Validations of detector-based radiometric calibrations using fixed-point blackbodies

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NIST
Outline

1. Thermodynamic radiometric temperatures of ITS-90 fixed-points
2. Development of transfer standard-quality radiation thermometers
3. Reduction of size-of-source effect (SSE) with novel optical designs and reduction of photocurrent measurement uncertainties
4. Use of fixed-points for validations of spectroradiometric scales
5. Proposal to NASA GSFC for validations of their facility
Fundamental Scales

Electrical Substitution Radiometry

Schwinger Equation

Planck Radiance

\[ P(E, R, \theta, \lambda) = \frac{4e^2 c R}{3\lambda^4} \gamma^{-4}(1 + \chi^2)^2 \left[ K_{2/3}^2(\xi) + \frac{\chi^2}{(1 + \chi^2)} K_{1/3}^2(\xi) \right] \]

\[ L_\lambda = \frac{c_1}{n^2 \lambda^5 \left( e^{c_2/n\lambda T} - 1 \right)} \]
International Temperature Scale of 1990 (ITS-90)

[Diagram showing temperature scale and fixed points with equations for S(To) and S(Ti)]
Thermodynamic temperatures

Ideal gas thermometry
• Constant-volume gas thermometry (< 900 K)
  \[ PV = nRT \]
• Acoustic gas thermometry (< 550 K)
  \[ kT = \left( \frac{m}{\gamma} \right) v^2 \]

Noise thermometry (< 1300 K)

Detector-based radiometry
• Total radiation thermometry (60 K to 400 K)
  \[ M(T) = n^2 \sigma T^4 \]
• Spectral radiation thermometry (1300 K to > 3000 K)
  \[ L(\lambda, T) = \frac{c_{1L}}{n^2 \lambda^5 \left( \exp \left( \frac{c_2}{n\lambda T} \right) - 1 \right)} \]
Current Differences $T - T_{90}$

- $T - T_{90}$
- $T$ / K
- $T_{90}$ / K
- Temperature / K

- Constant Volume Gas NBS 1989
- Radiation NPL 1991
- Radiation PTB 1996
- Radiation PTB 2002
- Acoustic Gas NIST 2002
- Constant Volume Gas NBS 1976
- R-JNT NIST 2006
Planck radiances of ITS-90 fixed points

Derivative of the Wien Approximation

\[ \frac{dL}{L} = \frac{c_2}{\lambda} \frac{\Delta T}{T^2} \]

For example, at Sn point uncertainty of 40 mK at 505 K at wavelength of 1600 nm leads to 0.17% in radiance.
Primary Radiometric Thermometry (MeP-K)

\[ L_{b,\lambda}(\lambda, T) = \left( \frac{2hc^2}{\lambda^5} \right) \frac{1}{\exp(hc/\lambda kT) - 1} \]

**Absolute primary radiometric thermometry**

All measurements of the quantities involved must be traceable to the corresponding units of the SI, in particular, the watt and the meter.

*Planck radiances have units of W/(cm^2 nm sr). Each of these units must be made traceable to their SI realizations.*
Detector-based temperature realization in SIRCUS

Diagram showing a laser, cryogenic electrical substitution radiometer, precision aperture, Si-trap detector, integrating sphere, and radiation thermometer.
Setup of the RT in NIST Integrating Sphere Facility (SIRCUS)

Radiation Thermometer

Integrating Sphere
SIRCUS spheres and their spatial uniformities (achieving 0.01 % transfer uncertainty ?)

- 25 mm
- 38 mm
- 305 mm
$\cos^4 \theta$ dependence for Lambertian sources

Lambertian source has irradiance out-of-plane dependence of

$$E(r) = E(d) \cos^4 \theta$$
Angular $\cos^4$ output of the NIST 308 mm diameter integrating sphere
Reproducibility of the SIRCUS calibrations

2 month SIRCUS calibration reproducibility of 0.02 %
Uncertainties in the SIRCUS calibrations

<table>
<thead>
<tr>
<th>SIRCUS Uncertainty Components ((k = 1))</th>
<th>Type</th>
<th>[ % ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Trap responsivity</td>
<td>A</td>
<td>0.025</td>
</tr>
<tr>
<td>2 Aperture Area</td>
<td>A</td>
<td>0.004</td>
</tr>
<tr>
<td>3 Distance</td>
<td>B</td>
<td>0.01</td>
</tr>
<tr>
<td>4 Sphere Spatial and Angular Uniformity</td>
<td>B</td>
<td>0.025</td>
</tr>
<tr>
<td>5 Amplifier gain</td>
<td>B</td>
<td>0.005</td>
</tr>
<tr>
<td>6 Temperature coefficient of Trap</td>
<td>B</td>
<td>0.002</td>
</tr>
<tr>
<td>7 Temporal Stability of Trap</td>
<td>B</td>
<td>0.013</td>
</tr>
<tr>
<td>Combined Standard Uncertainty ((k = 1))</td>
<td></td>
<td>0.040</td>
</tr>
<tr>
<td>Expanded Uncertainty ((k = 2))</td>
<td></td>
<td>0.080</td>
</tr>
</tbody>
</table>

Each of these uncertainty components should be experimentally determined and validated.
1. Use of graphite-epoxy rods (structural stability TCE < -0.5 ppm/K)
2. Use of a Lyot stop to reduce SSE
3. Development of calibration scheme for integrated preamplifier (low noise at low photocurrents)
Internal view of radiation thermometer: chassis of graphite-epoxy rods
Effect of the Lyot stop

![Graph showing the effect of the Lyot stop on SSE σ(d, 2 mm) vs. Source Diameter (d) [mm].]
## Current Measuring Electrometers or Preamps Accuracy (%)

### Comparison of Current Measurement Capability

<table>
<thead>
<tr>
<th>Expanded Uncertainties [%]</th>
<th>1.00E-10</th>
<th>1.00E-09</th>
<th>1.00E-08</th>
<th>1.00E-07</th>
<th>1.00E-06</th>
<th>1.00E-05</th>
<th>1.00E-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanford SR570</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Keithley/428</td>
<td>2.5</td>
<td>2.5</td>
<td>1.4</td>
<td>0.5</td>
<td>0.34</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Keithley/6517</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Keithley/6487</td>
<td>0.3</td>
<td>0.2</td>
<td>0.15</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Keithley/6485</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.15</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Keithley/2400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.035</td>
<td>0.033</td>
<td>0.031</td>
</tr>
<tr>
<td>Keithley/6430</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Keithley/263</td>
<td>0.25</td>
<td>0.065</td>
<td>0.065</td>
<td>0.035</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>NIST SDX</td>
<td>0.006</td>
<td>0.004</td>
<td>0.0022</td>
<td>0.0015</td>
<td>0.0013</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

- Current Measuring Electrometers or Preamps Accuracy (%)
Metal-fixed point furnace and cells
Detector-based radiance responsivity

\[ i_c = \int S_L \cdot L(\lambda, T) d\lambda \]
Calculated photocurrents vs. temperature

\[ i_c = \int S_L \cdot L(\lambda, T) d\lambda \]
Representative signals versus time: Co-C
Summary of Au point measurement in 2003

- **May 15, 2003**: 1337.344 K
- **May 23, 2003**: 1337.33 K
- **May 28, 2003**: 1337.344 K

**NIST**: 1337.344 K

**ITS-90**: 1337.33 K

Sequence Number
What are the current uncertainties at NIST for detector-based calibrations with 1 year use?

<table>
<thead>
<tr>
<th>Uncertainty Component</th>
<th>[ % ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Spectral Radiance Responsivity</td>
<td>0.040</td>
</tr>
<tr>
<td>2 Temporal Stability of Responsivity</td>
<td>0.050</td>
</tr>
<tr>
<td>3 Plateau Identification</td>
<td>0.005</td>
</tr>
<tr>
<td>4 Emissivity</td>
<td>0.010</td>
</tr>
<tr>
<td>5 Preamplifier Gain</td>
<td>0.025</td>
</tr>
<tr>
<td>6 Dark current drift</td>
<td>0.015</td>
</tr>
<tr>
<td>7 Size-of-source effect</td>
<td>0.010</td>
</tr>
<tr>
<td>Total Uncertainty in Signal</td>
<td>0.072</td>
</tr>
<tr>
<td>Expanded Uncertainty (k =2)</td>
<td>0.144</td>
</tr>
<tr>
<td>Temperature Uncertainty [ K ] (k =2)</td>
<td>0.116</td>
</tr>
</tbody>
</table>
Conclusion

1. Thermodynamic temperature measurements for non-contact thermometry are being performed at many NMIs.

2. NIST was/is leading the effort by developing new radiometric techniques and radiometer designs.

3. Measurements of thermodynamic temperatures of ITS-90 fixed points are extremely demanding tests of laser-based radiometric calibration facilities.