Support for the IR Radiometry at NIST – Status Update

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2011 Workshop on Far-Infrared Remote Sensing
November 09, 2011 Madison WI
Newly (Oct. 01, 2011) Formed
NIST Sensor Science Division 685

- **Temperature and Humidity** (contact and radiation temperature above 960 C)
- Fluid Metrology
- **Optical Radiation** (collision induced absorption – Baranov/Lafferty)
- Infrared Technology
- Lighting and Color
- Laser Applications
- **Ultraviolet Radiation** (NIST Synchrotron Radiation source)
- **Pressure and Vacuum**
Introduction

NIST IR Spectrophotometry and Spectroradiometry Project
(PI Leonard Hanssen):

- IR Optical Properties of Materials
  - DHR, Variable angle DHR, Variable Angle Regular Transmittance and Reflectance, BRDF, Emittance

- IR Reflectometry of Blackbody and Absolute Radiometer Cavities
  - DHR with Laser and Thermal Sources

- IR Radiometry
  - Spectral Radiance and Radiance Temperature
Concept of Radiance Scale Realization and Transfer

**Thermal and Far 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

<table>
<thead>
<tr>
<th>Facility</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHILR (24 um)</td>
<td>Laser Reflectometer (QCL)</td>
</tr>
<tr>
<td>SFIRR</td>
<td>Laser or Synchrotron (PTB)</td>
</tr>
<tr>
<td>CBS3</td>
<td>Variable Background Reflectometer</td>
</tr>
</tbody>
</table>

**CAVITY TEMPERATURE DISTRIBUTION MODELING**

Calculation of cavity temperature distribution, including gradient from the sensor to the radiating service, using two- and three-dimensional heat transfer analysis

**CAVITY EFFECTIVE EMISSIVITY MODELING**

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

<table>
<thead>
<tr>
<th>Software</th>
<th>Input Property Required</th>
<th>Facility</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEEP3.15</td>
<td>BB Coating Emittance</td>
<td>SOC 100</td>
<td>Mirror reflectometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIST Emittance PTB</td>
<td>Direct</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIST FIRES</td>
<td>Black sphere reflectometer</td>
</tr>
</tbody>
</table>

**Step 1. Scale Realization**

Effective Emissivity

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

**Step 2. Scale Validation**

**CAVITY TEMPERATURE DISTRIBUTION MODELING**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Method: INTERNAL COMPARISONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST CBS3</td>
<td>- Comparison of BB with different geometry, coating and thermometry principles</td>
</tr>
<tr>
<td>NIST CBS3</td>
<td>- Varying aperture size and ambient background for one of two compared Bbs</td>
</tr>
<tr>
<td>PTB RBCF KRISS</td>
<td>- Comparison via Transfer Standard Blackbody Source</td>
</tr>
</tbody>
</table>

**Step 3. Scale Transfer**

The Spectral Radiance Transfer can be implemented in the following ways:

- COMPONENT LEVEL CALIBRATION:
  - Calibration at CBS3 of the IR Sensor on-board Internal Calibration Sources

- SYSTEM LEVEL CALIBRATION:
  - Calibration at CBS3 of the Transfer Standard Source, to be subsequently used for calibration of the complete sensor at the integrator facility
  - Deployment of the CBS3 primary BB at the integrator facility for direct sensor calibration
NIST Capabilities: Reflectance / Transmittance

\[ \rho(\nu, T_{Sample}) = \frac{V_{Sample}(\nu) - V^{FT-source-off}_{Sample}(\nu)}{V_{Sphere}(\nu) - V^{FT-source-off}_{Sphere}(\nu)} = 1 - \varepsilon(\nu, T_{Sample}) \]
New Equipment for Reflectometry Extension to 30 µm

QMC LHe Cryostat (TK1813)
Height 20 " x Dia 9 "
Mass: 20 Kg

Si:As BIB Detector (Trap)

New IR Sphere

Heavy Duty Rotation Stage

Relative Responsivity
NIST Capabilities: Emittance

200 °C to 900 °C: FT-Based Spectral Radiance Comparator (includes Near IR Sphere)

\[
L_{\text{Sample}}(\nu, T_{\text{Sample}}) = \text{Re} \left[ \frac{V_{\text{Sample}}(\nu) - V_{BB_{\text{Cold}}}(\nu)}{V_{BB_{\text{Hot}}}(\nu) - V_{BB_{\text{Cold}}}(\nu)} \right] \left[ L_{BB_{\text{Hot}}}(\nu) - L_{BB_{\text{Cold}}}(\nu) \right] + L_{BB_{\text{Hot}}}(\nu)
\]

and

\[
L_{\text{Sample}}(\nu, T_{\text{Sample}}) = \varepsilon_{\text{Sample}}(\nu, T_{\text{Sample}}) \cdot B(\nu, T_{\text{Sample}}) + \left[ 1 - \varepsilon_{\text{Sample}}(\nu, T_{\text{Sample}}) \right] \cdot B(\nu, T_{\text{Ambient}})
\]
International Comparisons

• Regular Reflectance and Transmittance
  • Participants: NPL, NIST
  • Year: 2000-2001
  • Spectral Range: 2.5 µm to 18 µm
  • 4 Materials

• Regular Reflectance and Transmittance
  • Participants: NIST IR vs. UV-VIS-NIR Scales
  • Year: 2002
  • Spectral Range: 1 µm to 2.5 µm
  • 6 Materials

• Directional-Hemispherical Reflectance
  • Participants: NRC, NIST
  • Year: 2006
  • Spectral Range: 2.5 µm to 18 µm
  • 3 Materials

• Near Normal Absorptance
  • Participants: NMIJ, NIST
  • Year: 2004
  • Spectral Range: 2.5 µm to 10 µm
  • 5 Materials

• Near Normal Emittance
  • Participants: INRIM, LNE, NMIJ, PTB, NIST
  • Year: 2007-2009
  • Spectral Range: 2 µm to 14 µm
  • Temperature Range: 23 °C to 800 °C
  • 3 Materials x 11 Temperatures

INRIM: Instituto Nazionale di Ricerca Metrologica (Italy)
LNE: Laboratoire National de Métrologie et d’Essais (France)
NMIJ: National Metrology Institute of Japan (Japan)
NPL: National Physical Laboratory (United Kingdom)
NRC: National Research Council (Canada)
PTB: Physikalisch-Technische Bundesanstalt (Germany)
SOC-100 Design and Features

Hemispherical-Directional Reflectance Factor Measurement

\[ \frac{V_s}{V_r} = \frac{R_{s,h,d} \Omega_d \rho_m \Phi_i}{\rho_m \Phi_i \Omega_d} = R_{s,h,d} \]

Output To FTIR

<table>
<thead>
<tr>
<th>HDR DATA AS A FUNCTION OF</th>
<th>RANGE OF MEASUREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Directional Angles ( \theta ): 20, 30, 40, 50, 60, 70, 75, 80°</td>
<td>Near-normal, 20 to 80°</td>
</tr>
<tr>
<td>b. Azimuthal Angles ( \phi )</td>
<td>0 to 360°</td>
</tr>
<tr>
<td>c. Wavelength</td>
<td>2.0 to 25.0 µm, 2.0 to 45.0 µm*, 2.0 to 200 µm*</td>
</tr>
<tr>
<td>d. Beam Polarization</td>
<td>Parallel and Perpendicular</td>
</tr>
<tr>
<td>e. Sample Temperature</td>
<td>Room temperature to 500°C with heated sample holder</td>
</tr>
</tbody>
</table>
Evidence of Need for FIR Reflectance Standards

Comparison of Commercial Far IR Reflectometers with the NIST Primary Standard
Establishing Intermediate FIR Emittance Scales for Near–Ambient Targets

<table>
<thead>
<tr>
<th>Lab</th>
<th>NIST</th>
<th>PTB</th>
<th>SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Type</td>
<td>Temp., °C</td>
<td>Spectral Range, µm</td>
<td>Spectral Range, µm</td>
</tr>
<tr>
<td>Directional Emittance</td>
<td>200</td>
<td>3 - 100, variable angle</td>
<td>3 - 40, variable angle</td>
</tr>
<tr>
<td>HD Reflectance, Specular/Diffuse Resolved</td>
<td>RT</td>
<td>2 - 14, fixed angle</td>
<td></td>
</tr>
</tbody>
</table>

At the time of conception of the study, NASA had immediate requirement in Specular/Diffuse Resolved Hemispherical-Directional Reflectance in Far IR at near-ambient temperatures. Such measurements are supported by the SOC Calibration Lab, which until now has no direct SI traceability. One of outcomes of the study should be establishing indirect traceability for calibration labs.

Properly addressing the issue requires building dedicated primary facilities, such as RBCF (operational at PTB) or CBS3 (may be built at NIST).
PTB Directional Emittance System

\[
\varepsilon_{\text{Sample}} = \frac{Q \cdot \left( L_{\text{Planck}} \left( T_{\text{BB}} \right) - \varepsilon_{\text{Detector}} L_{\text{Planck}} \left( T_{\text{Detector}} \right) \right) + \varepsilon_{\text{Detector}} L_{\text{Planck}} \left( T_{\text{Detector}} \right) - \varepsilon_{\text{Env.}} L_{\text{Planck}} \left( T_{\text{Env.}} \right)}{L_{\text{Planck}} \left( T_{\text{Sample}} \right) - \varepsilon_{\text{Env.}} L_{\text{Planck}} \left( T_{\text{Env.}} \right)}
\]
• Agreement very good at for $\lambda > 25 \, \mu m$, differences to maximum of 5% at 100 $\mu m$. 

Silicon Carbide Sample Results
PT-401 (Specular) Paint Results

- PT-401 being studied as potential specular black paint replacement for discontinued standard.
- Plot shows paint thickness dependence; effects of primer also to be evaluated.
SOC and NIST Results of PT-401
(Diffuse Component)

- Diffuse component – limit on performance of cavity designed for specular surfaces
- NIST and SOC have similar effective geometries for diffuse component measurements
- Discrepancies to be discussed with SOC
Conclusions and Future Plans – Far IR Emittance of Materials

• Initial results are reasonable, but challenge to sort out differences remains.

• Both labs have active internal projects to further improve respective capabilities

• Candidate specular black paint standard (PT401) shows promise (low overall and very low diffuse reflectance) for FIR

• A new batch of PT401 samples will be prepared for full evaluation

• Near-future improvements (PTB Emittance Facility upgrade with new Vertex 80 FTS and new emittance capabilities of RBCF, and BIB and Boron doped Si detectors at NIST) will further enhance both partners capabilities in the area

Path to reflectance standards / emittance calibrations to 100 µm is started
Blackbody Emissivity – a Misnomer

Effective Emissivity:

- Used mostly to in radiometry as a convenient descriptor for spectral signature of a complex system, allowing to calculate and interpolate spectral radiance from nominal (reference) temperature.

- May include effects of reflected background radiation, multiple reflections in a cavity, non-uniform cavity temperature, radiation background, atmospheric absorption and definition of reference temperature.

- Unlike EMITTANCE (which NIST now prefers to use to characterize materials), blackbody emissivity has no other meaning than a CATCH-ALL MEASURE OF NON-IDEALITY of the radiation source compared to one abiding by the Planck Law and HAS NO PHYSICAL MEANING beyond that.

It may be helpful to talk about reflectance (absorptance) if it is what is being measured (such as with QCL or halo)
## Flavors of Emissivity:

<table>
<thead>
<tr>
<th>Wavelength Related:</th>
<th>Spatial:</th>
<th>Generalized:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral (Monochromatic)</td>
<td>Directional</td>
<td>- Intrinsic - <em>most common</em> (material property)</td>
</tr>
<tr>
<td>Band</td>
<td>Conical</td>
<td>- Effective isothermal (includes multiple reflections)</td>
</tr>
<tr>
<td>Total</td>
<td>Hemispherical</td>
<td>- Effective non-isothermal (for given reference T)</td>
</tr>
</tbody>
</table>

There is no such thing as directional-hemispherical or directional-conical emissivity – only OBSERVATION GEOMETRY qualifier is used.

- Apparent (includes reflected background radiation)
Cavity Reflectometry (DHR) Measurement Sequence

\[ R = \frac{V_{sc} - V_{ap}}{V_r - V_{back}} R_r \]
NIST Complete Hemispherical Infrared Laser-based Reflectometer (CHILR)

- 8 inch diameter gold-coated integrating sphere
- Input port: 6 mm diameter
- Collecting port: 50.8 mm diameter

Laser sources:
- OPO tunable laser- 1 µm to 5 µm
- CO$_2$ laser - 9 to 11 µm
- QCL: 4 µm and 5 µm
- Ability to measure reflectance to <0.00001
Recent CHILR Measurements of Specular Cavities

CHILR with CrIS ICT Cavity

CHILR with ACRIM III Cavity

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Tilt</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 mm</td>
<td>76 mm</td>
<td>100 mm</td>
<td>± 10 °</td>
<td>± 30 °</td>
</tr>
</tbody>
</table>
Future Spherical Far IR Reflectometer (SFIRR) Implementation Steps

- Design Sphere appropriate to Far IR and source geometries
- Find / develop / test and validate diffuse coating
- Obtain sphere pricing, determine construction process / place orders
- Assemble, complete sphere system including detectors
- Characterize sphere: overall throughput, throughput uniformity
- Test with “known” samples, local laser sources
- Transport to appropriate Far IR sources – synchrotron, lasers
SFIRR (Spherical Far IR Reflectometer) Simplified Schematic

- Synchrotron U180 or FIR Laser Beam (U180 waist at the sphere entrance)
- Chopper, FIR band filter and polarizer are NOT SHOWN
- Top detector (Si Bolometer or BIB)
- Side Detector (Pyroelectric)
- 12" Far IR Sphere Reflectometer with 8" flange
- Blackbody Under Test (4" max opening)
- Diffuse Reflective Baffle, translated together with the Blackbody
- Vertical Cross-section View
- Pivot Point
- Lateral Scan Stage
- Roller
- Top View - Normal with 1.4" offset
- Top View - Rotated with -1.4" offset
- SFIRR (Spherical Far IR Reflectometer)
Description of 23 μm QCL system

Cryostat system:

Janis Research Supertran (ST) System ---- a continuous flow research cryostat from 1.5 to 325 K using LHe or LN2

Cryostat head, Laser holder, Cryo-shield, Cryostat cap, Output window (KRS-5 for optimal transmission at 23 μm)

Lake Shore Cryotronics temperature controller, model 325

23 μm QCL, pulser, driver, and power supply:

1. LN2-P-FPQCL-430 (s/n sb3233) by Alpes Lasers ---- generates the cryogenic temperature pulsed multimode emission centered at 430 cm⁻¹ or 23.25 μm with average power < 1 mW @ 80 K. The divergence of output beam: far field elliptical (FWHM), vertical 60°, and horizontal 40°

2. TPG pulser ---- timing pulse generator
pulse duration: 0 ~ 200 ns, pulse period: 200 ns ~ 105.1 μs

3. LDD QCL driver ---- pulser switching unit
Up to 30 A, 60 V (DC), Rep rate 1MHz, controlled by TPG, and power by DC PS

4. High-precision DC adjustable power supply
Model: PS5005U, Boston Electronics, Output voltage: 0 ~ 50 V, Output current: 0 ~ 5A
23 μm QCL and Test Setup

QCL Output Window (KRS-5) & Electronics (in background)

Operational Setup w/ Cryogen Flow and Intermittent Vacuum
Future improvement needed

• Detection: MCT (cutoff 24 μm), BIB detector or Bolometer
• Beam focusing: Lens, focusing mirror
• Large volume cryostat to hold LN$_2$ longer with flow regulation
• Use the transfer line with flow regulator
• Re-evacuation due to outgas and o-ring permeation causes insulation problem between the cryostat and a pump to ground
• Insulation from ground between the cryostat and LN$_2$ container during flowing.
• Shield the flowing gas for the pyro-detector
• Plastic box to prevent the KRS5 window from the dripping water of transfer pipe
Far IR Bandpass Filters

Freestanding Mesh Filters

• From Lakeshore Cryogenics
• Any center wavelength available
• Wings extended – needs to be characterized
• 23 µm filter in hand; available for use.

Example Filter Spectra
PTB Far-IR Laser Facility

SIFIR-50 CO₂-pumped laser

Gas and QCL lasers are typically operated at \(wl > 100\) microns, although there is one minor gas line at 48 microns.

Towards traceable radiometry in the terahertz region

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Abstract

PTB and DLR join their expertise and experience in optical radiometry and in THz techniques to perform what is to our knowledge the first traceable measurement of radiant power of a THz quantum cascade laser and the first absolute calibration of a THz radiation detector against a cryogenic radiometer (CR). A total standard uncertainty of 7.3 % was achieved at a frequency of 2.5 THz corresponding to a wavelength of 120 μm. This uncertainty is dominated by the limited knowledge of the absorbance of the CR cavity. All other uncertainty contributions including those arising from diffraction are only 2%.
PTB Metrology Light Source (MLS) – Layout

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Wavelength</th>
<th>Radiant power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator IR</td>
<td>2 µm – 20 µm</td>
<td>up to mW</td>
</tr>
<tr>
<td>IR beamline</td>
<td>0.6 µm – 7 mm</td>
<td>up to µW</td>
</tr>
<tr>
<td>THz beamline</td>
<td>100 µm – 7 mm</td>
<td>up to µW (mW with CSR)</td>
</tr>
</tbody>
</table>
Spectral Tuning Capabilities of MLS U180 Undulator

Undulator radiation at the IDIR beamline

U180

M1 planar mirror
M2 toroidal mirror
M3 planar mirror

Acceptance:
8 mrad (ver)
14 mrad (hor)

ZnSe

M1 M2 M3

Undulator radiation wavelength can be tuned by changing the electron energy of the storage ring

Wavelength of 1. harmonics:
2 μm (630 MeV)
80 μm (105 MeV)
Operational Spectral Band of Undulator U180
(can be expanded using diamond optics)

Photon flux at the MLS

-coherent synchrotron radiation

undulator radiation

IR and THz radiation from bending magnet
Effective Power of the Far IR QCL, currently procured from Alps Electronics, is below 0.05 mW at the only band at 23 microns!
Spectroradiometry - Outline

- Current Status of IR Spectroradiometry

- Unfulfilled Demand

- Common solution: vacuum chamber with a high accuracy spectral comparator, plus application-specific tools. Physics behind each scale realization approach.

- Concept of the multifunctional modular IR testbed for infrared radiometry and spectrophotometry support of spaceborne, airborne and ground-based targets and sensors.

- Performance goals and results of the detailed design and analysis. Critical technologies for implementation.

- Current budgetary constraints. Action plan and cooperation opportunities.
PTB: Reduced Background Calibration Facility (RBCF)

Certainly the most sophisticated of all reported facilities for thermo-vacuum calibrations of IR BB sources at near-ambient temperatures.

No actual measurements in the radiance mode were reported yet (expected later this year).
Reduced Background Calibration Facility RBCF – Photos
The only successful experiment with high accuracy (mK level) radiometric measurements of near-ambient temperature.

Used TOTAL (spectrally unresolved) measurements, which limits its relevance for CLARREO.
NPL: Attempt at ACR-Traceable Measurement of Near-Ambient Source Band Limited Radiance

Since its construction in 1996 and initial paper with general description, no results from AMBER setup were reported.
Virtual European Metrology Centre for Earth Observation and Climate (EMCEOC)

Confirmed Euramet Project. Starts in July 2011 / 3 years duration

Goal: establish new transfer standards and methodologies to enable improved accuracy and traceability (factors of 2 to 10) for:

- Pre-flight calibration of optical and microwave imaging cameras (air and vacuum)
- In-flight (on-board) calibration for optical imagers and atmospheric limb sounders
- Surface based “test-sites“ for the post-launch calibration and validation of Land and Ocean imaging radiometers
- Models and algorithms to improve performance and traceability of L2 Land products
- Prototyping techniques to enable the establishment of “SI traceable benchmark measurements from space“ to facilitate and underpin the upgrade of current sensors to the performance needed to form a global climate observing system
- 320 man-months (~27 man-years) + equipment

IR CLARREO-relevant results may be anticipated only in the follow-up to current project, which is Vis-NIR only
Pre-flight laboratory-based calibration standards and methodologies

Adapting NMI-based state-of-the-art to enable climate quality pre-flight calibration/characterisation
- Tuneable lasers for stray-light characterisation of optical imagers
- High uniformity large aperture radiance source for wide FOV sensors
- In-vacuum, on-site, traceable spectrally resolved radiance calibration of satellite imagers
- Traceability for microwave radiometers
Partnership: NPL, PTB, DLR + (CNES / RAL / SSTL...)
85 MM +

On-board calibration standards
IR limb sounders drift – radiometric uncertainties of 0.1% (relative) and 1% (absolute) need to be maintained during operation
- Establish capabilities to achieve uncertainties on ground
- Design, characterise, test aircraft-based standard
- Evolve design and test balloon-based standard
- Design Satellite-based standard
Partnership: NPL, PTB, BUW, FZJ (76 MM)

Recovering/establishing in-flight traceability through reference standard measurements and test-sites
All optical sensors degrade in orbit, and measure radiation at top-of-atmosphere to infer the properties of the Earth’s surface. Representative ‘test-sites’ are a critical element of any EO Calibration/Validation strategy and a major focus of the GEO and CEOS community.

Creating impact
Primary impact through technical work packages - dissemination and use:
Also increase stakeholder awareness of the importance of traceability and the limitations of existing data products.
Key interfaces to the EO community are through the major international organisations but must also include industry, academia and policy makers.
- Community website linked to international portals to provide focal point for European EO metrology
- Identify metrological requirements for next generation sensors
  - Provide EO tailored training on uncertainty analysis
  - Develop concept of EMCEOC with key stakeholders
- Papers, presentations, media news items
- European focus for international EO metrology
  (CEOS, OAEO, GEO, WMO, GSICS, GEWEX, GCOS)
Partnership: NPL, LNE, PTB (13 MM) + All (WP1-4)

An ‘NMI in space’ for benchmark measurements of climate
Climate-quality uncertainties and a ‘global climate observing system’ requires regular traceability directly to primary standards. Since satellites cannot be brought back to the NMs on Earth, the primary standards need to be flown in space.
- Evaluate performance of prototype primary standard designed for space
- Prototype techniques to use primary standard in space
- Design and test transfer radiometer needed to link primary standard and imaging spectrometer (also for use in WP1).
Partnership: NPL, LNE, PTB, SFJ-Fevco (44 MM)

Collaborators
Spectral Radiance Metrology at NIST

- **PYROMETRY** Setup + FASCAL: $T > 962 \, ^\circ C$, $\lambda < 2.5 \, \mu m$ (Howard Yoon)
  - **Principle:** Extrapolation from Au point (+ compared with ACR at 900 nm)
  - **New:** R2T facility (not yet fully operational). Numerous improvements planned, including use of multichannel spectrometers for much faster scale transfer. DETAILS BEYOND THE SCOPE OF CURRENT TALK

- **SDE Facility:** $150 \, ^\circ C < T < 1000 \, ^\circ C$, $3 \, \mu m < \lambda < 23 \, \mu m$, purged.
  - **Principle:** Interpolation between VTBB, using FTIR;

- **AIRI:** $-45 \, ^\circ C < T < 1000 \, ^\circ C$, $2.5 \, \mu m < \lambda < 14.8 \, \mu m$, not purged.
  - **Principle:** Interpolation between FP and VTBB, using filter radiometers;
  - RT Comparisons with NMI of Germany, UK and Canada in the -50 to 300 $^\circ C$ temperature range, in the 8 $\mu m$ -12 $\mu m$ spectral band;
  - Now a regular calibration service

- **LBIR** (new capability with LHe cooled FTIR)
  - Spectral coverage up to 28 microns, performance limited by the FTIR stability (0.5%)

In spite of substantial experience in realization spectral radiance scales, no immediately usable capability exists to support CLARREO-type applications
Advanced Infrared Radiometry and Imaging (AIRI) facility, among other functions, is enabling a national level traceability for measurements of absolute spectral radiance and spectral emissivity of BB sources and targets at near ambient and elevated temperatures at ambient environment.
Unfulfilled Demand

- Approximately 30% of requests for IR calibrations cannot be fulfilled
  - (1) extended geometry (DHR),
  - (2) controlled background (vacuum/high purity purge or radiation background),
  - (3) extended temperature (lower Ts) and spectral range (longer wl),
  - (4) improved uncertainty (very few),
  - (5) clean room/controlled contamination lab (very few)

- Most of these customers can afford substantial calibration fees, but cannot sponsor extensive facility upgrade or wait until it happens;

- We are supporting these requirements, such as via reflectometry of paints and BB cavities as a proxy for direct radiance measurements;

- This addresses most of immediate needs, but in the long run it is essential to offer direct support, not relying on modeling or other assumptions;

- Report describes recent design efforts to address a number of those shortcomings on calibration services. The effort was programmatically tied to the climate science mission but had much wider objectives.
Example: TXR Traceability Issues

- The Thermal-infrared Transfer Radiometer (TXR) is a two-channel portable radiometer for providing thermal-infrared scale verifications of large-area calibration sources
- For many years, stays central for maintaining nationwide TIR traceability, was deployed multiple times for both ambient and thermo-vacuum applications

Traceability Options

- **Current - WBBB**
  - Scale based on ITS-90 and emissivity data
  - Easy to use; excellent for reproducibility studies

- **IR SIRCUS / ACR (Future Possibility)**

Summary – Present Status:

- Remains to be the primary tool for IR Radiance scale transfer in Tvac
- Limitations: calibrated in the ambient air and radiation background
Multifunctional Modular IR Testbed Concept - Design Principles

- After analysis of emerging requirements in metrology of thermal emission sources and optical materials and components, and evaluation of several existing IR calibration facilities, a Controlled Background Spectroradiometry and Spectrophotometry System (CBS3) concept was developed;

- Criteria in selecting CBS3 design included:
  - **Multifunctionality**: facility should advance state of the art in all our three main areas – spectroradiometry of IR sources and sensors, and spectrophotometry of materials and BB cavities;
  - Widely **variable environmental conditions** for the UUT: form high vacuum to atmospheric pressure and from LN$_2$ to above-ambient radiation background;
  - **Modularity**: separate functional modules should be easily replaceable, serviceable and upgradable;
  - **Advanced optical alignment and diagnostic capabilities**, both before and during the measurements;
  - **Low contamination environment**: use only technical solutions which allow, if necessary, certification of environment to allow handling clean artifacts
Radiance Temperature Modes of CBS3

CBS3 Facility: Primary Realization of Radiance Temperature and Spectral Radiance in the Thermal and Far Infrared

**SPECTROMETRY of INFRARED SOURCES**

- **Internal Source Calibration**
  - Spectral Radiance / Emissivity
  - 180 K to 520 K

- **External Source Calibration**
  - Spectral Radiance / Emissivity
  - 180 K to 520 K

- **Internal Sensor Calibration**
  - Radiance Temperature
  - 180 K to 520 K
Optical Property Metrology Modes of CBS3

CBS3 Facility: Primary Realization of Spectral Directional Emittance and Hemispherical-Directional Reflectance in the Thermal and Far Infrared

**OPTICAL MATERIALS AND COATINGS CHARACTERIZATION**

- **Configuration 1**
  - Sample Emissometry
  - Unit: Spectral Directional Emissivity
  - Sample at: 250 K to 520 K
  - Works best for: Hot black targets

- **Configuration 2**
  - Sample Reflectometry
  - Scale: Hemispherical-Directional Reflectance
  - Sample at: 80 K to 350 K
  - Works best for: Cold grey targets

- **Configuration 3**
  - Cavity Reflectometry in Mid/Far IR
  - Scale: Hemispherical-Directional Reflectance
  - Cavity at: 80 K to 200 K

**BLACKBODY CAVITY CHARACTERIZATION**

- **Configuration 3**
  - FT / CVF Spectrometer on a Rotating Platform (above the chamber)
  - Reference BB 1
  - Reference BB 2
  - Temperature Controlled Shroud (80K to 320 K)

- **Configuration 2**
  - FT / CVF Spectrometer on a Rotating Platform (above the chamber)
  - Reference BB 1
  - Reference BB 2
  - Variable T Emitting Sphere
  - Sample

- **Configuration 1**
  - FT / CVF Spectrometer on a Rotating Platform (above the chamber)
  - Reference BB 1
  - Reference BB 2
  - “Cold” Shroud (80 K partial or 200 K full)
  - Free Standing Sample
Selected Box Chamber design was suggested by Joel Fowler (NIST, ret.), who originally came up with this design 15 years earlier setting up MBIR.
CBS3 - Design Effort Scope and Results

Developed design is supported by detailed analysis and optimization, which included:

- Structural analysis, including stress and deformations (L-1);
- Optical performance analysis (L-1);
- Thermal performance for the shrouds (L-1);
- Effective emissivity analysis for the primary blackbody cavities (NIST / Virial)
- Thermal analysis for the primary fixed point blackbodies (Pond Engineering)
- Effective emissivity analysis for the variable background reflectometer (NIST / Virial)

Remaining activities in this area include:

- Diffraction analysis of the foreoptics
- Thermal analysis for the primary variable temperature blackbodies (pending optical and thermophysical properties of the paint)

Results of the design effort:

- Machine-ready design for the vacuum chamber and spectral comparator
- Advanced stage of the primary BB sources design
- Conceptual design stage for reflectometry components
Schematic Cross-Section of the CBS3 Concept
CBS3 3D Model Views (with TXR in the right figure)
Foreoptics and Upper Chamber Assembly Design

**Upper Internal Rotation Assembly**
1. Precision Rotary Stage
2. Pointing Mirror
3. Lyot Stop
4. Ellipsoidal Mirror

**Diagram:**
- Precision Rotary Stage
- Foreoptics Assembly
- Foreoptics Enclosure
- 3X Detector Assembly
- 2X Ferrofluidic Bearing
- Pointing Mirror with Precise Rotation and Dual Axis Linear Translation Stages
- Ellipsoidal Mirror with Manual Pointing
- Aperture Stop
- Baffle
- Section A-A
- CBS Chamber Optics Path Overview
Modeling and Design Results (L-1)

The Left plate’s temperature ranges from 190.21 to 191.11 K.

Isometric view of Stress Test, Trial 2 (12.7 mm plates).

ZEMAX layout for tow geometries. The image at Lyot Stop using the image analysis tool in ZEMAX.
End user requirements in radiance temperature uncertainty at the level of 25 mK, such as CLARREO, translate into effective emissivity requirements for the primary blackbody sources to be at the level of 0.99995 or greater (see Fig. below left). Some existing near-ambient sources, such as the water bath variable temperature BB and Ga fixed point BB meet these specifications in the thermal IR. Their performance in the far IR has to be evaluated and potentially improved.
Fluid Bath-Based BB Cavity Absorptivity Modeling: Input Parameters

9.2 mm and a full viewing angle of 5.8 deg is measured in Geometry # 1, while a source with a size of 17 mm and a full viewing angle of 2.4 deg is measured in Geometry # 2.

<table>
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<tr>
<th>Surface No.</th>
<th>ζ</th>
<th>Z</th>
<th>R</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
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Calculations performed using Monte-Carlo-based software show that emissivity requirements can be met with a modest size cavity, if a specular black similar in performance to LORD Z302 or PTI PT-401 is used. Calculations were made with reflectance values TWICE as large as those actually measured, to account for high incidence angle effects.
Primary Fixed Point BBs

- For all three substances (water, mercury and gallium):
  - Common SS crucible design and coating
  - Common T control (Peltier elements)
  - Common housing and insulation
  - Common T sensors and read-outs

- LN2 source is also anticipated (0.1 K uncertainty)

- A vendor with unique experience in handling pure substances and making primary fixed points has expressed interest in fabrication (Pond Engineering), may participate in fabrication of VTBB also
Vacuum Spectral Comparator (VSC) Concept

BLACKBODY CALIBRATION

INFRARED MATERIALS CHARACTERIZATION

Configuration 1
Spectral Radiance

Configuration 2
Directional-Hemispherical Reflectance

Configuration 3
Spectral Directional Emittance
Stand-Alone Vacuum IR Spectral Comparator Concept

BRUKER 70V FTS

Si Bolometer or BIB

Heavy Duty Rotation Stage and Hollow Shaft Rotary Feedthrough

Optical axis height
1000 mm to 1100 mm

Docking Point

Rotary Feed for T control of Aperture & Field Stops and Reference Source

Lab Floor
VSC with Primary and Transfer BB and Optional Chamber

Optional User BB and Far IR Reflectometry Chamber

Variable Temperature Primary BB Source 1

Infrared Vacuum Spectrocomparator

Bolt-On UUT (Transfer Standard BB) or Fixed Point Source

Variable Temperature Primary BB Source 2
# Thermal and Far IR Radiance Support - Trade Study

<table>
<thead>
<tr>
<th>Option</th>
<th>Functionality</th>
<th>Benefits</th>
<th>Risks / Drawbacks</th>
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</thead>
</table>
| Wait until full funding for original CBS3 concept becomes available | BB Spectral Radiance, DHR, Emittance, Cavity Reflectance | Comprehensive Far IR Coverage and Flexibility | 1. Funding may never materialize  
2. It may come too late for mission support |
| Build a stand-alone Infrared Spectral Comparator (ISC) + Bolt-On Primary BBs | BB Spectral Radiance (F/20 and F/7); includes spatial gradient assessment | Substantially reduced fabrication cost, weight and footprint (compared with CBS3 concept) | 1. If a bolt-on transfer standard BB is not sufficient for CLARREO successor and other missions, a UUT chamber is needed |
| Build Primary and Transfer Standard Sources, use PTB RBCF Facility for scale transfer | BB Spectral Radiance (F/8 geometry) | Save ISC Fabrication and Operation Costs | 1. Wrong geometry and single stage optics  
2. BB Compartment is extremely small  
3. Overseas, potential issues with access |
<p>| Build Transfer Standard Sources and use PTB RBCF Facility for scale realization and transfer | BB Spectral Radiance (F/8 geometry) | As above, plus save on primary BB fabrication and characterization | As above, plus - resident primary BBs (a) have 50 mK spec; (b) were not designed for Far IR, and (c) rely on modeling only |
| Rely on indirect characterization and modeling of a Transfer Standard BB Source | None directly related to spectral radiance | No hardware costs except cavity reflectometry support | No direct SI traceability |</p>
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<th>WBS</th>
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<th>FY2012</th>
<th>FY2013</th>
<th>FY2014</th>
<th>FY2015</th>
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<tr>
<td>1.1 Establish Material Properties Metrology in Far IR</td>
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<tr>
<td>1.1.1 Establish a Transitional FIR DHR and Emittance Scales</td>
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<td>1.1.1.1 Add BIB detector to the DHR setup to extend spectral range</td>
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<td>1.1.1.2 Validate DHR and SDE scales using PTB, NPL and SOC data</td>
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<td>1.1.2 Characterize candidate FIR black coatings for BB sources</td>
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<td>1.1.2.1 Measure emittance/reflectance with S/D breakdown</td>
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<td>1.1.2.2 Evaluate outgassing/contamination</td>
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<tr>
<td>1.2 Establish Cavity Reflectance Metrology in Far IR</td>
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<td>1.2.1 Upgrade NIST CHILR laser reflectometer</td>
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<tr>
<td>1.2.1.1 Install FIR QCL Laser and FIR detector (PC or BIB) and filter</td>
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<td>1.2.1.3 Test/validate CHILR with QCL</td>
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<tr>
<td>1.2.2 Build SFIRR to Achieve Continuous FIR Coverage</td>
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<td>1.2.2.1 Investigate/optimize FIR diffuse reflective coatings</td>
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<td>1.2.2.2 Design/Build a FIR integrating sphere reflectometer</td>
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<td>1.2.2.3 Steps to complete arrangements with PTB (MOU, SOW etc.)</td>
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<td>1.2.2.4 PTB upgrades MLS High Intensity FIR source</td>
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<td>1.2.2.5 Test SFIRR with MLS source, compare with TIR / 24 µm TStd</td>
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<td>1.3 Build Primary Standard Blackbody Sources</td>
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<td>1.3.1 Build Variable Temperature BBs (ethanol baths)</td>
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<td>1.3.1.1 Prepare conceptual design, select technologies</td>
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<td>1.3.1.2 Thermophysical and radiometric modeling of BB performance</td>
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<td>1.3.1.3 Build, paint and evaluate a prototype cavity, finalize design</td>
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<td>1.3.1.4 Build and test VT BBs</td>
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<td>1.3.2 Build Fixed Point BBs (water, mercury, LN2)</td>
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<td>1.4 Build Infrared Spectral Comparator (ISC)</td>
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<tr>
<td>1.4.1 Build the IR Spectral Comparator</td>
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<td>1.4.1.1 Finalize a concept, develop a set of specifications</td>
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<td>1.4.1.2 Perform diffraction analysis and evaluation</td>
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<td>1.4.1.3 Design and Build the ISC</td>
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<td>1.4.1.4 Procure FTS (Bruker V70v)</td>
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<td>1.4.1.5 Install and test ISC</td>
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<tr>
<td>1.4.2 Assemble, Align, Test and Operate ISC and BBs</td>
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<tr>
<td>1.5 Establish Far IR Spectral Radiance / RT Scales</td>
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<td>1.5.1 Establish Uncertainty Budget of the Radiance Scale</td>
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<td>1.5.1.1 Compare BBs with different exit apertures (SSE)</td>
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<td>1.5.1.2 Compare BBs at different BG (emissivity)</td>
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<tr>
<td>1.5.1.3 Compare BBs at different set points (linearity)</td>
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<tr>
<td>1.5.1.4 Evaluate individual components and calculate total uncertainty</td>
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Conclusions

- Critical Supporting Technologies, Modeling and Concept Demonstration
  - Far IR Optical Properties of Materials / Preliminary Scales
    - Achieved positive results for PT-401 paint, intercomparison and cross validation of capabilities is in progress (with PTB and SOC); NPL participation likely will enable resolution of discrepancies;
  - Far IR Optical Properties of BB Cavities
    - NIST has adequate capability for Thermal IR performance evaluation. Prior to SFIRR development, we can rely on extrapolation of the Far IR portion, using new coating data and developed software;
    - Ongoing experiment with QCL, BIB, IR sphere, and far IR filter to evaluate adequacy of PTB MLS for cavity reflectance;
    - SFIRR design and implementation, in cooperation with PTB, can then be continued; identification/development of diffuse coating at 50 µm is a major element;
- Realization and Transfer of Spectral Radiance for Thermo-Vacuum Environment
  - Primary and transfer standard FIR BB sources
    - Design and prototyping to continue (with possible cooperation with PTB Facility), if required modest resources are available;
  - Spectral Comparator Facility
    - Multipurpose full scale facility is completely designed and ready for construction;
    - The ISC concept leaves CBS3 core features and could be constructed immediately, with at least a 50% cost reduction and shorter production time
- Realization of Far IR Spectral Emittance and Reflectance
  - In case of further delay with CBS3 / ISC funding, such effort can be undertaken independently of the high accuracy radiance facility, as these applications do not has as challenging requirements to the uncertainty. For example, an available legacy IFS 66v can be employed.