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Recent research and development in photometry at NIST

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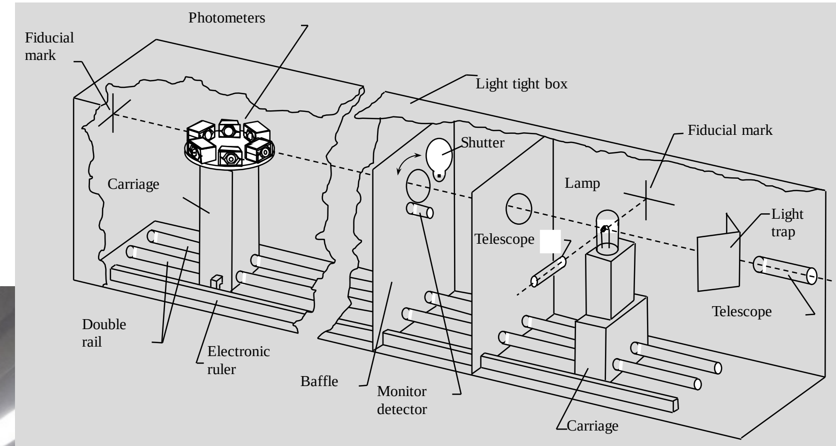
Outline

- New photometry bench
- New generation of photometers
- Tunable laser based calibration facility

  - photometer calibrations

  - spectroradiometer calibrations

The old photometry bench



- 40 years old, failing
- Boxed, difficult to work with
- not expandable, limited space for light sources and detectors

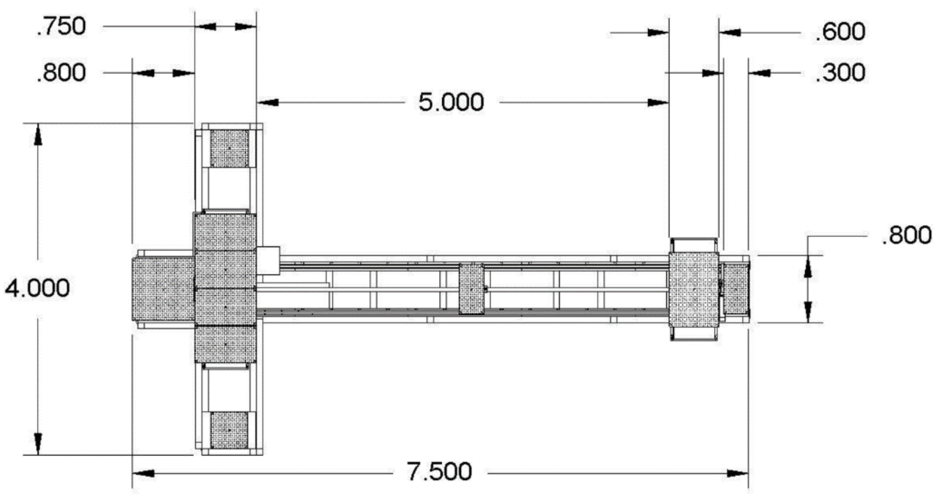
Overview of the new photometry bench project

Goals:

- Reduce uncertainties
- Increase calibration efficiencies
- Add new measurement capabilities

Milestones:

- 5/2015, design started
- 1/2018, installed in lab
- 5/2019, used for calibrations



The new Photometry bench shall meet the minimum requirements below:

1. The long rail system shall provide motion for the moving carriage with the Photometer Stage along the direction intersecting the Source Stage with a range of at least 5 m.
2. The 5 m motion shall be provided by a ball screw to provide vibration-free positioning and to simply the cable management.
3. The ball screw shall be covered to avoid oil contamination to the laboratory.
4. The moving carriage with the Photometer Stage shall have a maximum speed of at least 3 cm/s.

30. The complete Photometry bench including the Photometer Stage and Source Stage shall be installed onsite by the manufacturer in a condition ready for acceptance testing. During the installation both Photometer Stage and Source Stage shall be aligned so that their motions are at 90 degrees ± 10 arc-seconds to the direction of 5 m rail system.
31. Emergency stop switches shall be installed for all motions if possible in addition to the one on the motion controller.

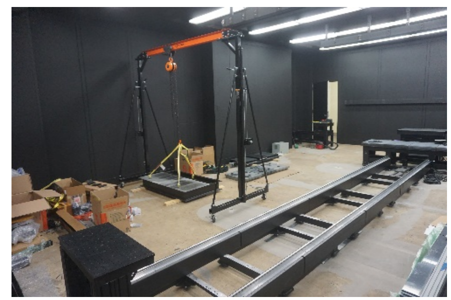
Optional deliveries (quote them separately):

1. A 1 m (travel direction) x 0.6 m metric optical breadboard that is mounted on the Photometer Stage.

Installation of the new bench – big job!



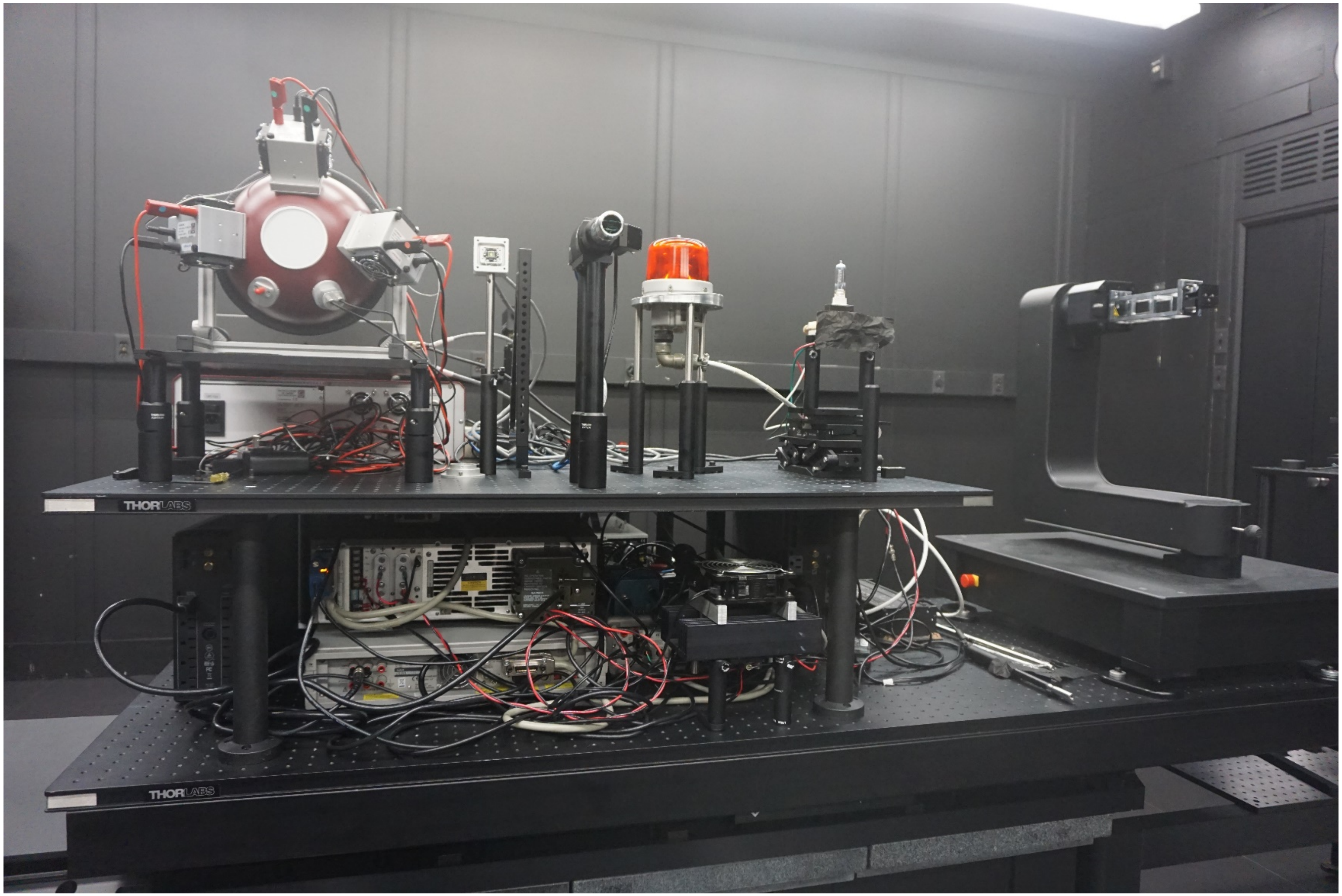




The completed new photometry bench

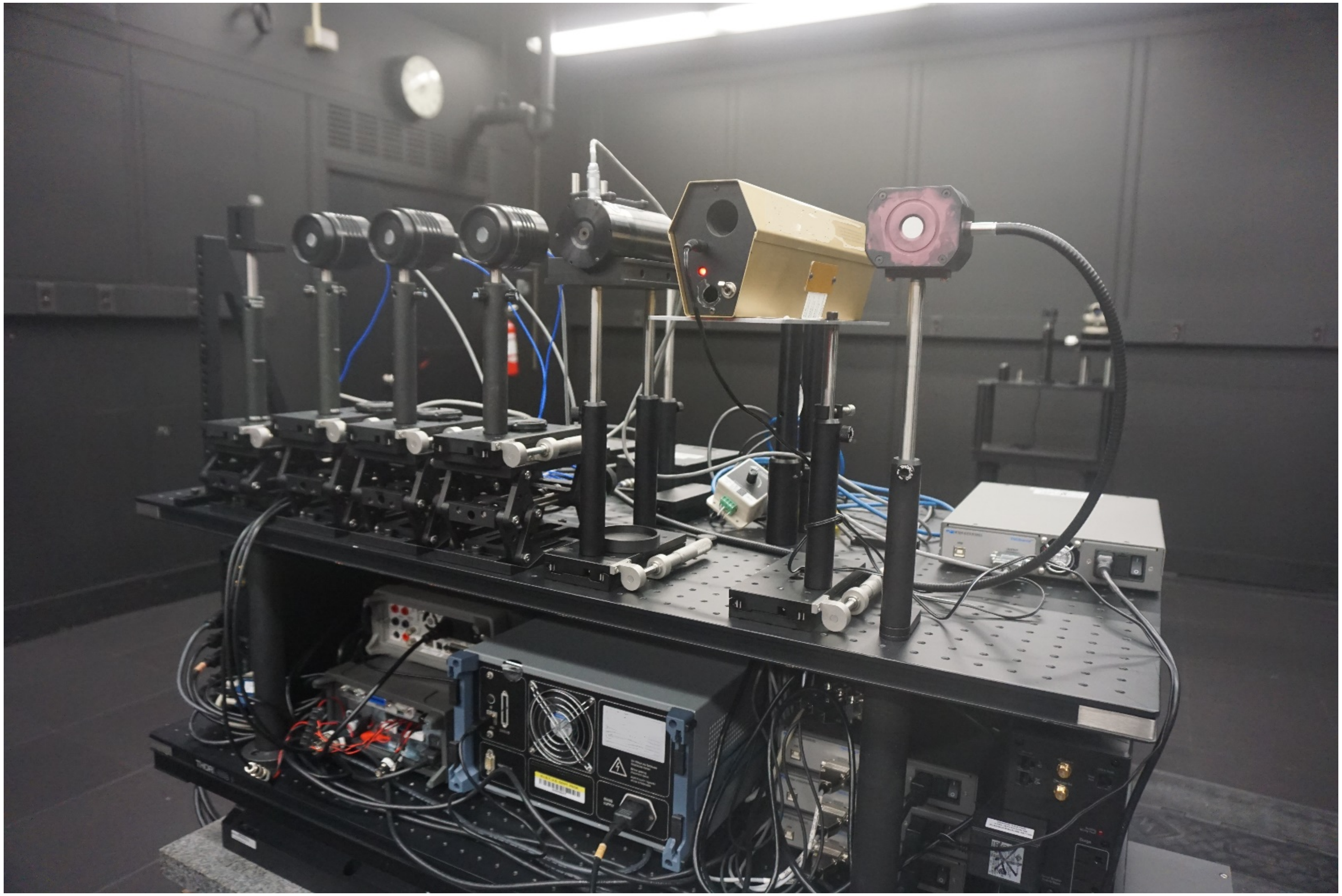
6 m ball screw, 5 m travel, Δd = 50×10^{-6} m, with a source stage and sensor stage

Sources Stage



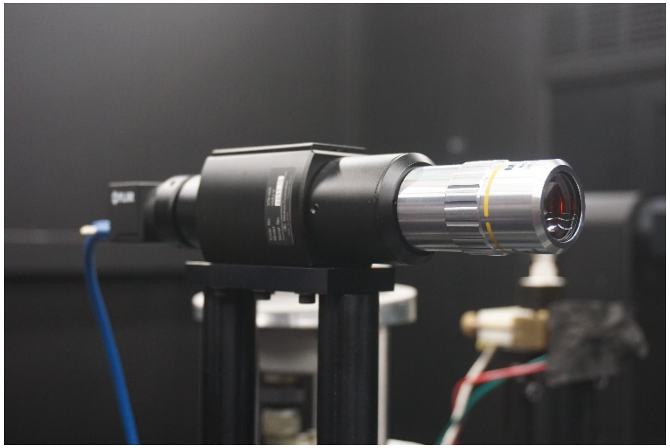
1.5 m long travel sources stage for FEL lamp, LED, flashing light, integrating sphere, tunable laser, even a goniophotometer.

Sensors stage

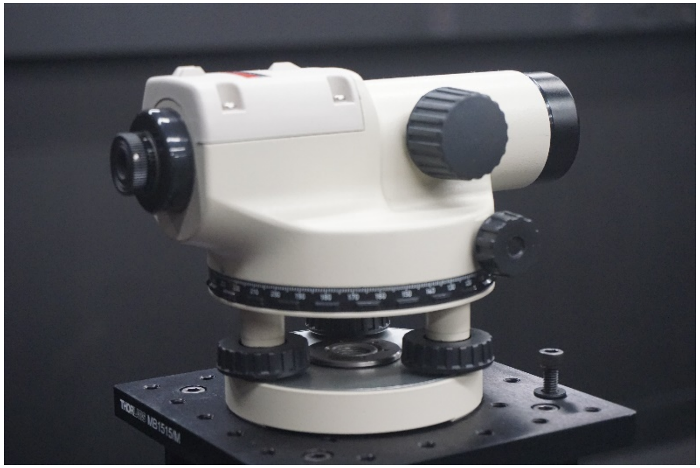


0.8 m long travel sensors stage for photometer, colorimeter, radiometer, and spectroradiometers, cameras, hyperspectral imagers…

Alignment tools



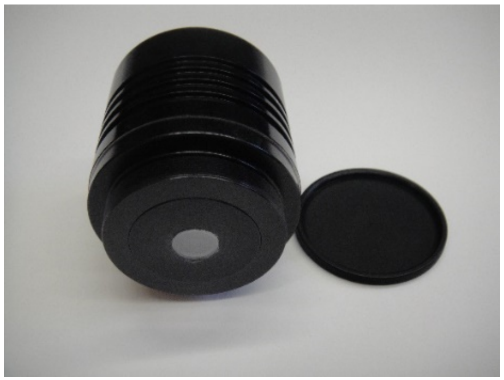
Microscope



Telescope

He-Ne laser

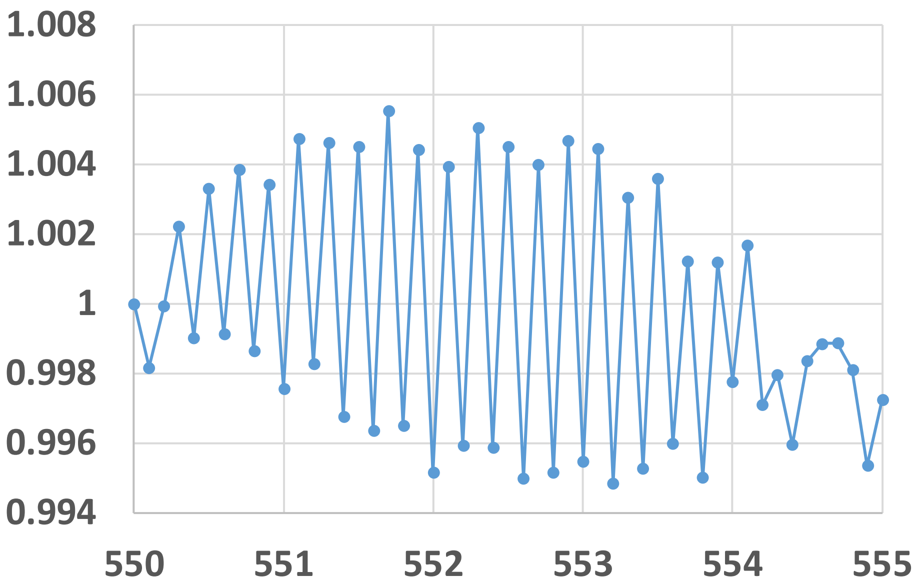
New generation of illuminance photometers for realization of the SI base unit - candela



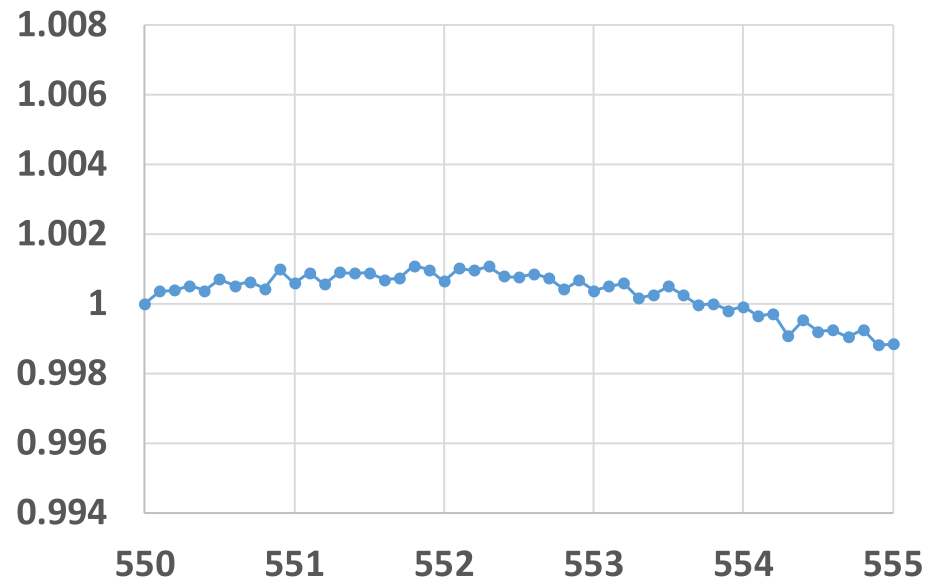
- Sealed, temperature-controlled, low noise
- Superior long-term stability (<0.05 % for 12 months)
- Calibrated against trap detectors using the OPO tunable laser, no interference fringes
- Reduced the uncertainty of NIST candela unit by more than a factor of 3 (to be <0.2 %)

Interference fringes are eliminated

Old photometer

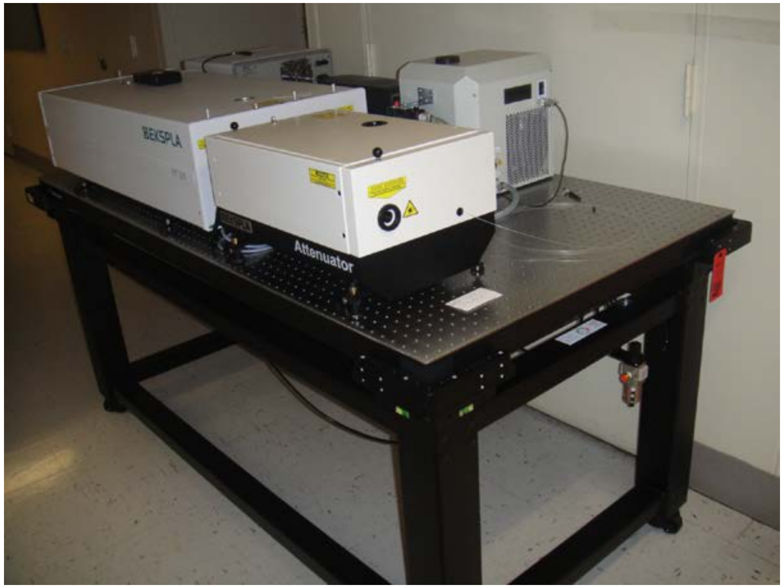


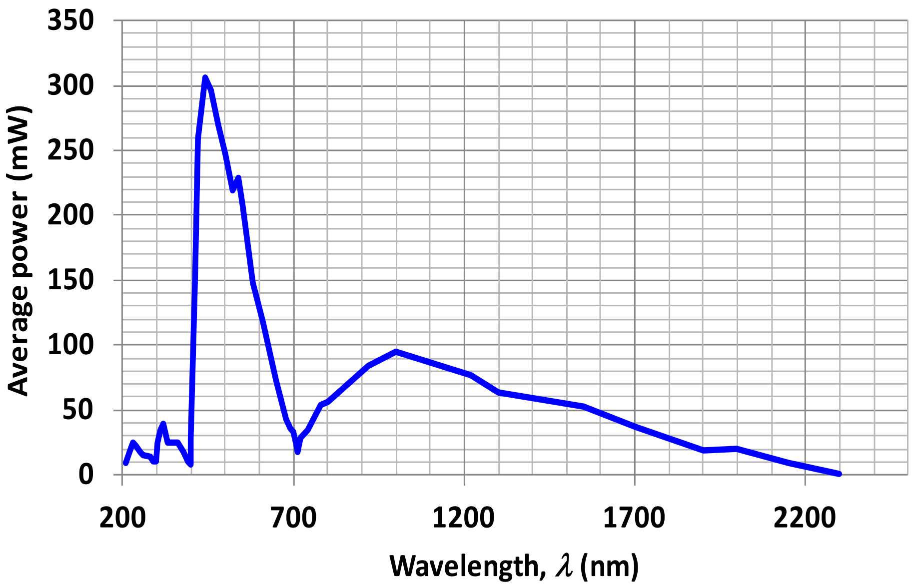
New photometer



- Scanning interval = 0.1 nm.
- Enables high accuracy tunable laser-based calibration.

Tunable laser based calibration facility

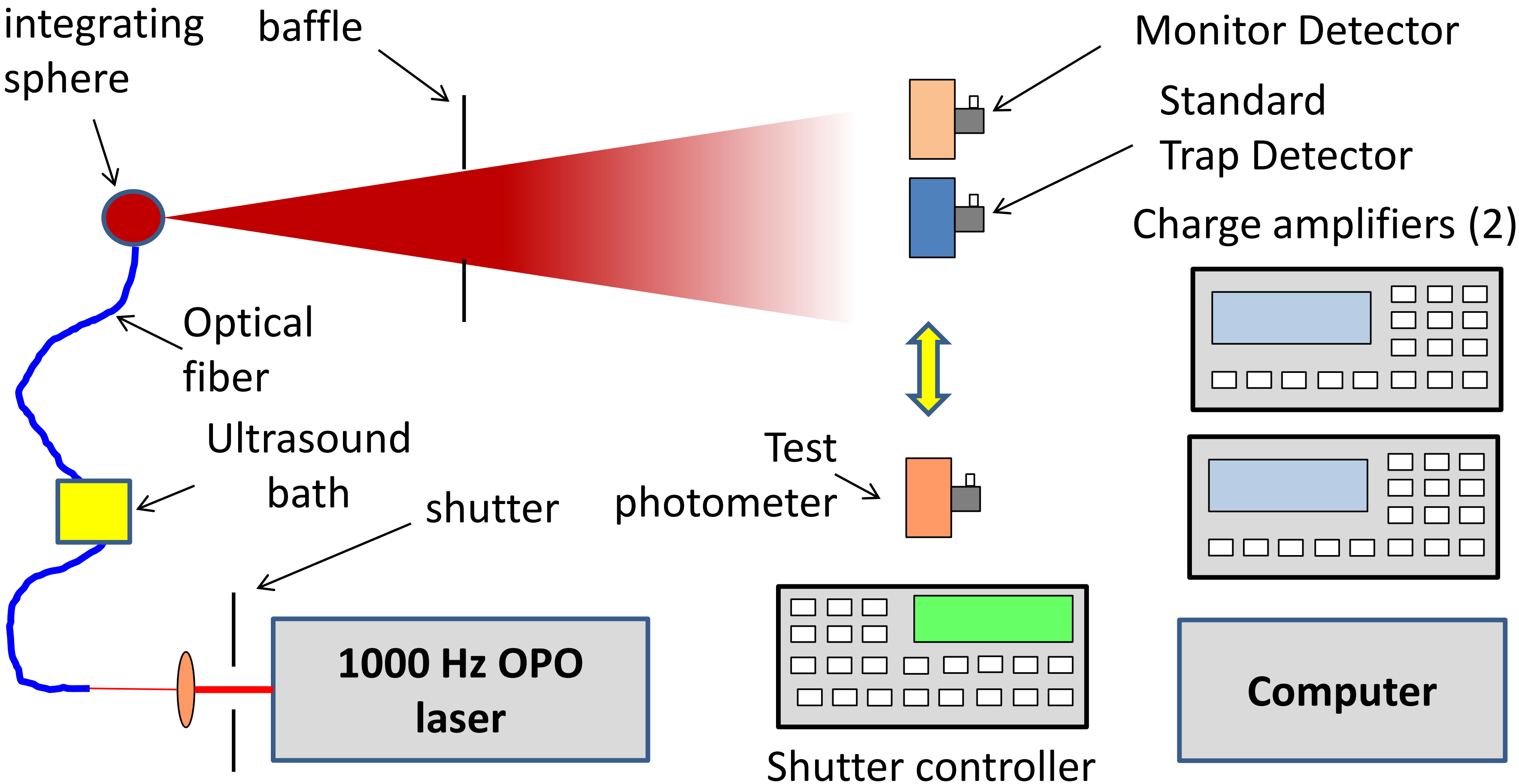




- OPO
- 210 nm - 2400 nm tunable range
- 1 kHz repetition rate
- 5 ns pulse width
- ≈ 0.2 nm in visible range

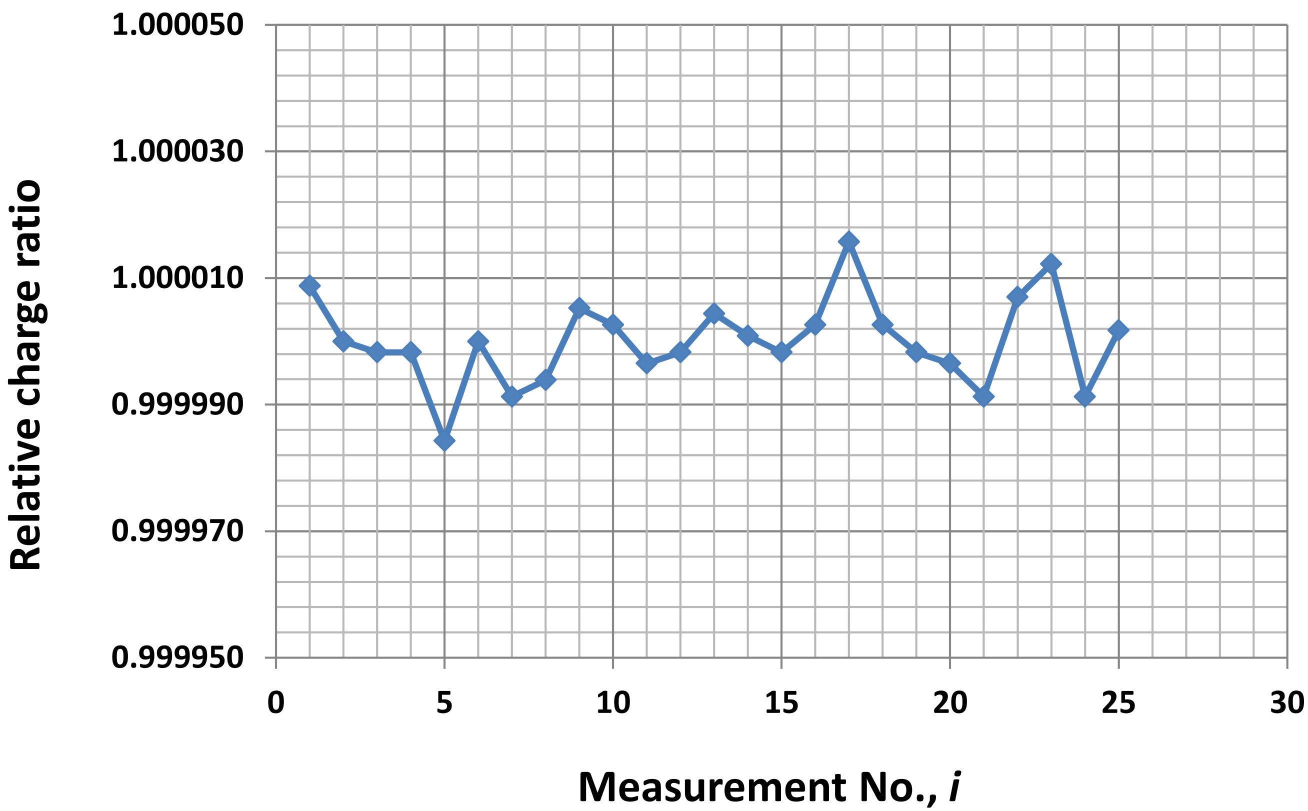
- Extremely low duty cycle (10^{-5})
- Large pulse-to-pulse variation and difficult to stabilize

Schematic for photometer calibration



- Use energy mode (dose) instead of power mode.
- Use charge amplifiers instead of trans-impedance amplifiers.
- All 3 dominant uncertainties are minimized; wavelength (<0.01 nm), aperture position (<0.01 mm), and beam geometry (underfilled/power mode vs overfilled/irrad. mode).

Measurement repeatability



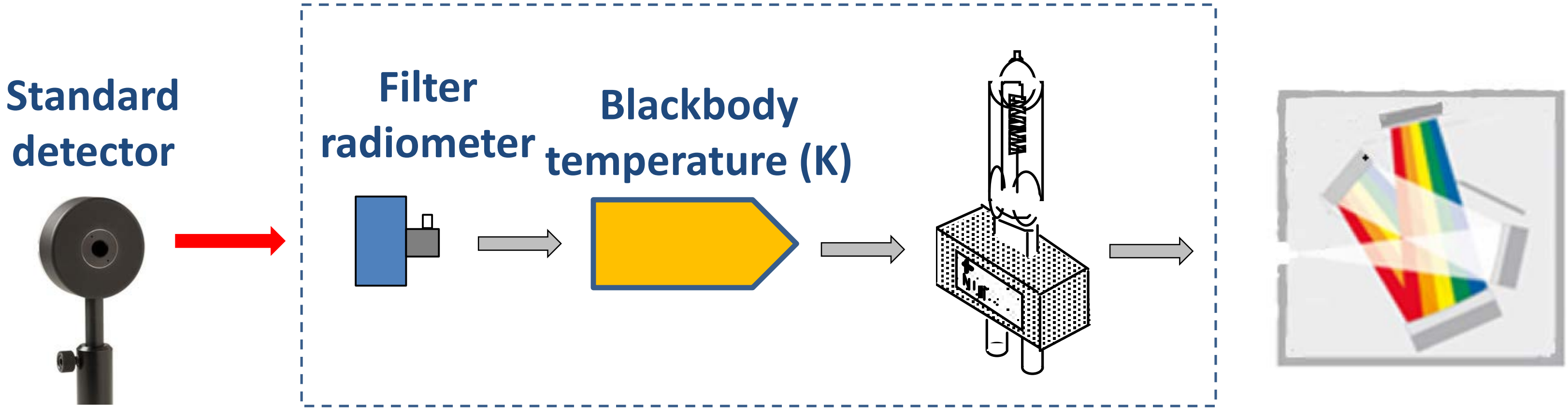
- Excellent repeatability ≈ ±**10** ppm!
- Fluctuation of the pulsed laser (≈ 20 %) does not matter

Uncertainty budget for spectral irrad responsivity

		Standard relative uncertainty (%) at selected wavelength, λ (nm)									
Uncertainty component	Type	380	400	450	500	555	600	650	700	750	780
1. Spectral irradiance responsivity standard		**0.220**	**0.170**	**0.121**	**0.042**	**0.042**	**0.042**	**0.042**	**0.043**	**0.045**	**0.048**
Uncertainty of the spectral power responsivity of the trap detector	B	0.220	0.170	0.120	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Precision aperture area of the trap detector	B	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Back reflection of the trap precision aperture	B	0.010	0.010	0.010	0.010	0.010	0.010	0.012	0.015	0.020	0.025
2. Calibration of the photometer using pulsed OPO		**0.111**	**0.090**	**0.074**	**0.076**	**0.074**	**0.075**	**0.075**	**0.206**	**1.225**	**23.197**
Trap detector aperture reference plane (10 microns)	A	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Trap detector position	A	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Trap detector angle	A	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Trap detector non-linearity vs the pulsed OPO	B	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Ambient temperature of the trap detector (S1337-1010BQ, ±1 °C)	A	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Transfer from the trap detector to monitor detector	A	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Ambient temperature of the monitor detector (S2281, ±1 °C)	A	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Photometer aperture reference plane (10 microns)	A	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Photometer position	A	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Photometer angle	A	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Photometer non-linearity vs the pulsed OPO	B	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Temperature of the photometer (temperature-controlled, ±0.1 °C)	A	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
OPO sphere source irradiance non-uniformity (the same aperture size)	B	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
OPO wavelength error (0.01 nm)	A	0.000	0.000	0.002	0.015	0.000	0.013	0.006	0.000	0.000	0.000
Scattered light	B	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Electrometer charge amplifier range-to-range gain variation	B	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Measurement repeatability (due to random noise and dark-charge substraction)	A	0.086	0.056	0.022	0.022	0.021	0.021	0.025	0.194	1.223	23.20
3. Long-term stability of the photometer (one year)	A	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**	**0.050**
Combined uncertainty (%)		0.25	0.20	0.15	0.10	0.10	0.10	0.10	0.22	1.23	23.20
Expanded uncertainty (*k* =2) (%)		**0.50**	**0.40**	**0.30**	**0.20**	**0.20**	**0.20**	**0.20**	**0.43**	**2.45**	**46.39**

Expanded Irradiance/Illuminance responsivity uncertainty for 1 year = 0.20 % (*k*=2)

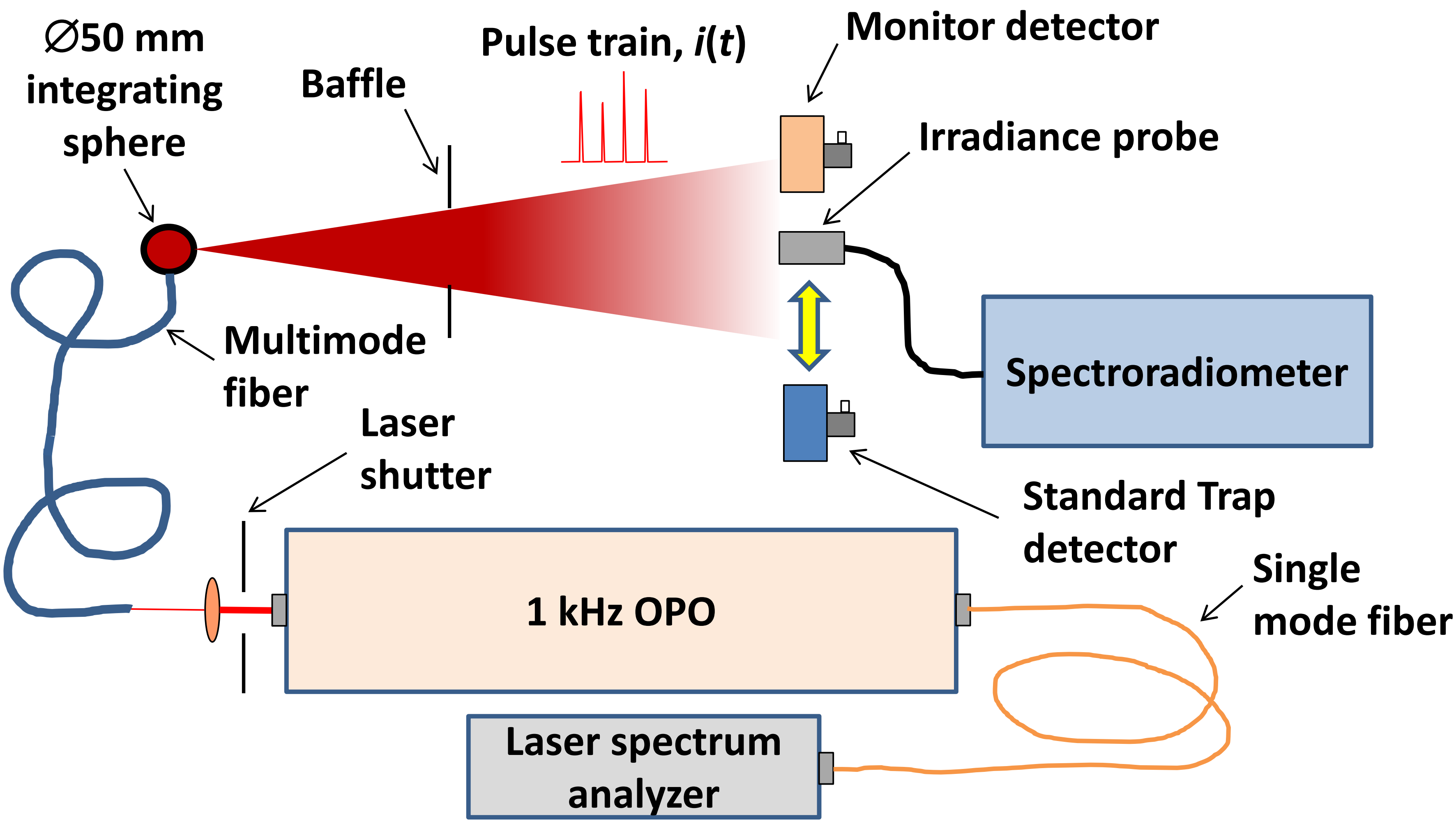
Calibration of spectroradiometers



Conventional lamp-based method; long calibration chain
Uncertainty (≥ 1 %)

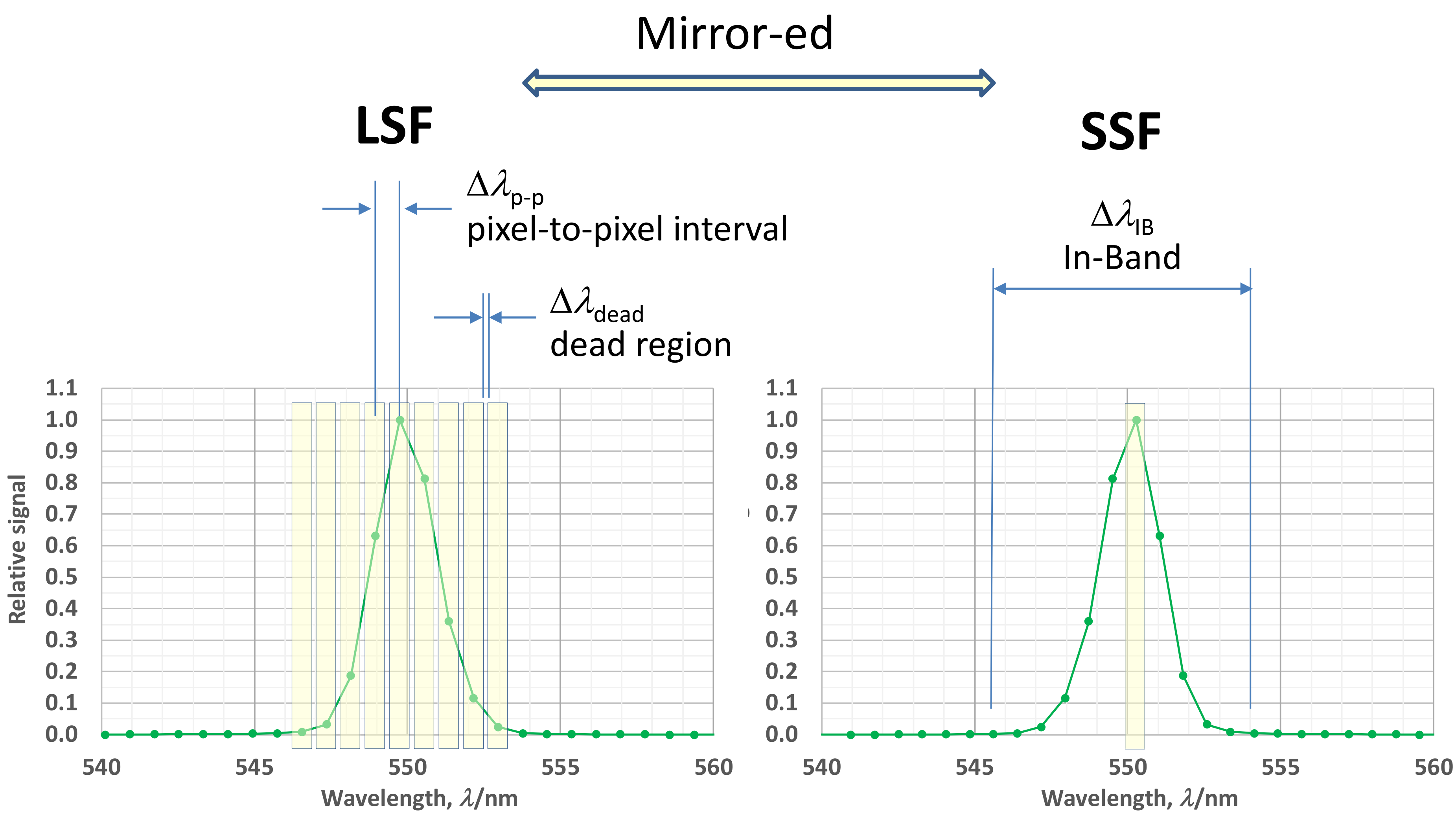
New detector-based method (0.2 %); enables a new independent way to realize spectral irradiance/radiance scales on spectroradiometers.

Schematic for calibration of spectroradiometers

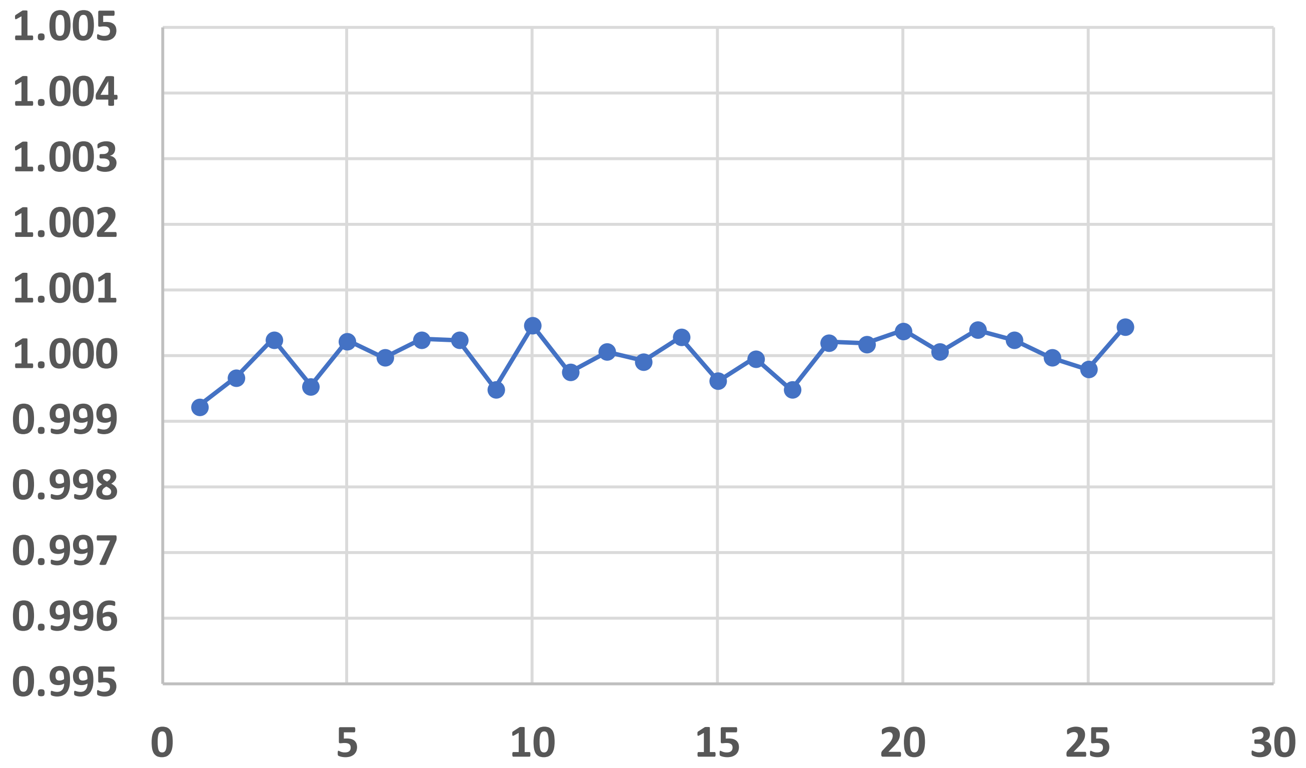


- Use energy mode (dose) instead of power mode.
- Use charge amplifiers instead of trans-impedance amplifiers.

Line Spread Function (LSF) and Slit Scattering Function (SSF)



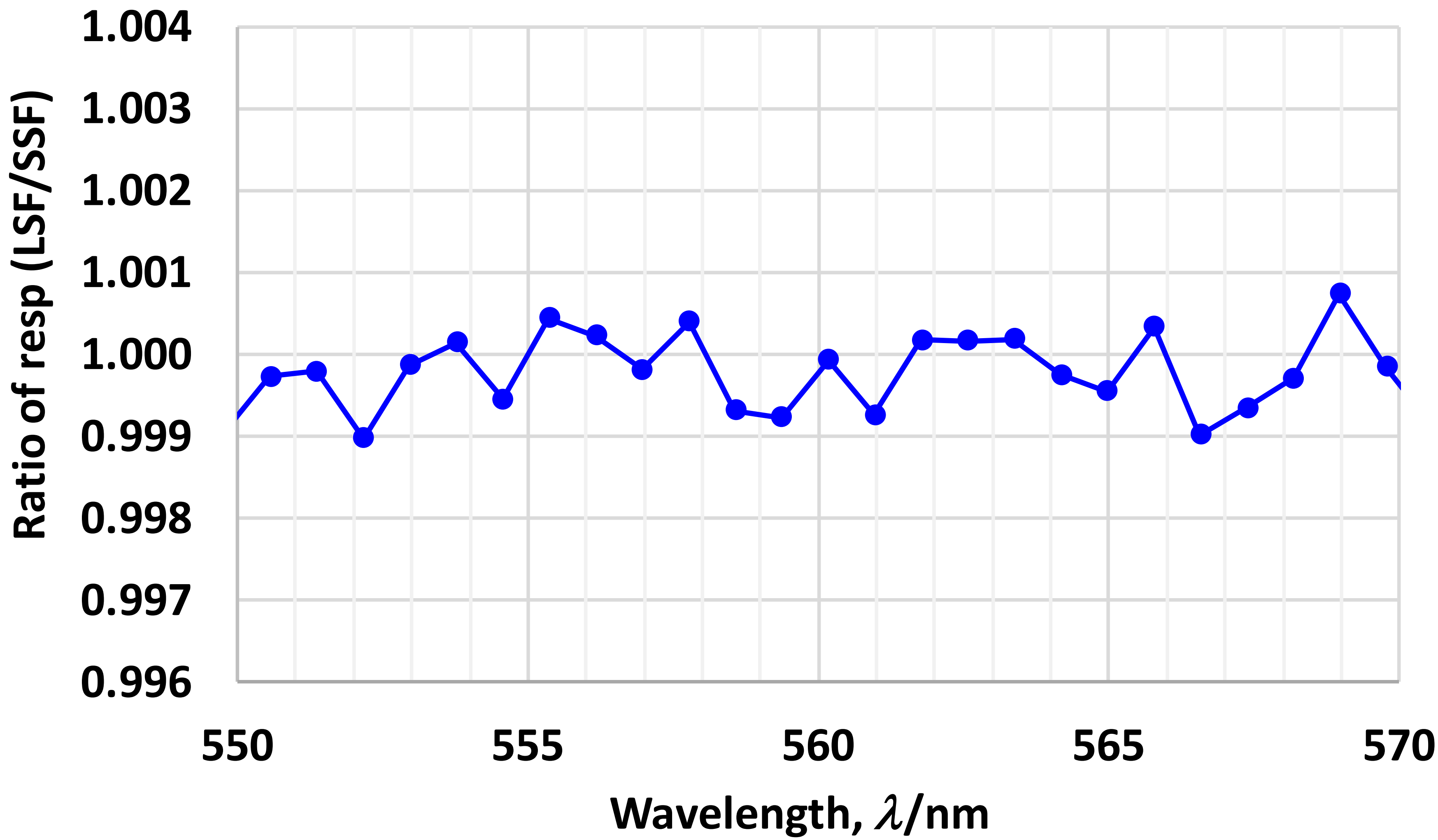
Measurement repeatability between spectroradiometer and Si monitor detector



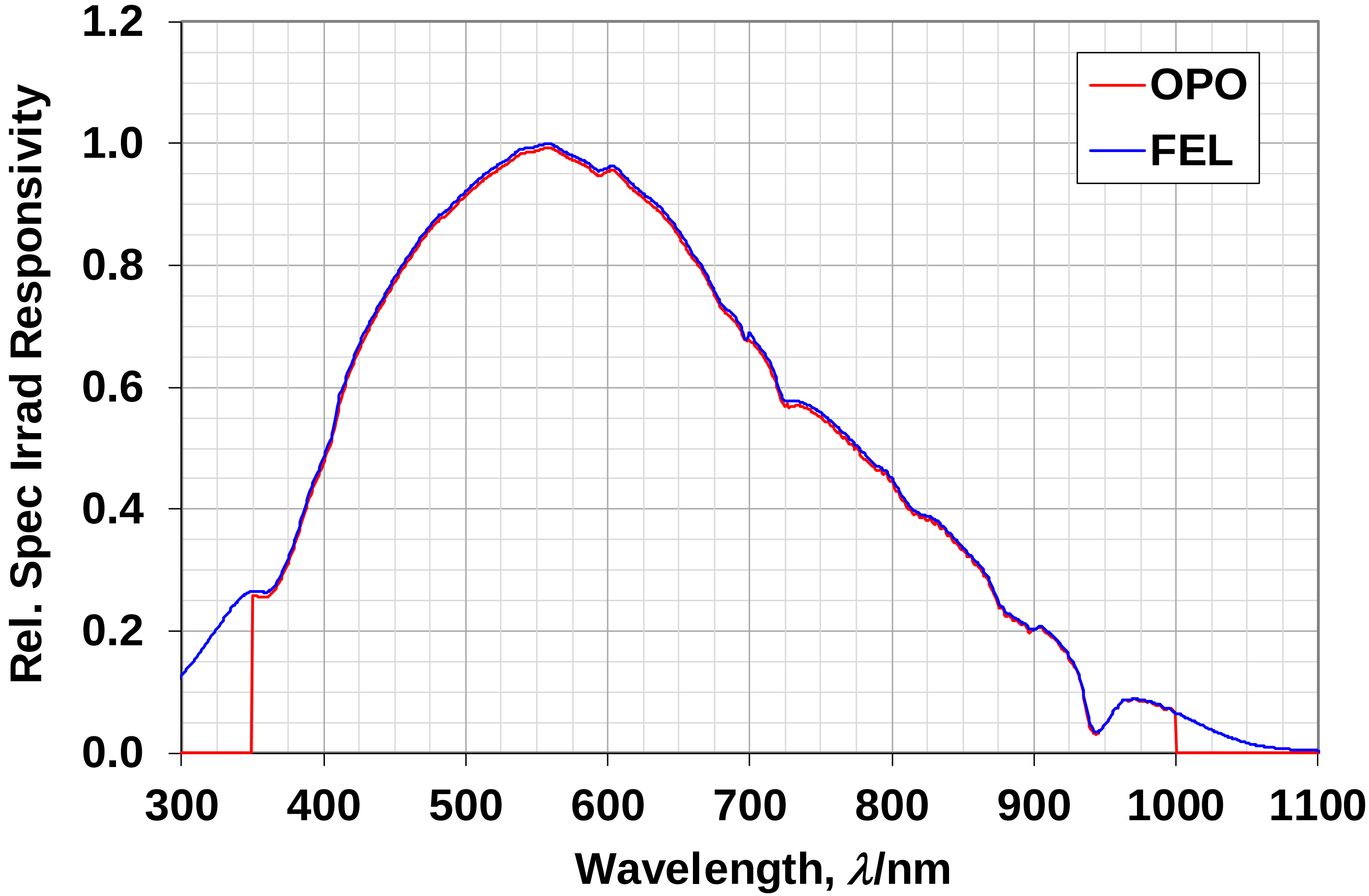
- Ratio of total spectroradiometer signal to Si monitor signal
- 5 (s) integration time for each point

Comparison of LSF method and SSF method

(SSF method uses 0.1 nm step scan)

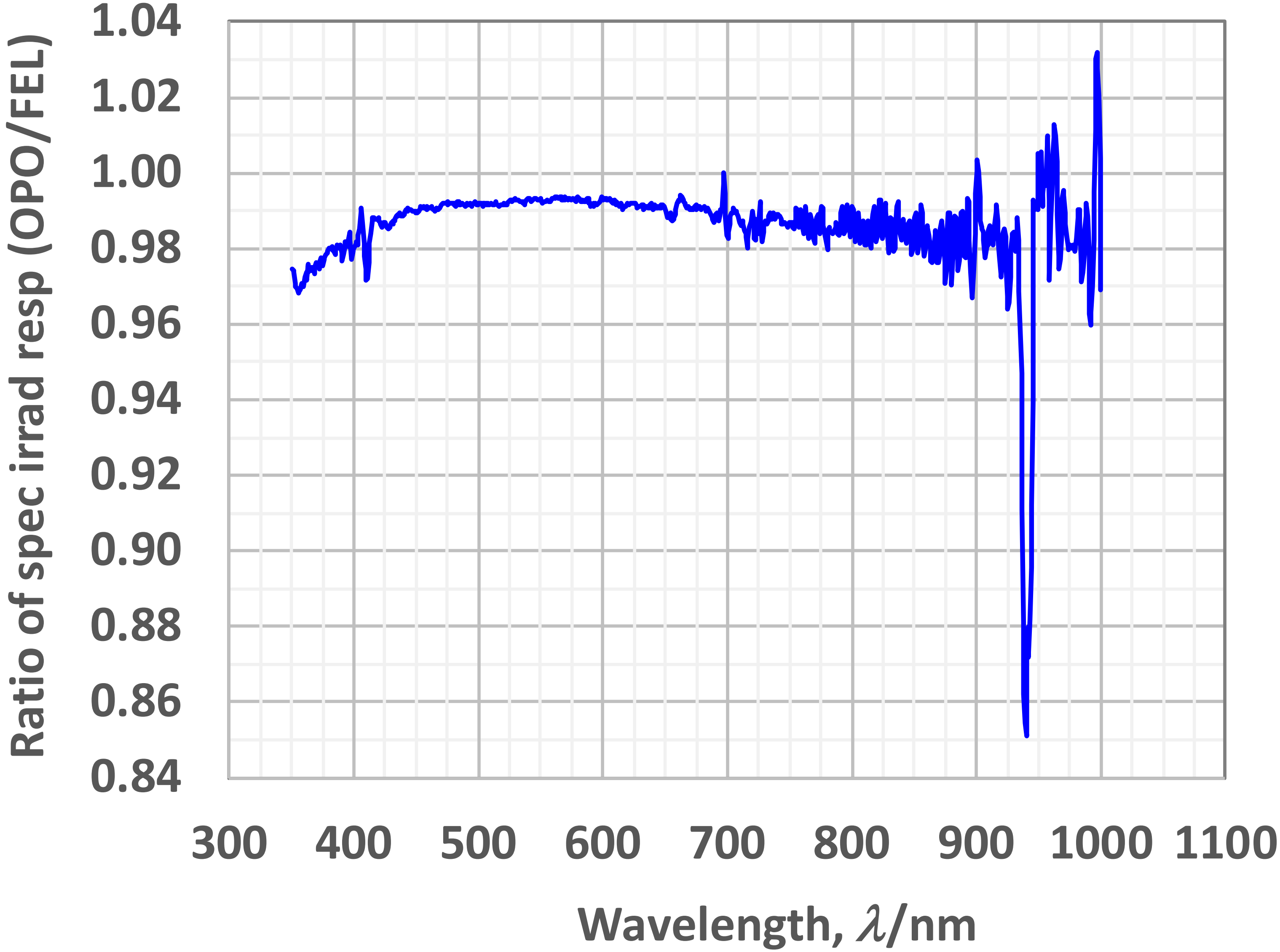


Comparison of spectral irradiance responsivities



OPO scans at 1 nm wavelength step from 300 nm to 1100 nm

Comparison of spectral irradiance responsivities



Summary

- A new photometry bench has been developed at NIST and the uncertainties of illuminance responsivity and luminous intensity scales are significantly reduced to the level of 0.2 % (k=2).
- A tunable-laser based calibration facility is established that is capable of performing calibrations for photometers and spectroradiometers with small uncertainties.

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NIST Plant Division

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Thank you

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