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, $\Delta d = 50 \times 10^{-6}$ m, with a source stage and sensor stage
1.5 m long travel sources stage for FEL lamp, LED, flashing light, integrating sphere, tunable laser, even a goniophotometer.
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

- 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
- \( \approx 0.2 \) nm in visible range

- Extremely low duty cycle \((10^{-5})\)
- Large pulse-to-pulse variation and difficult to stabilize
- 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).
- Excellent repeatability $\approx \pm 10$ ppm!
- Fluctuation of the pulsed laser ($\approx 20\%$) does not matter
## Uncertainty budget for spectral irradiance responsivity

### 1. Spectral irradiance responsivity standard

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Type</th>
<th>380</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>555</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral irradiance responsivity standard</td>
<td></td>
<td>0.220</td>
<td>0.170</td>
<td>0.121</td>
<td>0.042</td>
<td>0.042</td>
<td>0.042</td>
<td>0.042</td>
<td>0.043</td>
<td>0.045</td>
<td>0.048</td>
</tr>
<tr>
<td>Uncertainty of the spectral power responsivity of the trap detector</td>
<td>B</td>
<td>0.220</td>
<td>0.170</td>
<td>0.120</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>Precision aperture area of the trap detector</td>
<td>B</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
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</tr>
<tr>
<td>Back reflection of the trap precision aperture</td>
<td>B</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td>0.012</td>
<td>0.012</td>
<td>0.015</td>
<td>0.020</td>
<td>0.025</td>
</tr>
</tbody>
</table>

### 2. Calibration of the photometer using pulsed OPO

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Type</th>
<th>380</th>
<th>400</th>
<th>450</th>
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<th>650</th>
<th>700</th>
<th>750</th>
<th>780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap detector aperture reference plane (10 microns)</td>
<td></td>
<td>0.111</td>
<td>0.090</td>
<td>0.074</td>
<td>0.076</td>
<td>0.074</td>
<td>0.075</td>
<td>0.075</td>
<td>0.206</td>
<td>1.225</td>
<td>23.197</td>
</tr>
<tr>
<td>Trap detector position</td>
<td></td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
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<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Trap detector angle</td>
<td></td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Trap detector angle vs the pulsed OPO</td>
<td></td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Ambient temperature of the trap detector (S1337-1010BQ, ±1 °C)</td>
<td>A</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Transfer from the trap detector to monitor detector</td>
<td>A</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>Ambient temperature of the monitor detector (S2281, ±1 °C)</td>
<td>A</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Photometer aperture reference plane (10 microns)</td>
<td>A</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Photometer position</td>
<td>A</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>Photometer angle</td>
<td>A</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
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<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Photometer non-linearity vs the pulsed OPO</td>
<td>B</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>OPO sphere source irradiance non-uniformity (the same aperture size)</td>
<td>B</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>OPO wavelength error (0.01 nm)</td>
<td>A</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>0.015</td>
<td>0.000</td>
<td>0.013</td>
<td>0.006</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Scattered light</td>
<td>B</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
</tr>
<tr>
<td>Electrometer charge amplifier range-to-range gain variation</td>
<td>B</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Measurement repeatability (due to random noise and dark-charge subtraction)</td>
<td>A</td>
<td>0.086</td>
<td>0.056</td>
<td>0.022</td>
<td>0.022</td>
<td>0.021</td>
<td>0.021</td>
<td>0.025</td>
<td>0.194</td>
<td>1.223</td>
<td>23.20</td>
</tr>
</tbody>
</table>

### 3. Long-term stability of the photometer (one year)

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Type</th>
<th>380</th>
<th>400</th>
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<th>750</th>
<th>780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty (%)</td>
<td></td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
</tr>
<tr>
<td>Combined uncertainty (%)</td>
<td></td>
<td>0.25</td>
<td>0.20</td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.22</td>
<td>1.23</td>
<td>23.20</td>
</tr>
<tr>
<td>Expanded uncertainty (k=2) (%)</td>
<td></td>
<td>0.50</td>
<td>0.40</td>
<td>0.30</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.43</td>
<td>2.45</td>
<td>46.39</td>
</tr>
</tbody>
</table>

**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)

LSF

\[ \Delta \lambda_{p-p} \]

pixel-to-pixel interval

\[ \Delta \lambda_{\text{dead}} \]

dead region

Mirror-ed

SSF

\[ \Delta \lambda_{\text{IB}} \]

In-Band
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

Ratio of spec irr rad resp (OPO/FEL)

Wavelength, $\lambda$/nm
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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