A Novel Vacuum FIR Calibration System in Support of ESA’s 9th Earth Explorer Mission at PTB

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Working Group 7.32 Infrared Radiation Thermometry

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Earth Radiation Budget

Wild, M. The global energy balance as represented in CMIP6 climate models *Climate Dynamics*, 2020, 55, 553-577
Outgoing Longwave Radiation

Earth radiation budget

OLR

Spectral Simulation

So far measured outgoing longwave radiation

The Far-infrared-Outletgoing-Radiation Understanding and Monitoring (FORUM) Mission

Will measure the spectral distribution of the Earth’s OLR and will fill the long-standing gap in FIR spectral observations
The FORUM Mission Statement

FORUM will deliver an improved understanding of the climate system, informing climate policy decisions by supplying, for the first time, a complete characterisation of the Earth’s OLR spectrum.

This goal will be achieved by spectral measurements that:

• cover the Earth’s top-of-atmosphere (TOA) emission spectrum from 6.25 µm to 100 µm
• fill the observational gap across the far-infrared from 17 µm to 100 µm
• provide a three-years dataset benchmarked against international standards with an absolute radiometric accuracy of at least 0.1 K \((k = 3)\) in the spectral range from 9 µm to 33 µm and 0.2 K in the other ranges.

In this way, FORUM will deliver a truly unique dataset of the Earth’s entire emission spectrum up to 100 µm which can be used to probe FIR energetics but will also efficiently complement existing and planned future missions.

It will provide a stringent test of our understanding of, and ability to model, the links between key underlying physical processes driving climate change, their spectral signatures, the Greenhouse Effect, and the overall ERB.

0.1 K \((k = 3)\) uncertainty requires: 30 mK \((k = 1)\) uncertainty of on-board blackbody
15 mK \((k = 1)\) uncertainty of on-ground reference blackbody
Reduced Background Calibration Facility 2 – RBCF2

Traceability for MIR and FIR Spectral Radiance and Radiance Temperature standards in vacuum

Source chamber with vacuum blackbodies
- VLTBB: -170 °C to 170 °C
- VMTBB: 80 °C to 450 °C
- LN$_2$BB: -196 °C

Detector chamber with Vacuum Infrared Radiation Standard Thermometer VIRST

Vacuum-Fouriertransformspectrometer
0.400 µm to 1000 µm
Summarized Capabilities of the RBCF2

Characterisation of Sources
• Radiance temperature: - 170 °C to 450 °C
• Spectral radiance: 0.4 µm to 1000 µm

Characterisation of Detectors and Cameras
• With respect to calculable blackbody radiation: -170 °C to 450 °C

Emissivity
• Sample temperature: -40 °C to 800 °C
• Spectral range: 0.4 µm to 200 µm

Directional Transmissivity- and Reflectivity
• Spectral range: 0.4 µm to 1000 µm

*All in vacuum or under controlled pressure and gas purity and ISO 5 cleanroom conditions*

However, current uncertainty of radiance temperature is 30 mK

*Improvement necessary!*
Sensitivity Analysis

**Governing equation**

\[ L_{\lambda,\text{Rad}}(\lambda, T_{BB}) = \varepsilon_{BB} \cdot L_{\lambda,\text{Planck}}(\lambda, T_{BB}) + (1 - \varepsilon_{BB}) \cdot L_{\lambda,\text{Planck}}(\lambda, T_{\text{Back}}) \]

**Uncertainty components**
- Blackbody temperature \( T_{BB} \)
- Effective emissivity of cavity \( \varepsilon_{BB} \)
- Background temperature \( T_{\text{Back}} \)

**Approach**

Investigate the spectral distribution of the partial derivatives of \( L_{\lambda,\text{Rad}}(\lambda, T_{BB}) \) with respect to \( T_{BB} \), \( \varepsilon_{BB} \) and \( T_{\text{Back}} \) in terms of temperature.
Sensitivity Analysis

Spectral distribution of individual contributions to uncertainty of radiance temperature

- Uncertainty of $\varepsilon_{BB}$ dominant if background temperature is different to black body temperature
- For warmer background temperatures the uncertainty of $T_{Back}$ is also relevant
Sensitivity Analysis

Spectral distribution of individual contributions to uncertainty of radiance temperature

Uncertainty requirement achievable by:

- Ensure background temperature to be slightly below black body temperature – Radiation screen!
- Measure black body temperature with $u(T_{BB}) < 10$ mK
- Realize highest possible blackbody emissivity
- However, $\varepsilon_{BB} = 0.999$ is sufficient to achieve $u_{combined}(T_{rad})$ of 15 mK

$u_{comb}(T_{Rad}) < 15$ mK!
Based on the feasibility Study of 2020 ...

... to improve the RBCF2 to achieve the targeted uncertainties ...

... new ESA Project signed in 11.2021

**New vacuum reference blackbody (VRBB)**
with 15 mK uncertainty

**Coldscreen for thermal uniform environment**

- Production design completed
- Prototype tested
Coldscreen – Design

Beamline Access Port

Cooling Channels 12x12 mm
Milled Aluminium 6061 Plate
15 mm

1750 mm
540 mm
Finite Element Analysis of Coldscreen

Conditions:
- Fluid -50 °C
- Uniform heat load
- 2 l/min volume flow

Complete area of Coldscreen
Peak-to-Valley: 10.6 K

Integrated FoV of VRBB
Peak-to-Valley:
2000 mK, entire range

But:
600 mK, central 1450 mm

Coldscreen uniformity sufficient to achieve uncertainty requirements on background
Temperature sensing of blackbody

In-liquid mounting of capsule SPRTs
- vacuum compatible non-conducting fluid with high thermal conductivity

Glass Capsule SPRT
- Comply to ITS-90
- -260 °C to 232 °C
- Thermal cycle drift: <1 mK
- Drift Rate: <5 mK/year
- Reproducibility: 1 mK
- Self-heating TPW: <2 mK
- Ø5.8 mm, 56 mm long

Readout electronics
- Uncertainty < 1 mK

Verified performance

Contact temperature uncertainties better than 5 mK in the temperature range -30 °C to 29 °C
VRBB – Design

- In-Liquid Mounting
- Cavity
- Aperture
- SPRT borehole
- Copper cylinder
- Preliminary mount
**VRBB – Design**

- **Sleeve**
- **114 mm**
- **500 mm**
- **Bifilar wound fluid channel**
- **Separate channel at front**
- **Aperture close to separate channel**
- **Temperature sensor holes**
- **In-Liquid Mounting**
- **100 mm**
VRBB – FEM Simulation

Temperature deviation on the outer black body surface.

On the outer surface a peak-to-peak difference of 35 mK is found.

Temperature deviation on the inner surface of the black body cavity.

On the inner cavity surface a peak-to-peak difference of 19 mK is found.
VRBB – STEEP Simulation -50 °C

\[ \Delta T_1 = -14 \text{ mK} \]

\[ \Delta T_2 = -16 \text{ mK} \]

\[ T_{\text{ref}} = 223.116 \text{ K} \]

- Better performance of VANTABLACK S-IR in the FIR
- Also for Nextel 811-21 effective emissivity well above 0.999
Summary

\( u(t_{\text{Rad}}) \sim 15 \text{ mK} \) is achievable by the following means

- Use of **capsule type SPRTs** with appropriate readout electronics to achieve few mK uncertainty of cavity temperature measurement.
- Use of **in-liquid mounting of SPRTs** for good thermal contact and easy recalibration to maintain this uncertainty over a long period of time.
- A **liquid operated blackbody** with bifilar heat exchanger and copper body is sufficient to achieve cavity temperature uniformities of 20 mK and effective emissivities of 0.999.
- A **radiation screen** operated at similar temperature as the reference blackbody keeps the radiance temperature uncertainty below the 15 mK limit.
- The **radiation screen minimizes time dependent thermal loads** on the reference blackbody and the blackbody under test during typical calibration schemes when blackbodies are moved with respect to the comparison instrument.
- The **radiation screen might be used to simulate the later application conditions** and corresponding thermal loads of the blackbody under test.

The design and manufacturing of the VRBB and Coldscreen are on its way and the RBCF2 will be extended by both in 2023 to support the FORUM mission.
Thank you!

Acknowledgement
Funding by ESA Project - Contract No. 4000136343/21/NL/GLC/zk

*Novel Reference/Calibration System to Measure Spectral Radiance on the Range 4 μm to 100 μm* is gratefully acknowledged.

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