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

- Light source (Watt)
- Light source (Watt.m⁻²)

Detector

\[ i_o(\lambda) \text{ (Ampere)} \]

- Spectral POWER responsivity (Underfilled geometry) (Ampere/Watt)
- Spectral IRRADIANCE responsivity (Overfilled geometry) (Ampere/(Watt.m⁻²))

- 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

- **NIST POWER**
  - Cryogenic Radiometer
  - Power responsivity (0.01 %)

- **NIST SIRCUS facility**
  - Trap detectors
  - Irradiance responsivity (Ampere/(Watt.m⁻²))
  - (0.025 %)*

- **NIST SCF**
  - Trap detectors
  - Irradiance responsivity (Ampere/(Watt.m⁻²))
  - (0.025 %)*

- **NIST SCF**
  - Working std. photodiodes
  - Power responsivity (Ampere/Watt)
  - (0.20 %)*

* BEST expanded uncertainty (k=2)

**POWER**: primary optical watt radiometer

**SIRCUS**: Spectral irradiance and radiance responsivity calibrations using uniform sources

**SCF**: Spectral comparator facility

**Trap detector**: 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
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

\[ R_{\text{test}}(\lambda) = R_{\text{standard}}(\lambda) \times \frac{Q_{\text{test}}^M(\lambda)}{Q_{\text{standard}}^M(\lambda)} \]
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

After 50 mm sphere

After 5 m MM fiber

After 50 mm sphere
OPO spectra

Wavelength, $\lambda$ (nm)

Relative SPD

348 349 350 351 352
0 0.2 0.4 0.6 0.8 1 1.2

350 nm

1098 1099 1100 1101 1102
0 0.2 0.4 0.6 0.8 1 1.2

1100 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

\[ Q = \int_{0}^{T} i(t) dt = C \times V \]
Measurement timing

Electrometer’s synchronized charge measurement

start

Laser shutter

open

close

end
Measurement repeatability

- two Hamamatus S2281 silicon photodiodes (PD)
  - standard deviation = 7 ppm!
- one 3 silicon PD trap and one S2281 Si PD
  - standard deviation = 12 ppm!

1 s integration time for each point
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 $\approx 0.02\%$
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

<table>
<thead>
<tr>
<th>Uncertainty component</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference trap detector</td>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td>OPO wavelength (0.02 nm)</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Sphere source irradiance non-uniformity</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Detector reference plane</td>
<td></td>
<td>0.010</td>
</tr>
<tr>
<td>Detector non-linearity</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Transfer to test detector</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Electrometer (range to range gain error)</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Combined uncertainty (%)</td>
<td></td>
<td>0.025</td>
</tr>
<tr>
<td><strong>Expanded uncertainty (k=2) (%)</strong></td>
<td></td>
<td>0.05</td>
</tr>
</tbody>
</table>
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Stray light problem with spectrometers

Stray light is often the dominant source of error even 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

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

\[
\begin{bmatrix}
    d_{1,1} & d_{1,2} & \ldots & d_{1,n-1} & d_{1,n} \\
    d_{2,1} & d_{2,2} & \ldots & d_{2,n-1} & d_{2,n} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    d_{n,1} & d_{n,2} & \ldots & d_{n,n-1} & d_{n,n}
\end{bmatrix}
\]

\[
d_{i,j} = \frac{f_{\text{SLSF},i,j}}{\sum_{i \in \text{IB}} f_{\text{SLSF},i,j}}
\]

for $i \notin \text{IB}$

\[
d_{i,j} = 0
\]

for $i \in \text{IB}$

\[
Y_{\text{s_spec}} = D Y_{\text{IB}}
\]

\[
Y_{\text{meas}} = Y_{\text{IB}} + Y_{\text{s_spec}} = Y_{\text{IB}} + D Y_{\text{IB}}
\]

\[
= (I + D) Y_{\text{IB}} = A Y_{\text{IB}}
\]

\[
Y_{\text{IB}} = A^{-1} Y_{\text{meas}} = C Y_{\text{meas}}
\]

Correction of signals

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

Results of stray-light corrections

A Green LED

1 count

1 count

log

linear
Stray-light correction for measurement of UV LEDs

Reference:
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

A White Spot

A Black Spot

log

linear

Relative Value

Position (mm)

Relative Signal

Position (mm)

Measured Sig

Corrected Sig

Measured Sig

Corrected Sig
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)
  - ...
References


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