Validation of NIST’s Low Temperature Infrared Spectral Radiance Scale

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CALCON
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I. Introduction

II. NIST IR Radiance Temperature (IRT) Calibration

Instrumentation

III. Derivation of the IR Spectral Radiance T Scale

IV. Validation of the IRT Scale
Key Instrumentation for Scale Realization

• Measurement Facilities and Systems
  1. **AIRI**: Advanced Infrared Radiometry and Imaging Facility
  2. **ISEMS**: Infrared Spectral Emittance Measurement System
  3. **FTIS**: Fourier Transform Infrared Spectrophotometry Facility
  4. **LIR**: Laser Infrared Reflectometry Facility

• Instrumentation
  A. **TFC**: Tunable Filter Comparator (AIRI)
  B. **IRIS**: Infrared Reference Integrating Sphere (FTIS) **
  C. **IGRT**: Infrared Gonio Reflectometer-Transmissometer (FTIS) **
  D. **CHILR**: Complete Hemispherical Laser-based Reflectometer (LIR)
  E. **ILGRI**: Infrared Laser-based Gonio-Reflectometer Instrument (LIR) **

• Blackbody Sources
  I. **GFPBB**: Gallium Fixed Point Blackbody (AIRI)
  II. **AHPBB**: Ammonia Heat Pipe Blackbody (AIRI & ISEMS)
  III. **WBBB**: Water Bath Blackbody (AIRI)
  IV. **LTBBB**: Low Temperature Ethanol Bath Blackbody (Customer, ISEMS)

  ** Not Described in Detail
Thermal IR Spectral Radiance Scale Realization and Validation

**CAVITY EMISSIVITY MEASUREMENT VIA REFLECTOMETRY**

- Assumptions:
  - T distribution is uniform
  - Measurement geometry is identical to used in the sensor

- Facility: CHILR
- Method: Laser Reflectometer

**CAVITY EFFECTIVE EMISSIVITY MODELING**

- Assumptions:
  - T distribution is CORRECTLY MODELED
  - Coating is uniform

- Software: STEEP3
- Input Property Required: BB Coating Emittance
- Facility: FTIS (Reflectance), ISEMS (Emittance)
- Method: Indirect - Hemispherical Reflectance, Direct - Radiance Comparison

**Planck Equation**

\[ L_{bb}(\lambda) = \varepsilon(\lambda) \cdot \frac{c_1 T^4}{n^2 \lambda^5} \cdot \frac{1}{\exp\left(c_2/(n^4 T^4)\right) - 1} \]

**Scale Validation**
1. National Primary Standard of Radiance Temperature (below 1100 °C) and IR Spectral Radiance

Advanced Infrared Radiometry and Imaging (AIRI) Laboratory: providing national level traceability for measurements of absolute spectral radiance and spectral emissivity of blackbody sources and targets at near-ambient temperatures and ambient environments.
1. Thermal IR Scales – Realization below 250 °C

IR Spectral Radiance and Radiance Temperature Scales Realization

Fixed Temperature Point (Phase Transition) Reference Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Temperature Range</th>
<th>Cavity Emissivity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury (FP BB)</td>
<td>-38.834°C to 8°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Water (FP BB)</td>
<td>0.01°C to 8°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Gallium (FP BB)</td>
<td>29.765°C to 8°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Indium (FP BB)</td>
<td>145.599°C to 8°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Tin (FP BB)</td>
<td>231.928°C to 8°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
</tbody>
</table>

Variable Temperature Reference Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Temperature Range</th>
<th>Cavity Emissivity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia (Heat Pipe BB)</td>
<td>-50°C to +50°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Water (Bath BB)</td>
<td>10°C to 75°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
<tr>
<td>Water (Heat Pipe BB)</td>
<td>55°C to 250°C</td>
<td>Measured/Calculated</td>
<td></td>
</tr>
</tbody>
</table>

Spectral Radiance and Temperature Comparisons

Transfer Standard Blackbodies (Customer)

Secondary Standard BB
0 to +150°C

T Controlled High Emissivity Background Plate

NIST TFC Comparator
2.5 to 12.5 mm
-50°C to 250°C

NIST InGaAs Pyrometer
1.5 mm
125°C to 250°C

NIST InSb Pyrometer
4.9 mm,
-50°C to 150°C
2. Infrared Spectral Emittance Measurement System

ISEMS Component Setup

- FT Based Based Spectral Radiance Comparator (includes Near IR Sphere)
- Purge, polarization; $\lambda$ range: 1 µm to $\geq$ 50 µm; $T$ range: 100 °C to 900 °C
- Designed for materials characterization – easily modified for blackbody calibration
- Replace sample holder with T-controlled background “Scene Plate” -> lower $T$ capability
3. Fourier Transform Infrared Spectrophotometry Facility: Reflectance and Transmittance

Infrared Gonio Reflectometer Transmissometer (IGRT)

Infrared Reference Integrating Sphere (IRIS)
A. Tunable Filter Comparator TFC (AIRI)

\[ L_{uut}(\lambda) = \left[ \frac{V_{uut}(\lambda) - V_A(\lambda)}{V_C(\lambda) - V_A(\lambda)} \right] \left[ L_C(\lambda) - L_A(\lambda) \right] + L_A(\lambda) \]

Measured spectra  
Known Spectral Radiiances of Ambient and Variable Temperature Reference BB’s

TFC has capacity to consistently measure temperature with standard deviation from 5 mK to 25 mK in the range -50 °C to 250 °C across spectral regions to 3 µm - 5 µm and 8 µm - 12.5 µm.

Example of CVF Filter Transmittance for several angles. Measured at NIST using FTIR Spectrometer

Example of CVF Filter Transmittance for several angles. Measured at NIST using FTIR Spectrometer

Spectral Resolution

Spatial Scatter

3.7 microns, InSb, relative 12 mm diameter source, source 50 °C, background 23 °C
D. Complete Hemispherical Laser-Based Reflectometer (LIR)

- **CHILR** setup designed especially for cavity emissivity determination
- Also good for very black samples
- Can measure spatial variation & angle dependence
- Entrance port 1/2 angle = 1°
- CO₂, diode, and OPO tunable laser sources
- Can measure down to approx. 10⁻⁵ (equiv to emissivity 0.99999)
Spectral Radiance Scale Realization Validation Chain

- ITS-90 via comparison to Fixed Point Blackbody Source(s), Platinum Resistance Thermometers (PRT) & Planck’s Law.

- Steps:
  1. Tunable Filter Comparator at AIRI compares Water Bath BB with Gallium FPBB at 29.765 °C.
  2. TFC & FTIR at AIRI compare Ammonia HPBB with Water Bath BB at 11 °C to 30 °C.
  3. Fourier Transform Spectrometer in ISEMS compares Low Temp Ethanol BBB to Ammonia HPBB from -45 °C to 25 °C.

- Reference PRTs used in all blackbody sources, including many UUTs

- Effective emissivities from measurements (CHILR) and/or modeling (STEEP3) using measured optical properties of cavity coatings are needed.
Effective Emissivities of Blackbodies Employed

<table>
<thead>
<tr>
<th>Blackbody Type</th>
<th>Nominal Temperature Range, °C</th>
<th>Emissivity calculated (10.6 μm)</th>
<th>Emissivity measured (10.6 μm)</th>
<th>Cavity Coating</th>
<th>Cavity Aperture, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia Heat Pipe</td>
<td>- 45 to 25</td>
<td>0.99994</td>
<td>-</td>
<td>Nextel Velvet Black</td>
<td>30</td>
</tr>
<tr>
<td>Water Bath</td>
<td>10 to 75</td>
<td>0.99997</td>
<td>0.99993</td>
<td>Testers Black</td>
<td>50</td>
</tr>
<tr>
<td>Ga Fixed Point</td>
<td>29.765</td>
<td>0.99992</td>
<td>0.99995</td>
<td>Z-302</td>
<td>43</td>
</tr>
</tbody>
</table>

- Measured results from CHILR instrument
- Calculated results from modeling (STEEP3) using coating reflectance measurements (specular, diffuse, and BRDF)
- LTBBB cavity geometry and coating specified identical to those of the WBBB
- Similar comparisons performed on numerous other blackbodies
I. Ga Fixed Point Blackbody Design
III. Water Bath Reference BB

- Converted from Oil Bath BB with new cone with a few design improvements
- CHILR Measurements of effective emissivity
- Currently serves as Primary Standard at the Temperature Range $10 \, ^\circ{C}$ to $75 \, ^\circ{C}$
- Stability < 2 mK
Step 1. TFC Comparison of WBBB and Ga Fixed Point (AIRI)

- ITS-90 Ga FP temperature 29.765 °C; $\varepsilon = 0.99995 \Rightarrow 3$ mK

- Spectral radiance against WBBB within ±10 mK across range
II. Ammonia Heat Pipe Blackbody

Gas heat Exchanger
Reference PRT
Micro-Ohm Meter
Refrigerated Circulating Bath, -50 °C to +55 °C

Blackbody Design
Cavity geometry
Step 2A. TFC Comparison of Ammonia HPBB to WBBB (AIRI)

TFC Random Uncertainty Evaluation
Using Auto-referencing of Ammonia BB @ -45.18°C and water bath @ 11°C

Measured Radiance Temperature of the Ammonia BB
Reference PRT Reading 30.06

Measured Radiance Temperature of the Ammonia BB
Reference PRT Reading 10.24°C

BB Ammonia Stability, PRT temperature
Step 2B. FTIR** Comparison of Ammonia HPBB against WBBB @ 15 °C (AIRI)

**Bruker IFS 66 temporarily installed on AIRI sensor calibration bench
Recent Production of Low Temperature Ethanol Bath

Blackbody (LTBBB)

- Supplied to Air Force Primary Standards Lab (AFPSL) via AFMETCAL funding.
- Produced by Fluke to NIST specifications and consultation.
- Followed proven design of NIST water bath BB.
- Temperature range: - 50 °C to + 25 °C
- Designed for operation in ambient conditions
- Additional improvements (hardware, software and operating procedures) developed after delivery and testing at NIST.
- Delivered to AFPSL after calibration
- Performance equivalent to Ammonia HPBB
IV. Large Aperture Fluid Bath BB with Purge for Air Force (AFPSL)

- Integrated Design
- Air purge or vacuum (optional)
- 3” aperture, $\varepsilon = 0.9999$ (Fluke)
- -60 °C to +25 °C

A Clone of NIST Water Bath BB.
IV. Blackbody Detail

- Outer Insulation
- Removable Snout
- Tank Insulation
- Inner Mounting Flange
- Internal Aperture Holder
- Internal Coated Cavity
- Cooled Dry Air Purge
- Warm Dry Air Purge
- Dust Cover
Step 3. FTIR Compares Low Temp Ethanol Bath BB against AHPBB at 25 °C (ISEMS)

LTBBB model name “7Bath-32”
Step 3. FTIR Compares Low Temp Ethanol Bath BB against AHPBB at -45 °C (ISEMS)

**Calibration 7 Bath-32**

- **Tset**: -45°C, **Tref**: -44.980°C (3.5-5.4 mic.)
- **Trad**: -44.99°C, **StDev Average**: 0.22°C

- **Trad (4.4-5.4 mic)**: -44.98°C, **StDev Average**: 0.11°C
- **Trad (3.5-5 mic)**: -44.88°C, **StDev Average**: 1.2°C

**Calibration 7 Bath-32**

- **Tset**: -45°C, **Tref**: -44.980°C (8-14 mic.)
- **Trad**: -44.99°C, **StDev Average**: 0.22°C

**Physical Measurement Laboratory**
## Results Summary
(for band averages)

<table>
<thead>
<tr>
<th>T&lt;sub&gt;set&lt;/sub&gt; °C</th>
<th>T&lt;sub&gt;reference&lt;/sub&gt;</th>
<th>T&lt;sub&gt;rad&lt;/sub&gt; 8 – 14 µm</th>
<th>Expanded Uncertainty (k=2)</th>
<th>ΔT</th>
<th>T&lt;sub&gt;rad&lt;/sub&gt; 4.4 – 5.4 µm</th>
<th>Expanded Uncertainty (k=2)</th>
<th>ΔT</th>
<th>T&lt;sub&gt;rad&lt;/sub&gt; 3.5 – 5 µm</th>
<th>Expanded Uncertainty (k=2)</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25.03</td>
<td>25.02</td>
<td>0.02</td>
<td>-0.01</td>
<td>25.05</td>
<td>0.07</td>
<td>0.02</td>
<td>25.05</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>15.02</td>
<td>15.00</td>
<td>0.07</td>
<td>-0.02</td>
<td>15.02</td>
<td>0.03</td>
<td>-0.01</td>
<td>15.02</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.10</td>
<td>-0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.05</td>
<td>-0.01</td>
</tr>
<tr>
<td>-15</td>
<td>-14.98</td>
<td>-14.95</td>
<td>0.12</td>
<td>0.03</td>
<td>-14.98</td>
<td>0.03</td>
<td>0.00</td>
<td>-14.99</td>
<td>0.08</td>
<td>-0.01</td>
</tr>
<tr>
<td>-25</td>
<td>-24.98</td>
<td>-24.98</td>
<td>0.15</td>
<td>0.00</td>
<td>-25.02</td>
<td>0.10</td>
<td>-0.04</td>
<td>-25.02</td>
<td>0.85</td>
<td>-0.04</td>
</tr>
<tr>
<td>-35</td>
<td>-34.98</td>
<td>-34.97</td>
<td>0.17</td>
<td>0.01</td>
<td>-34.96</td>
<td>0.10</td>
<td>0.02</td>
<td>-34.94</td>
<td>0.87</td>
<td>0.04</td>
</tr>
<tr>
<td>-45</td>
<td>-44.98</td>
<td>-44.99</td>
<td>0.22</td>
<td>-0.01</td>
<td>-44.98</td>
<td>0.11</td>
<td>0.00</td>
<td>-44.88</td>
<td>1.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\[
\int_{\lambda_1}^{\lambda_2} L(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} P_l(\lambda, T) d\lambda
\]

\[
P_l(T, \lambda) = \frac{c_{1L}}{n^2 \cdot \lambda^5 \left(\exp\left(c_2 / (n \cdot \lambda \cdot T)\right) - 1\right)}
\]
Summary & Comments

- Multiple instruments and systems are used at NIST for defining its scale for infrared spectral radiance and radiance temperature.
- Overlap between these also provide opportunities for comparisons to evaluate and validating and uncertainty budgets.
- Recent calibration of a low temperature ethanol bath blackbody has helped to validate our infrared radiance temperature scale down to -45 °C.
- We will continue to pursue studies of error sources to improve uncertainty budgets.
Questions?
### Example UUT Uncertainty Budget with Ammonia HPBB Reference

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>-15° C</th>
<th>0° C</th>
<th>+15° C</th>
<th>-15° C</th>
<th>0° C</th>
<th>+15° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB Reference Temperature with Hart Scientific 1502</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>Reference BB Emissivity</td>
<td>0.012</td>
<td>0.013</td>
<td>0.024</td>
<td>0.023</td>
<td>0.026</td>
<td>0.029</td>
</tr>
<tr>
<td>Reference Long Term Stability</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Reference BB Measurement Noise</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Ambient Blackbody Temperature</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>UUT BB PRT Probe Red Out Temperature</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>UUT BB Measurement Noise</td>
<td>0.027</td>
<td>0.026</td>
<td>0.003</td>
<td>0.022</td>
<td>0.013</td>
<td>0.003</td>
</tr>
<tr>
<td>UUT BB Long Term Stability</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Combined Standard Uncertainty(k=1)</td>
<td>0.039</td>
<td>0.038</td>
<td>0.035</td>
<td>0.039</td>
<td>0.037</td>
<td>0.037</td>
</tr>
<tr>
<td>Combined Standard Uncertainty (k = 2)</td>
<td>0.077</td>
<td>0.076</td>
<td>0.069</td>
<td>0.079</td>
<td>0.074</td>
<td>0.074</td>
</tr>
</tbody>
</table>