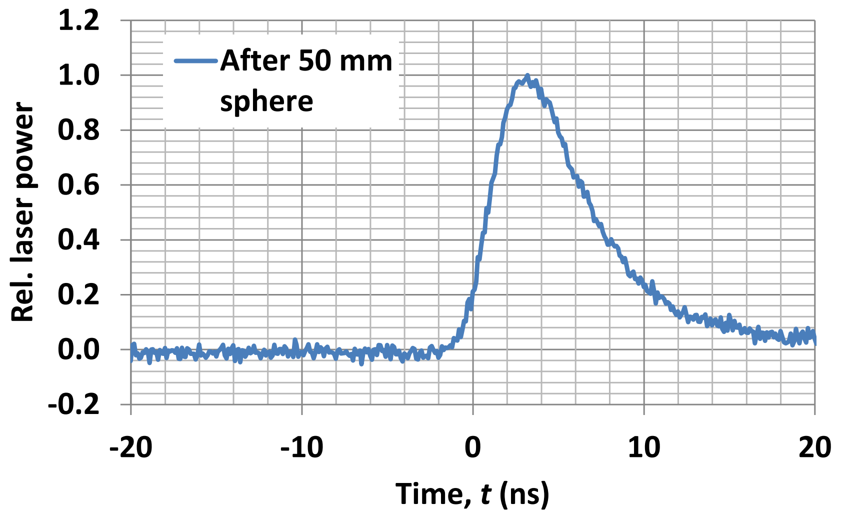


- 210 nm to 2400 nm tunable range
- 1 kHz repetition rate
- 5 ns pulse width
- 5 – 8 cm^{-1} bandwidth (≈ 0.2 nm in visible range)

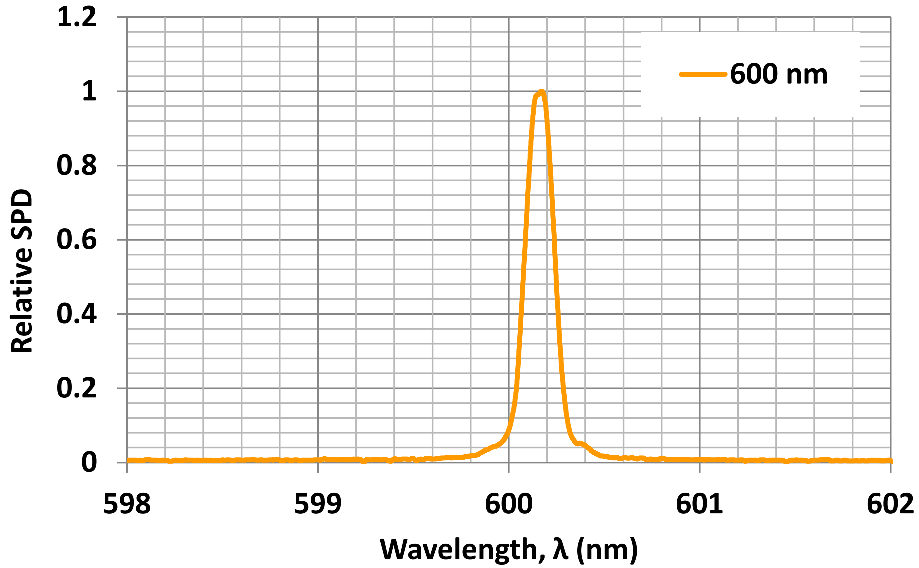
OPO pulse waveforms



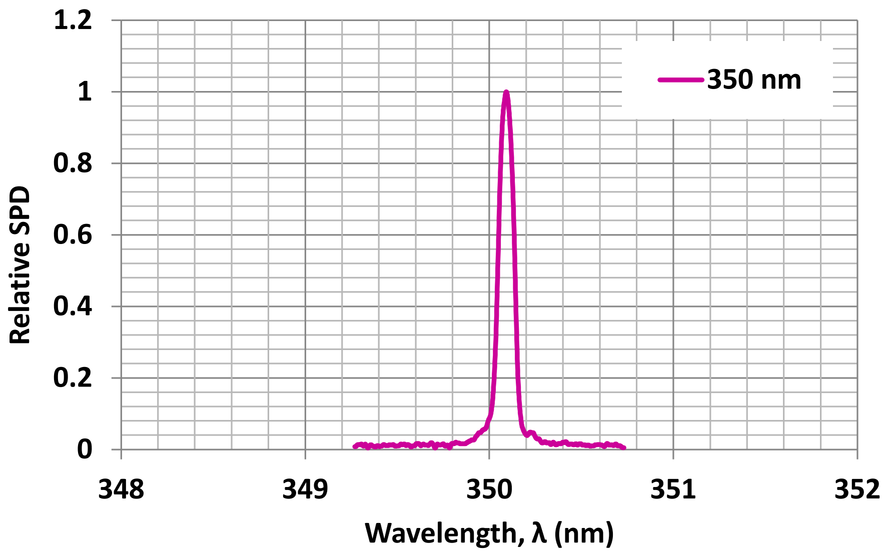




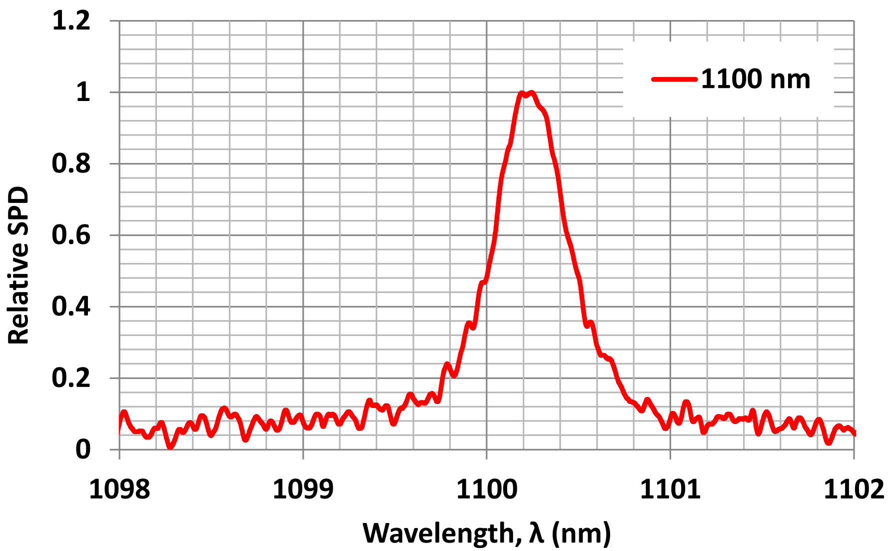
OPO spectra



1.2
1
0.8
0.6
0.4
0.2
0
Relative SPD
600 nm
598
599
600
601
602
Wavelength, λ (nm)

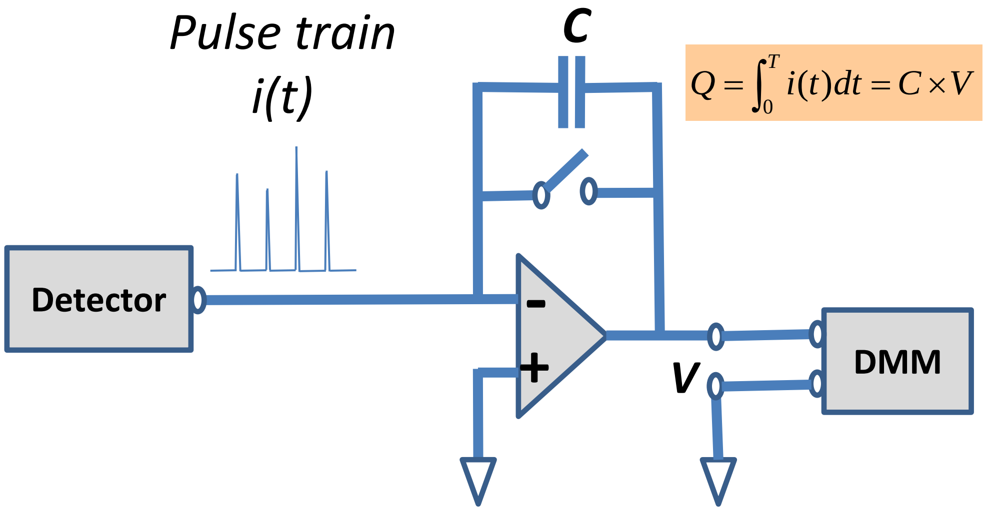


1.2
1
0.8
0.6
0.4
0.2
0
Relative SPD
350 nm
348
349
350
351
352
Wavelength, λ (nm)



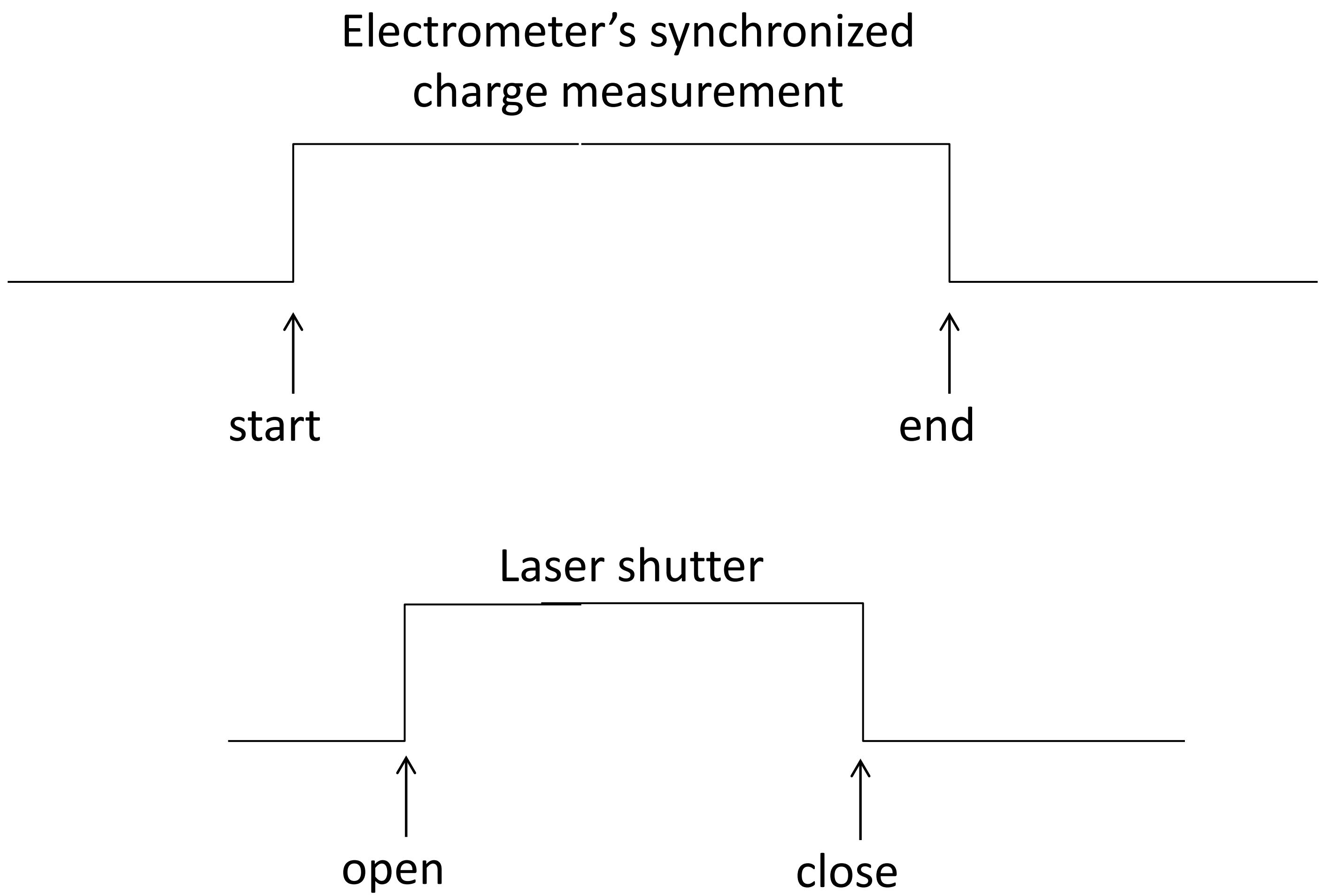
1.2
1
0.8
0.6
0.4
0.2
0
Relative SPD
1100 nm
1098
1099
1100
1101
1102
Wavelength, λ (nm)

The electrometers



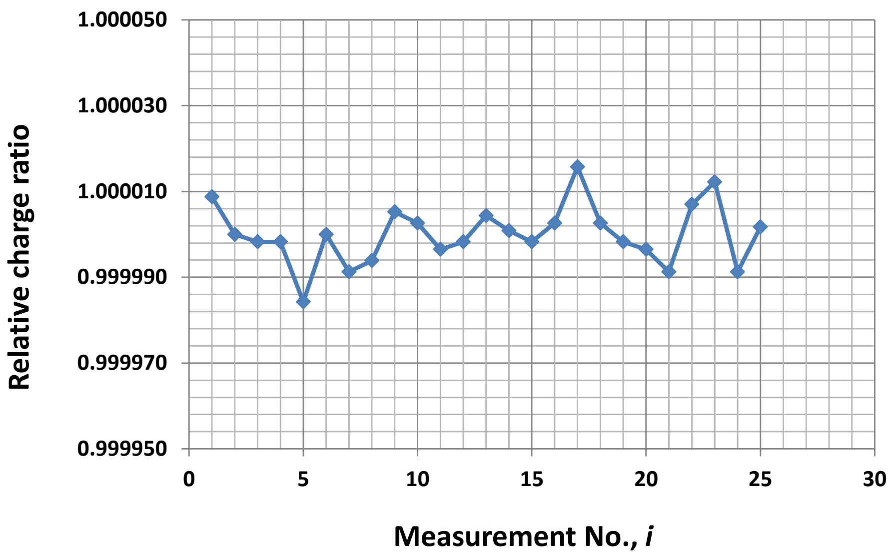
- Charge measurement function from 2 nC to 2 μC using a charge amplifier
- < 3 fA bias current
- < 20 μV burden voltage
- High performance multichannel switching card

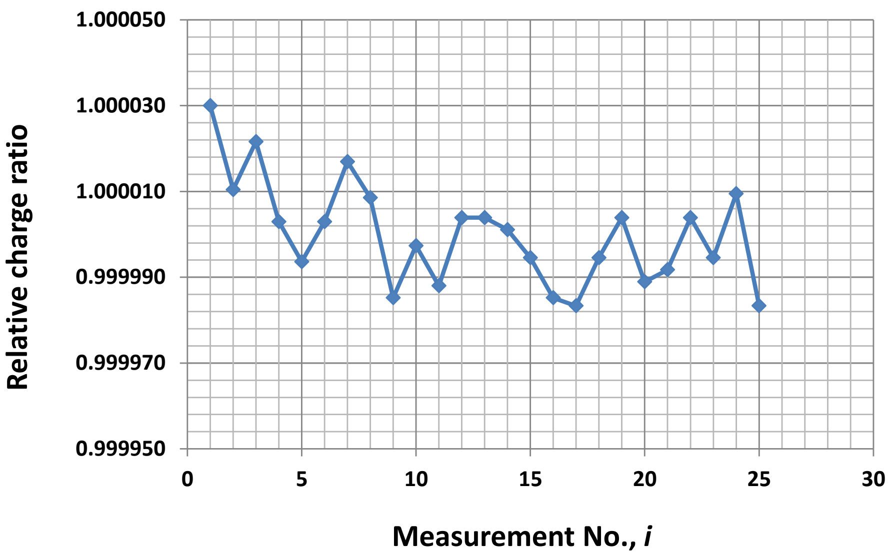
Measurement timing



Measurement repeatability

1 s integration time for each point

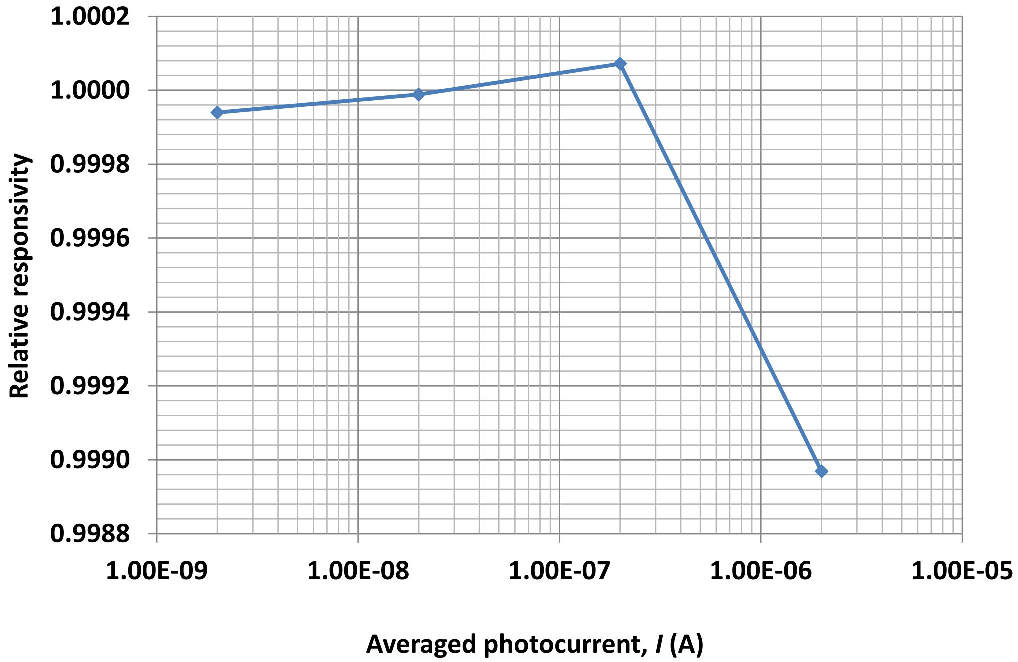




- two Hamamatus S2281 silicon photodiodes (PD)
- standard deviation = **7** ppm!

- one 3 silicon PD trap and one S2281 Si PD
- standard deviation = **12** ppm!

Detector non-linearity test



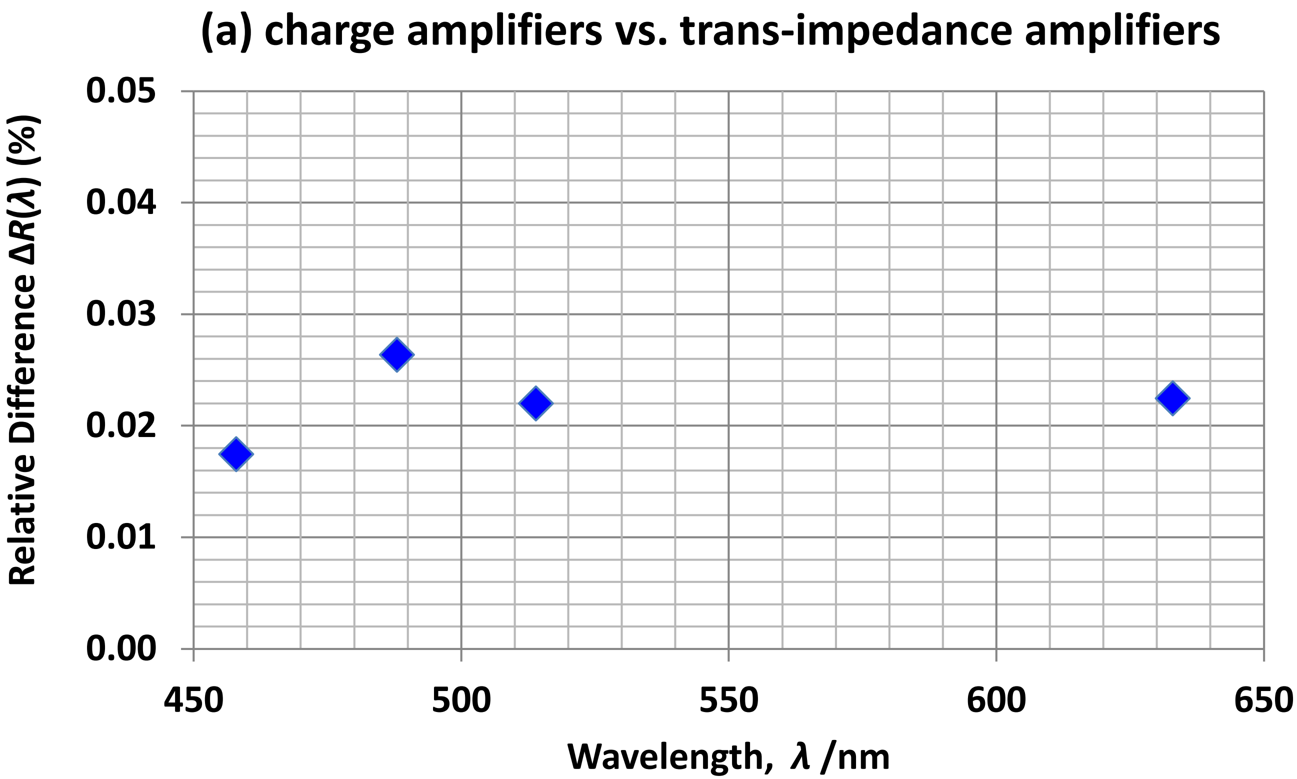
Obtained by normalizing the charge ratio $r(P_i)$ of the test detector (S2281 PD) to reference detector (S2281 PD with 2 orders of magnitude lower signal).

OPO at 450 nm.

Saturation starts at peak=100 mA, averaged=1 μA.

1) Nonlinearity depends on the detector and laser wavelength.
2) The instantaneous photocurrent without causing nonlinearity is several orders of magnitude higher than the threshold nonlinear DC photocurrent (0.1 – 1 mA typically).
3) The level of allowed averaged photocurrent is several orders of magnitude lower than the threshold nonlinear DC photocurrent.

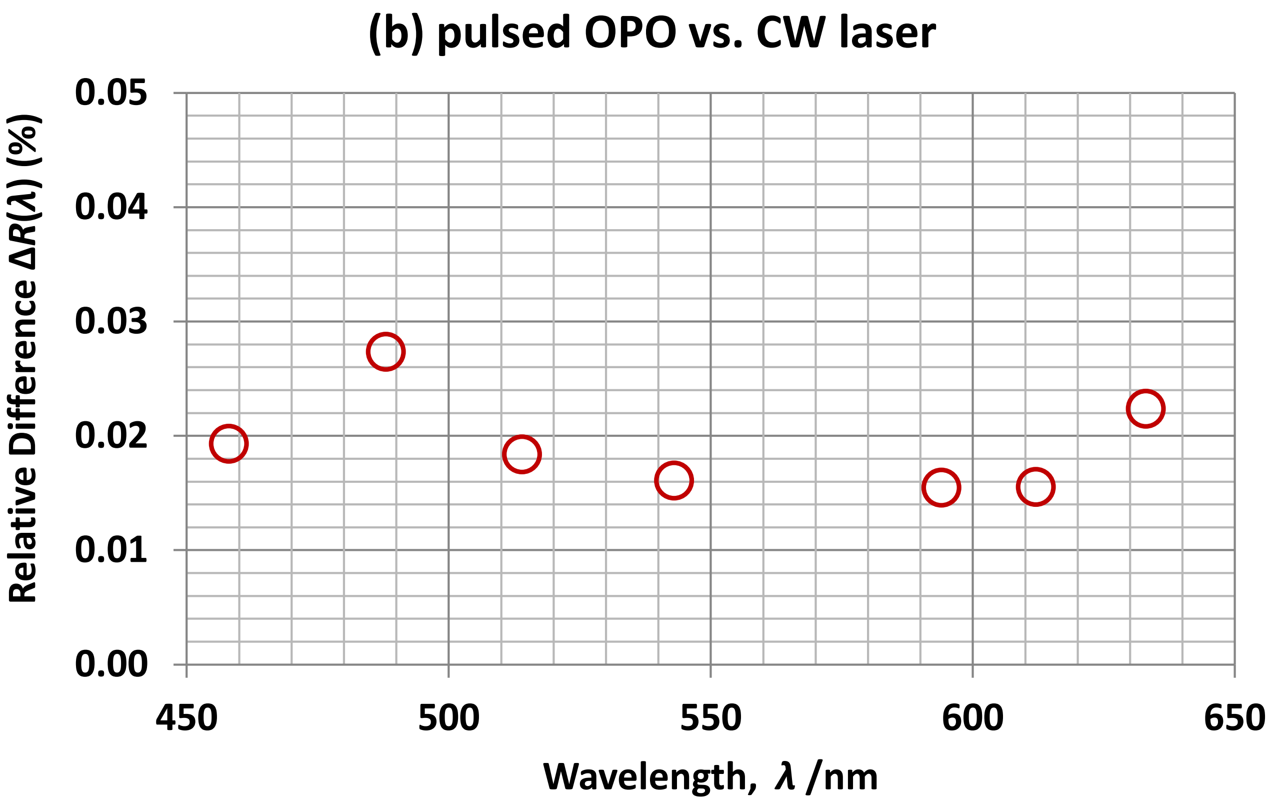
Validation: charge amp vs trans-impedance amp



"**CW laser** + charge amplifiers" vs. "**CW laser** + trans-impedance amplifiers"

Difference in measured responsivity is ≈ 0.02 %.

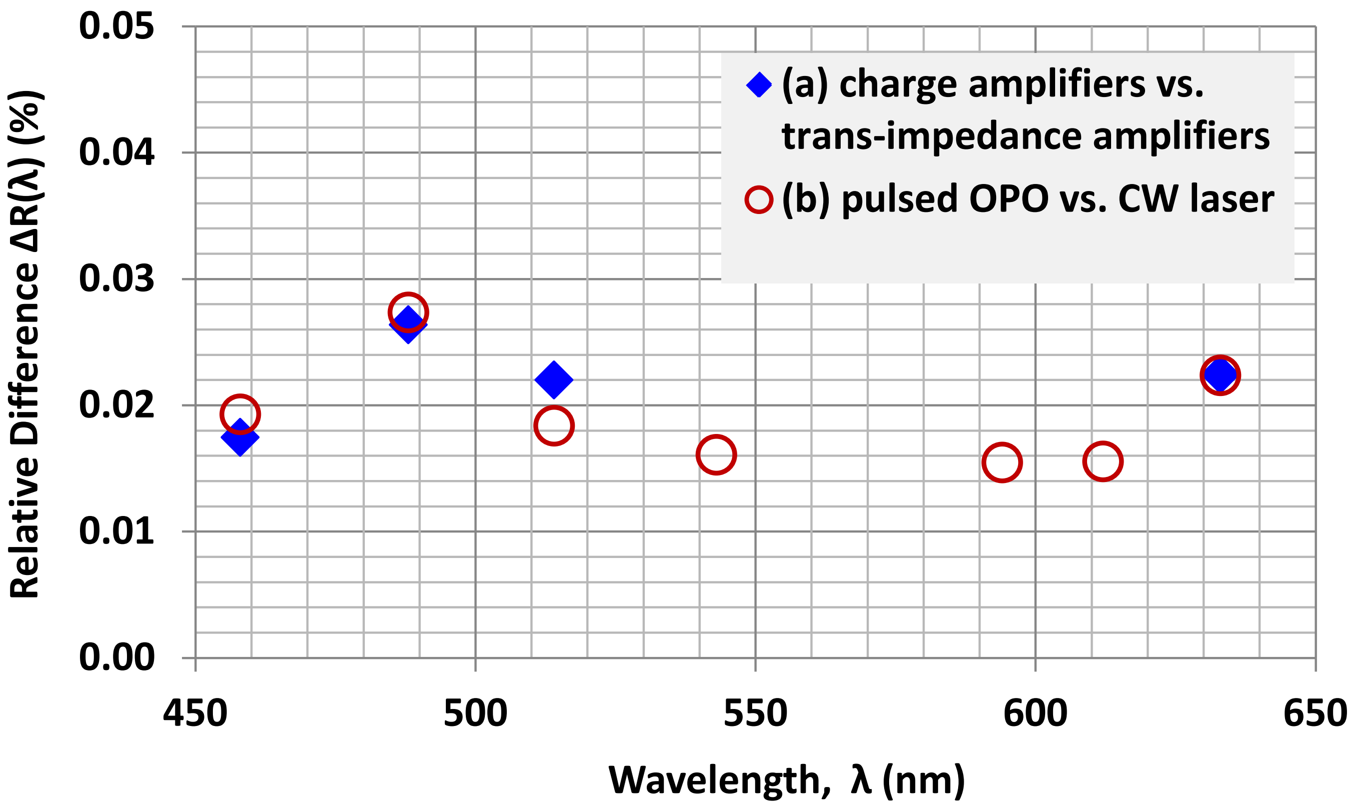
Validation: 1 kHz pulsed OPO vs CW lasers



"Pulsed OPO + charge amplifiers" vs. "**CW laser** + trans-impedance amplifiers"

Difference in measured responsivity is also ≈ 0.02 %

Comparison of results



Replacing **CW laser** with **pulsed OPO** for charge amplifiers does not make difference in measured responsivity.

Pulsed OPO ⟺ CW laser.

Uncertainty budget

	Relative standard unc. (%)	
Uncertainty component	Type A	Type B
Reference trap detector		0.020
OPO wavelength (0.02 nm)		0.005
Sphere source irradiance non-uniformity		0.005
Detector reference plane		0.010
Detector non-linearity		0.005
Transfer to test detector	0.005	
Electrometer (range to range gain error)		0.005
Combined uncertainty (%)	0.025	
Expanded uncertainty (*k*=2) (%)	**0.05**	

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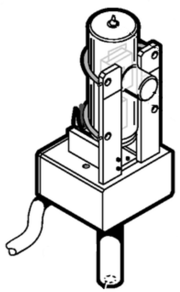
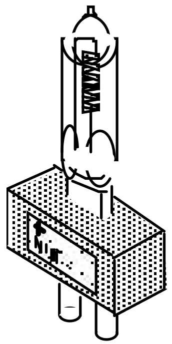
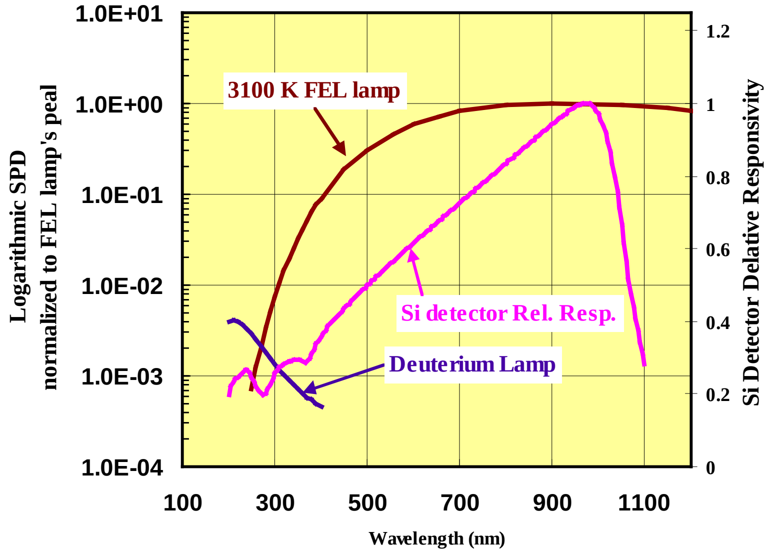
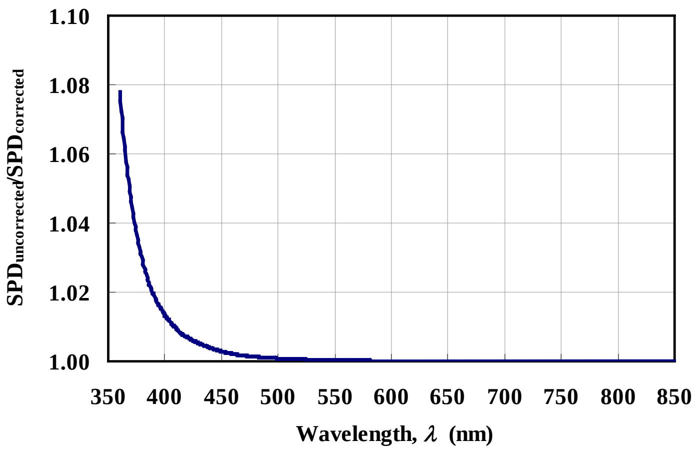
Stray light problem with spectrometers







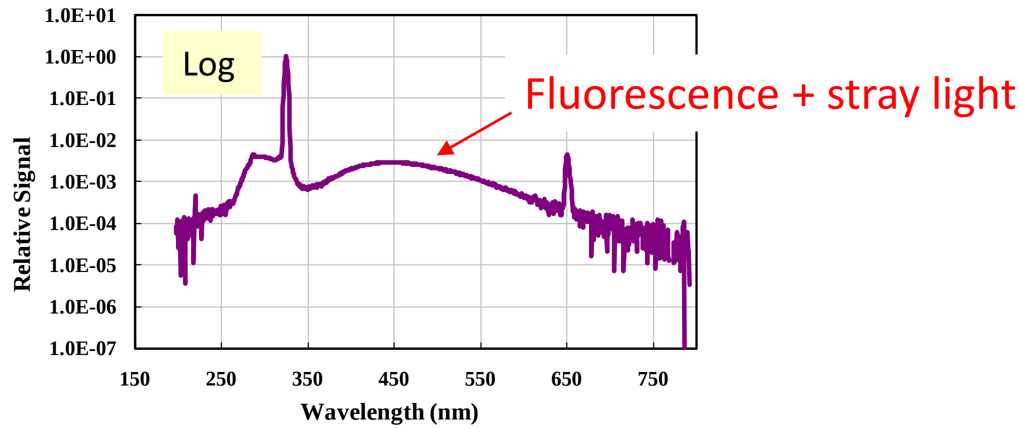
Ratio of measured SPDs of a 2856 K FEL lamp: the SPD without stray-light correction to the SPD with stray-light correction.

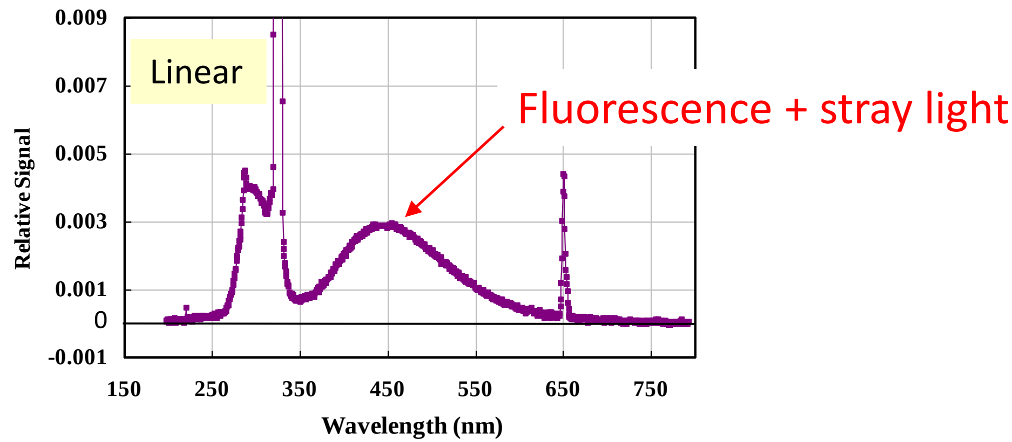


Stray light is often the dominant source of error <u>even</u> with an expensive, ‘high-quality’ spectroradiometer!

Characterization of spectral stray light:

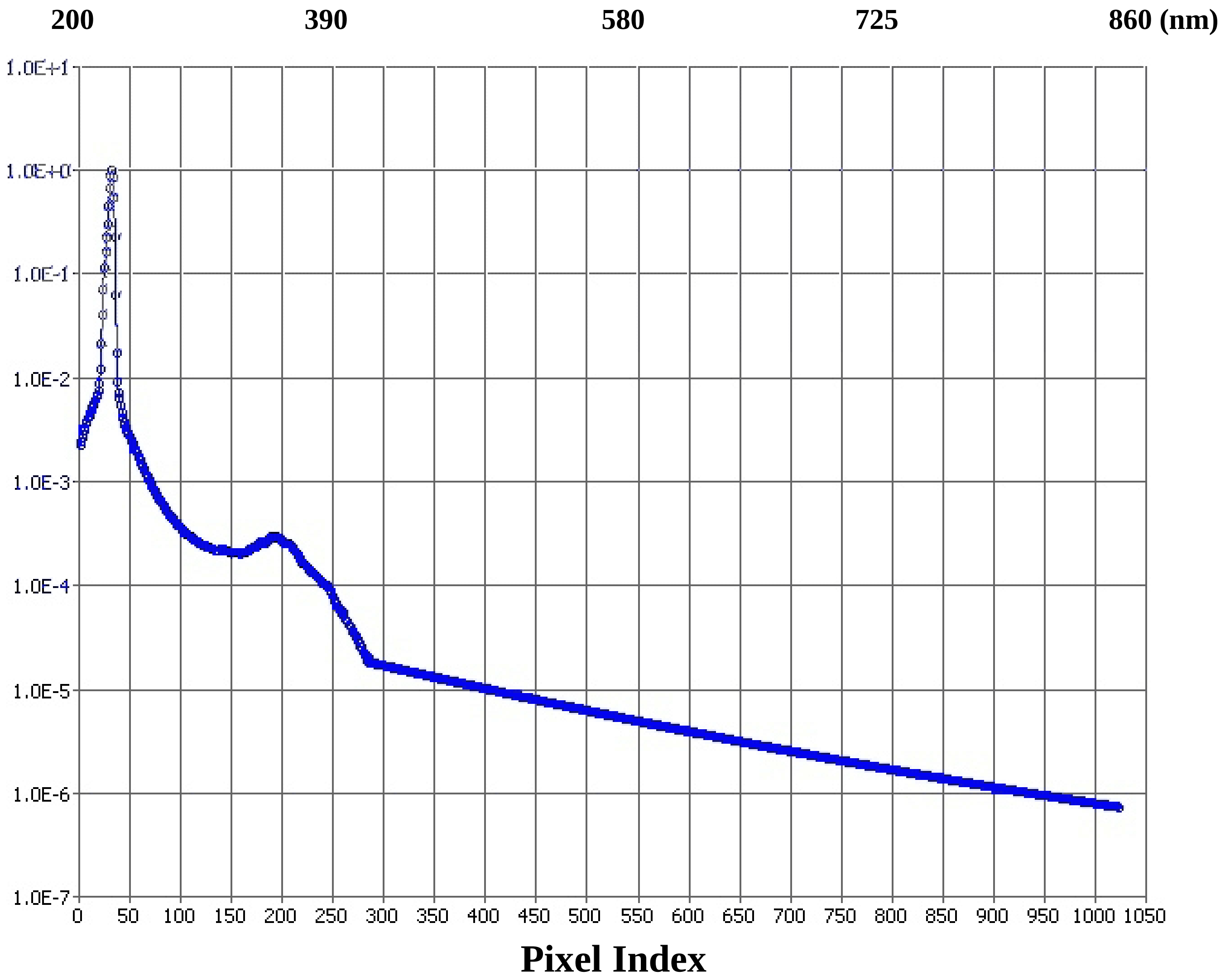
Spectral line spread function (SLSF)



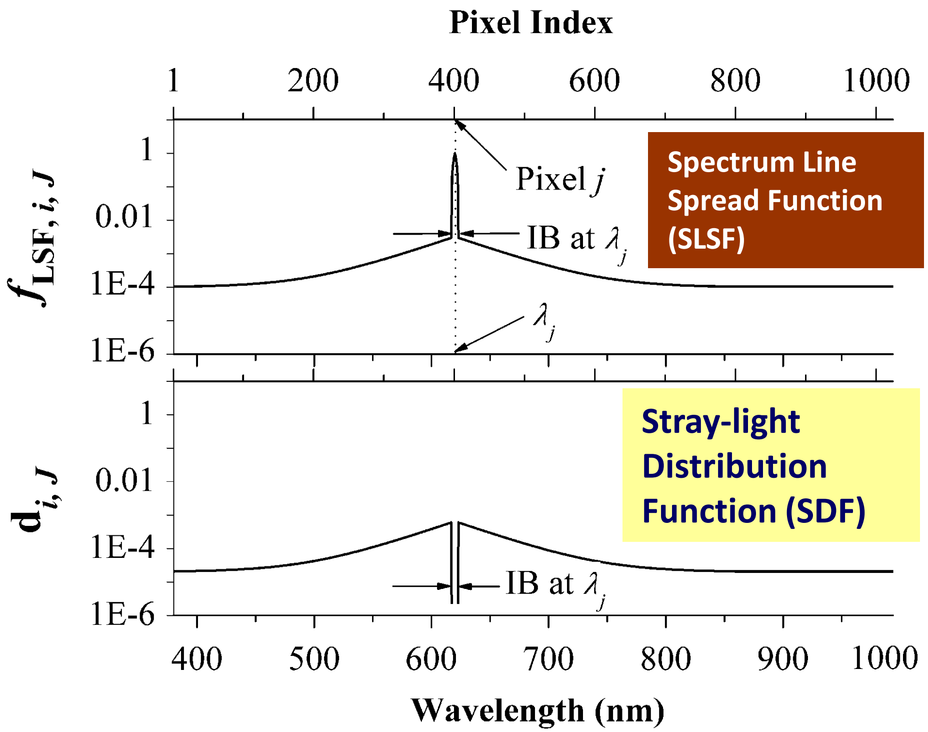


Measurement of an OPO laser source with a spectrometer.

Movie of measured SLSFs



Simple matrix method



$$d_{i,J} = \frac{f_{\mathrm{SLSF},i,J}}{\sum_{i \in \mathrm{IB}} f_{\mathrm{SLSF},i,J}}$$

for $i \notin \mathrm{IB}$

$$d_{i,J} = 0$$

for $i \in \mathrm{IB}$

The SDF matrix, $D_{n \times n}$

$$\begin{bmatrix} d_{1,1} & d_{1,2} & \cdot\ \cdot & d_{1,J} & \cdot\ \cdot & d_{1,n-1} & d_{1,n} \\ d_{2,1} & d_{2,2} & \cdot\ \cdot & d_{2,J} & \cdot\ \cdot & d_{2,n-1} & d_{2,n} \\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\ d_{i,1} & d_{i,2} & \cdot\ \cdot & d_{i,J} & \cdot\ \cdot & d_{i,n-1} & d_{i,n} \\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot\ \cdot & \cdot & \cdot \\ d_{n-1,1} & d_{n-1,2} & \cdot\ \cdot & d_{n-1,J} & \cdot\ \cdot & d_{n-1,n-1} & d_{n-1,n} \\ d_{n,1} & d_{n,2} & \cdot\ \cdot & d_{n,J} & \cdot\ \cdot & d_{n,n-1} & d_{n,n} \end{bmatrix}$$

$$y_{\mathrm{s\_spec},i} = \sum_{j=1}^{n} d_{i,j}\, y_{\mathrm{IB},j,\mathrm{true}} \approx \sum_{j=1}^{n} d_{i,j}\, y_{\mathrm{IB},j}$$

$Y_{s\_spec} = D\, Y_{IB}$

$Y_{meas} = Y_{IB} + Y_{s\_spec} = Y_{IB} + D\, Y_{IB}$

$= [I + D]\ Y_{IB} = A\ Y_{IB}$

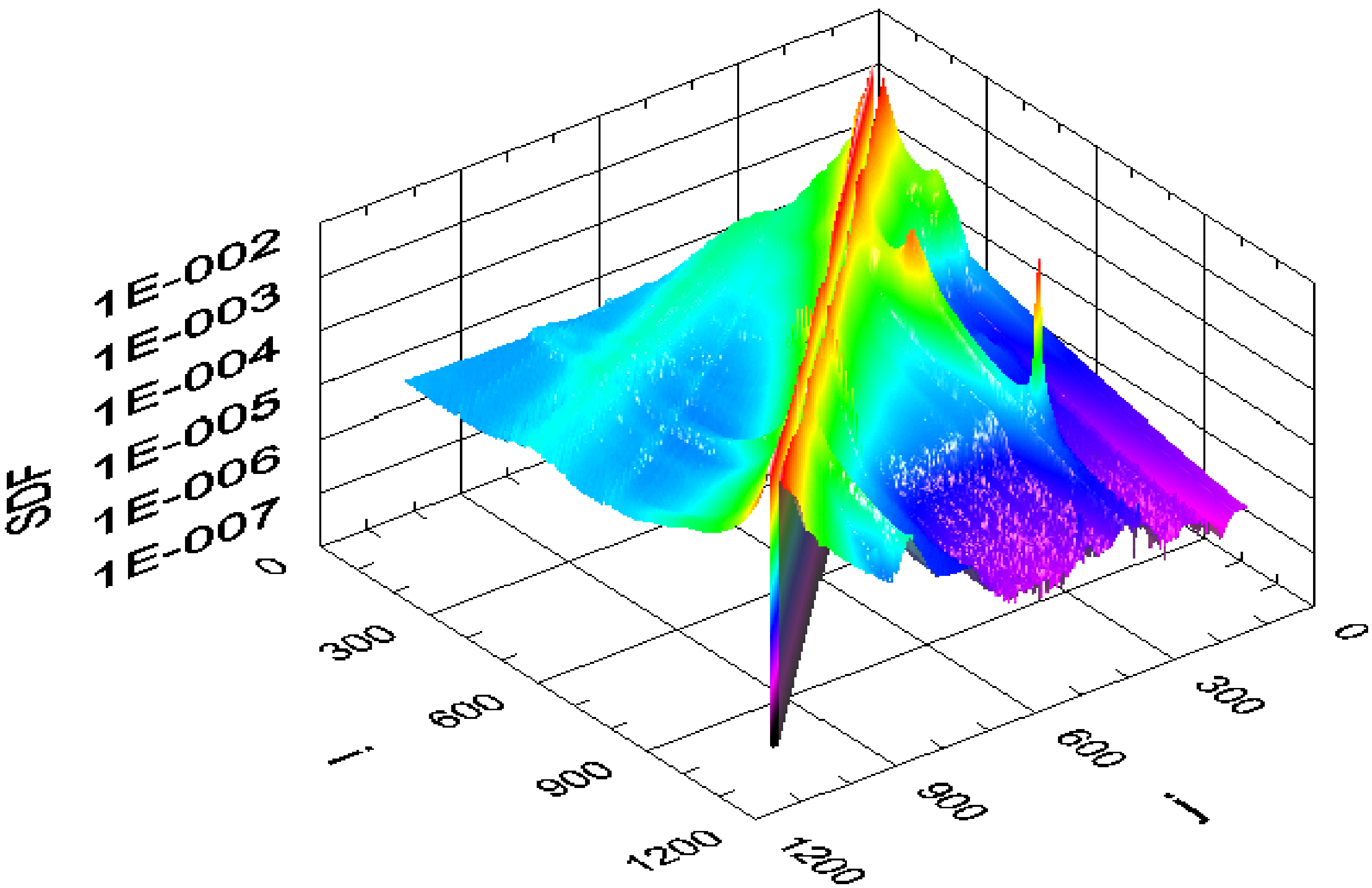
Correction of signals

$$\mathbf{Y}_{\mathrm{IB}} = \mathbf{A}^{-1}\ \mathbf{Y}_{\mathrm{meas}} = \mathbf{C}\ \mathbf{Y}_{\mathrm{meas}}$$

Stray-light corrected signals

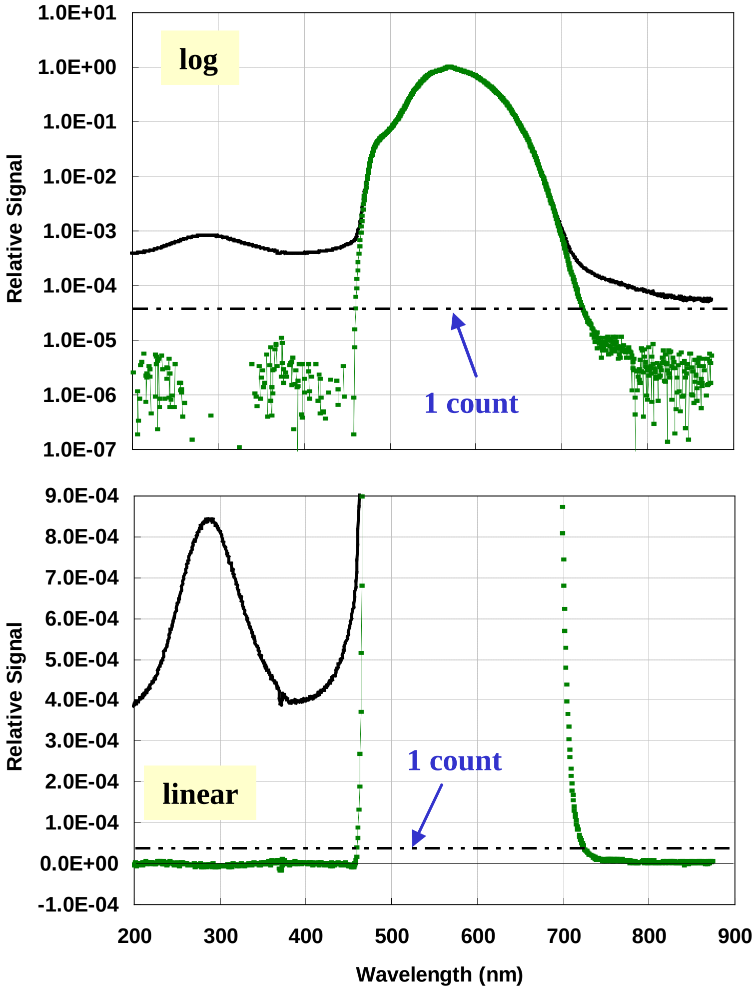
Stray-light correction matrix

3-D plot of a SDF matrix

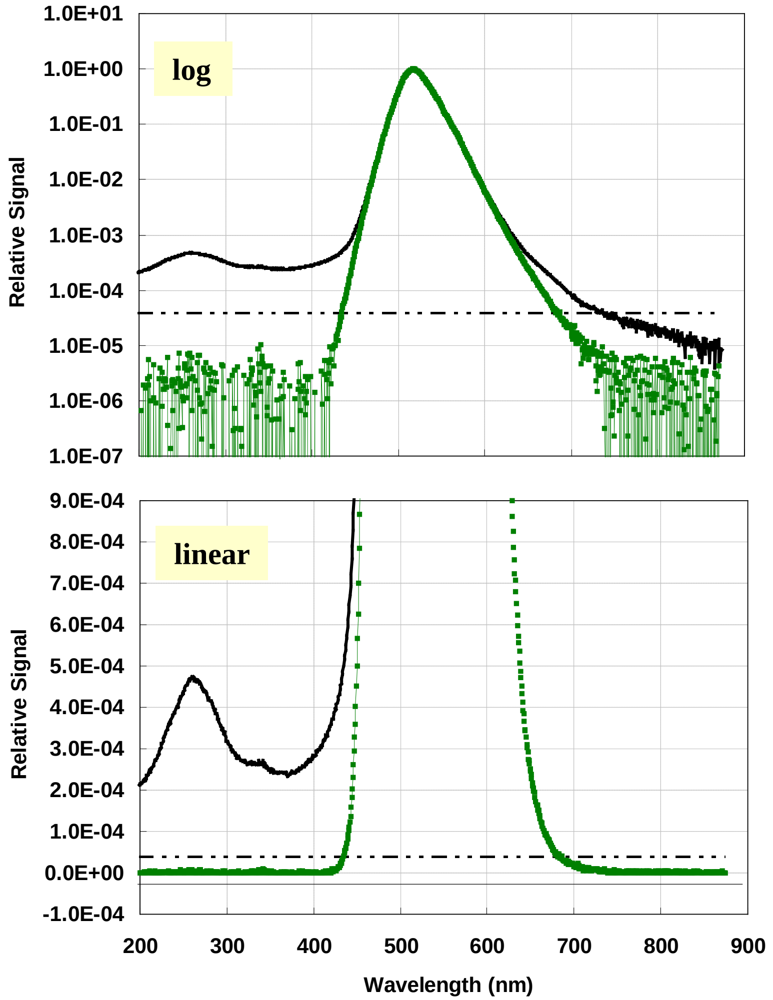


Correction of spectral stray light

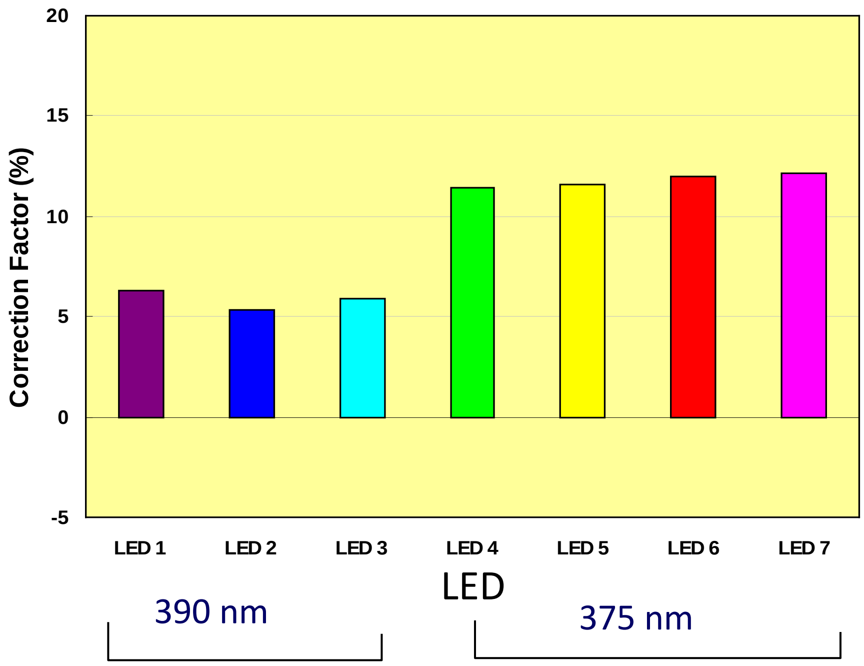
A Green Optical Filter



A Green LED



Stray-light correction for measurement of UV LEDs



Reference:

Zong Y., *et al*., Measurement of total radiant flux of UV LEDs, in Proc. CIE, CIE x026:2004, 107–110 (2004)

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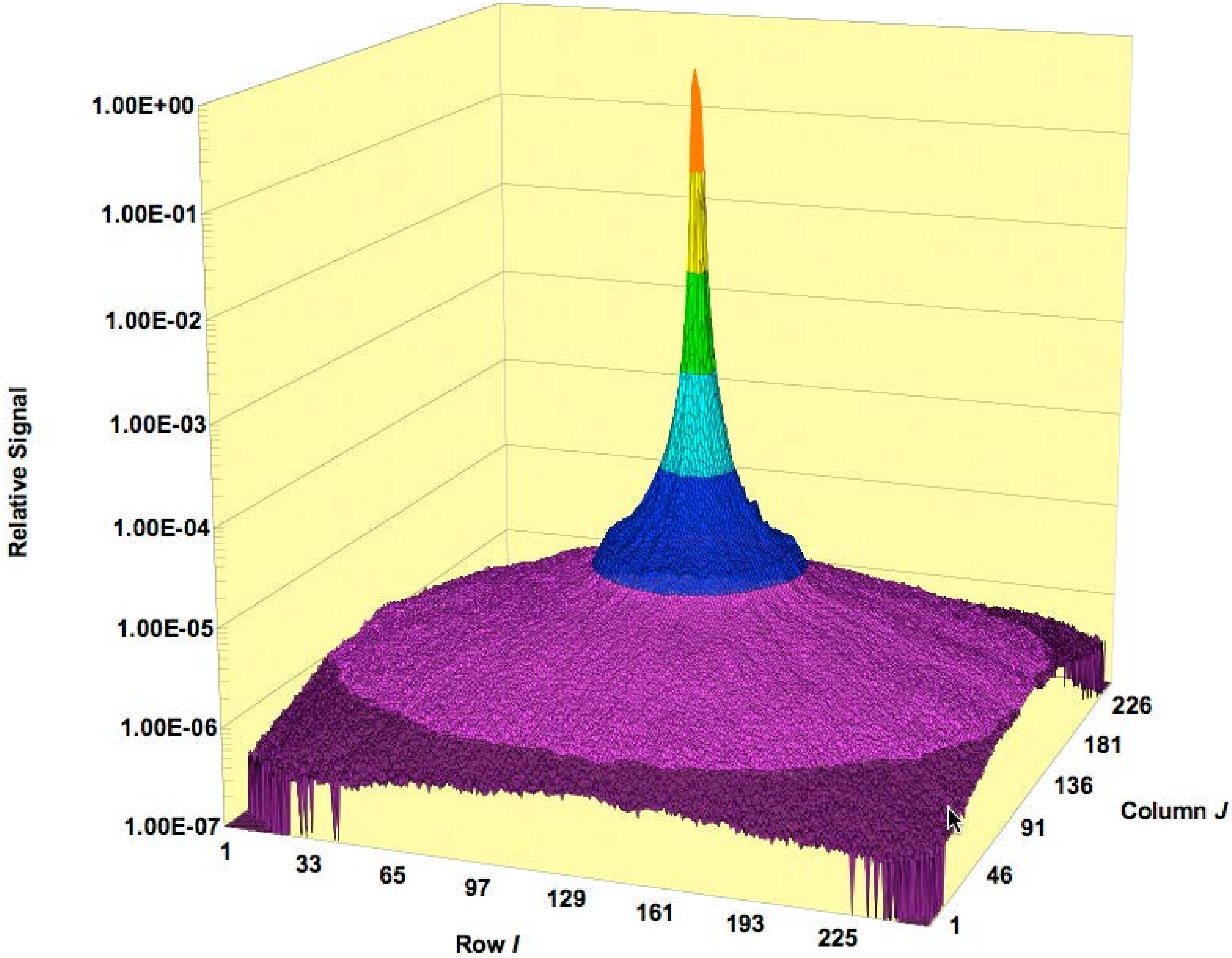
Spatial stray-light correction - imaging

Specifications:

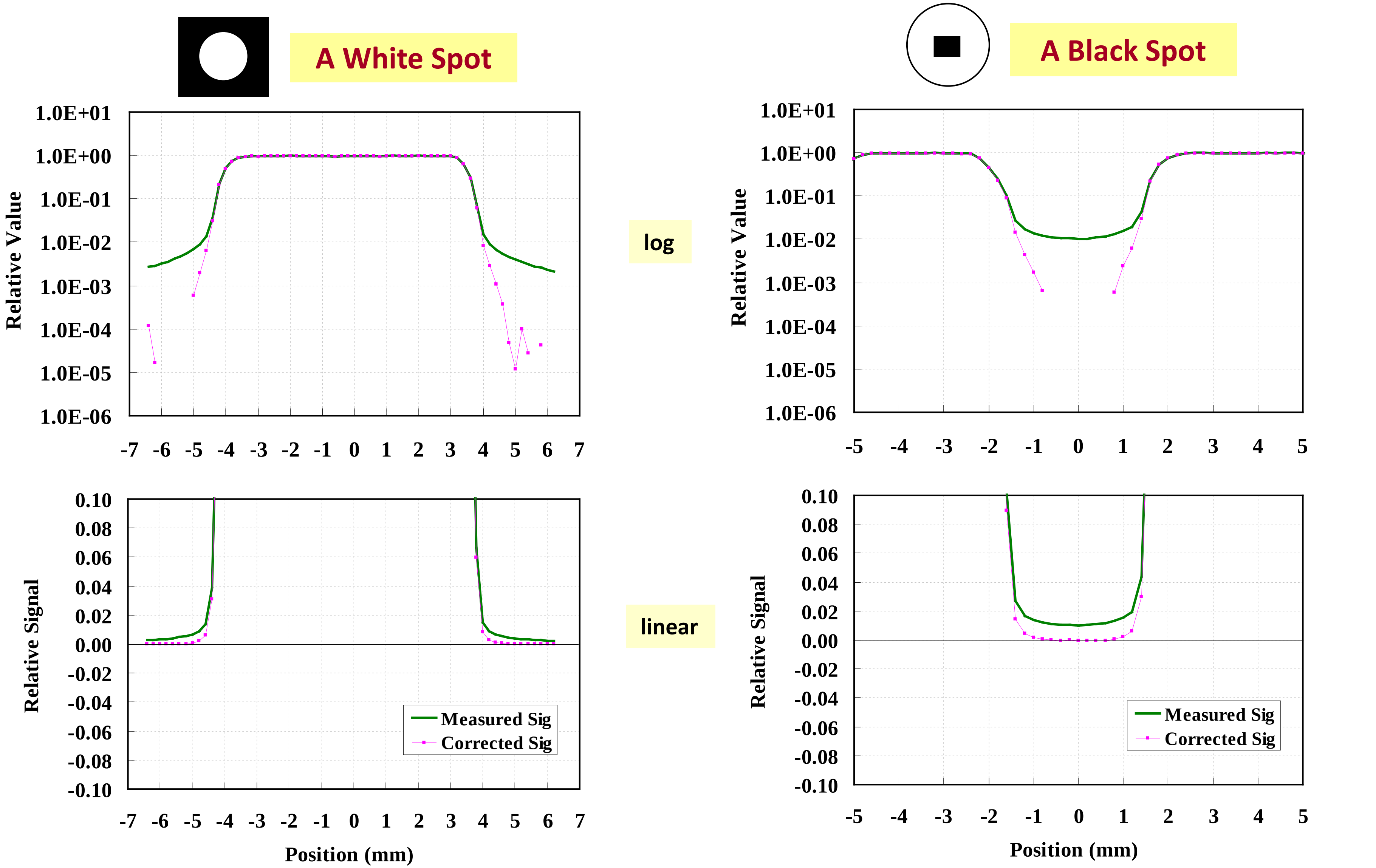
- 2-D CCD array: 1392x1040
- CCD size: 4.65 µm × 4.65 µm
- A/D: 12 bits
- Lens: 55 mm
- No TE-cooler

PSF test conditions:
Distance: 2 m
Pin hole size: 0.2 mm diameter
Iris: F2.8
Signal Dynamic range: > 6 orders

Point spread function (PSF)



Correction of spatial stray light



Summary

- A new, automated method for calibration of optical sensors using a low-cost kHz OPO laser system has been developed and validated. Calibration uncertainty is virtually the same as that by using tunable CW lasers.
- A kHz OPO is also a powerful tool for correction of spectrometers for stray light.
- kHz OPOs may be used to replace CW lasers or monochromators in:

  - Characterization and calibration of remote sensing instruments (e.g., ABI of GOES-R)
  - LIDAR
  - Measurement of optical property (e.g., BRDF)
  - Hyperspectral imaging (e.g., optical medical imaging)
  - ...

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References

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- Zong Y., Brown S. W., Johnson B. C., Lykke K. R., and Ohno Y., Simple spectral stray light correction method for array spectroradiometers, *Appl. Opt*., **45**, 1111-1119 (2006).
- Zong Y., Brown S. W., Meister G., Barnes R. A., and Lykke K. R., Characterization and correction of stray light in optical instruments, Proc. of SPIE, September 17-20, 2007, Florence, Italy, *Vol.* **6744**, 67441L-1-11 (2007).
- Zong Y., Brown S. W., Lykke K. R., and Ohno Y., Correction of stray light in spectroradiometers and imaging instruments, Proc. CIE, July 4-11, 2007, Beijing, China, CIE **178:2007**, D2-33 to D2-36. (2007)

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