Radiometry & Few-Photon Metrology at the National Research Council of Canada

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Outline

- Optical radiation calibration chain
  - Primary optical radiant power facility
  - Spectral irradiance facility
- Few photon metrology
  - Traceable characterization of single-photon detectors and NRC quantum dot-based single-photon sources
Optical radiation calibration chain

Absolute Cryogenic Radiometer

Transfer Standard Radiometers

Filter Radiometers

Working Standard Radiometers

Detector Calibrations

Photometers

Luminous Intensity Standard

Primary Standard Source High Temperature Black Body

High Temperature Fixed Point Thermodynamic Measurements

FEL Lamp

SI Traceable

Photometry

Spectroradiometry

Radiometry
Optical radiant power scale

Absolute Cryogenic Radiometer

Transfer Standard Radiometers

Filter Radiometers

Primary Standard Source
High Temperature Black Body

FEL Lamp

High Temperature Fixed Point
Thermodynamic Measurements

Working Standard Radiometers

Detector Calibrations

Photometers

Luminous Intensity Standard

Photometry

Spectroradiometry

Radiometry

Photometers

Working Standard Radiometers

Detector Calibrations

Photometry

Spectroradiometry

Radiometry
Advanced radiometry facility

- New cryogenic radiometer with closed-cycle helium cryocooler
- Double-subtractive monochromator
- Custom-designed motion apparatus for optical alignment

Cryogenic radiometer uncertainty improvements

<table>
<thead>
<tr>
<th>Source</th>
<th>old (%)</th>
<th>new (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity absorptance</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Nonequivalence effects</td>
<td>0.01</td>
<td>0.001</td>
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</table>
Advanced radiometry facility

- Broadband laser-driven light source (LDLS) and tungsten lamp
- Linear stage with pin and pivot system facilitates alignment to the common optical path (30° motion)
- Gate valves between the bellows vacuum chamber and the transfer radiometer mounting ports allow for detectors to be changed during system operation
Transfer standard radiometers

- Single element detector with quartz window
- Vacuum compatible front face
- Temperature monitoring
- Si and PtSi detectors for VIS and UV wavelength ranges

Boivin, Metrologia 32 565 (1995)
Transfer standard radiometers

- Sphere radiometer design
- Small integrating sphere and three 5 mm diameter InGaAs detectors
- Improved spatial uniformity in NIR
- Vacuum compatible front face and temperature monitoring

Boivin, Metrologia 37 237 (2000)
Spectral responsivity scale

- Scale realization from 300 nm to 1000 nm using Si transfer standard detectors
- Presently working on scale from 900 nm to 1600 nm

Next step:
- UV scale from 200 nm to 400 nm

Average of uncertainty components from four Si transfer standard detectors
Spectral irradiance scale

Absolute Cryogenic Radiometer

Transfer Standard Radiometers

Photometers

Luminous Intensity Standard

Primary Standard Source
High Temperature Black Body

FEL Lamp

Filter Radiometers

High Temperature Fixed Point
Thermodynamic Measurements

Working Standard Radiometers

Detector Calibrations

Photometry

Spectroradiometry

Radiometry

SI Traceable
Spectral irradiance scale transition

Detector based scale 700 -1600 nm

Absolute Radiometer (room temp ESR)

Narrow-band filter

FEL Lamp
Spectral irradiance facility

- Source and detector based scale from 250 to 2500 nm
Spectral irradiance facility

» Temperature stability verification

- FEL Lamp
- HTBB
- Monochromator
- Linear Pyrometer
- HeNe Laser
- Filter Radiometer
- PMT, Si or InSb
- Radiometry and Few-Photon Metrology at the National Research Council of Canada
Spectral irradiance facility

First thermodynamic temperature measurement
Spectral irradiance facility

- High temperature black body spectrum measurement
Spectral irradiance facility

- Second thermodynamic temperature measurement
Spectral irradiance facility

- FEL lamp spectrum measurement
Spectral irradiance facility
Thermodynamic temperature measurement

- NRC wideband filter radiometer
- Calibrated using transfer radiometers and monochromator based apparatus

![Graph showing Responsivity (A/W) vs Wavelength (nm) with FWHM~100 nm](image)

![Diagram with labels: TE coolers, heat sink RTD, filter RTD, Large area Si photodiode, Glass optical filters, Cu heat sinks, detector RTD, AD590 temperature transducer](image)
Spectral irradiance facility

- HTBB temperature stability 0.1 K/h
- Monochromator wavelength accuracy ± 0.05 nm
- Lamp distance of 50 cm
- Uncertainty budget in progress
Optical radiation calibration chain

- SI Traceable
- Absolute Cryogenic Radiometer
- Transfer Standard Radiometers
  - Photometers
    - Luminous Intensity Standard
  - Filter Radiometers
    - Primary Standard Source (High Temperature Black Body)
    - FEL Lamp
  - Working Standard Radiometers (Single-photon detector calibrations)
- Photometry
- Spectroradiometry
- Radiometry

Radiometry and Few-Photon Metrology at the National Research Council of Canada
Project Goals:
- Single-photon detector efficiency measurements
  - Free space and fibre-coupled detectors
- Construction of superconducting nanowire single-photon detector system (NIST)
- Characterize single-photon sources (NRC)

Looking forward:
- Multi-particle quantum state measurements
Single-photon detector calibration capabilities → Free space Si SPADs

- Multiple filters are used to attenuate the input of a nano-joule laser beam to a level measurable by the single photon detector

Efficiency measurements by substitution method

![Efficiency measurement setup](image)

Detection efficiency vs. Photon counts (kHz)

![Graph](image)
Quantum dot single-photon source

- For quantum information applications - Dan Dalacu and Robin Williams at NRC

Self-assembled quantum dot

Site-controlled nanowires

Structure of QD embedded in nanowire

InAs quantum dots within InP nanowire
Presently no *standard* way to characterize source efficiency → what has been accounted for?

- Efficiency $\varepsilon$: probability of collecting a photon
- Brightness $\beta$: number of photons collected per pump excitation pulse
Few photon measurements

NRC quantum dot photon sources $\rightarrow$ photons for multiparticle entangled states

Higher-order entangled states - double or triple quantum dots in semiconductor nanowire

New single photon source measurement apparatus

Image: D. Dalacu
Thank you

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