Metrology for Earth Observation and Climate

EMPIR EURAMET

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Pre-flight radiometric calibration facilities and reference 'black bodies' to meet the demands of the ESA FORUM mission

Calibrations to support full spectral measurements of far infrared irradiation from space

About half of Earth's outgoing long-wave energy is in the far-infrared part of the electromagnetic spectrum, but this part of the spectrum has not previously been measured in any spectral detail from space. FORUM, ESA's ninth Earth Explorer mission, will fill this gap. These measurements are important because Earth's outgoing radiation at these wavelengths is strongly affected by water vapour and ice clouds, which, in turn, play a key role in regulating surface temperatures. FORUM will improve confidence in the accuracy of climate change assessments that could form the basis of future policy decisions.

Context

Satellite observations of infrared radiation emitted from Earth to space could be used to measure changes in the planet's energy balance, and so reduce the uncertainties associated with climate predictions. However, current missions are not capable of detecting the full spectrum of infrared radiation of interest, limiting opportunities for improved understanding of the contributions of, for example, carbon dioxide and water vapour. Forthcoming missions such as ESA's FORUM promise to fill this observation gap but require improved pre-flight radiometric calibration facilities and reference 'black bodies' with unprecedented low measurement uncertainties.

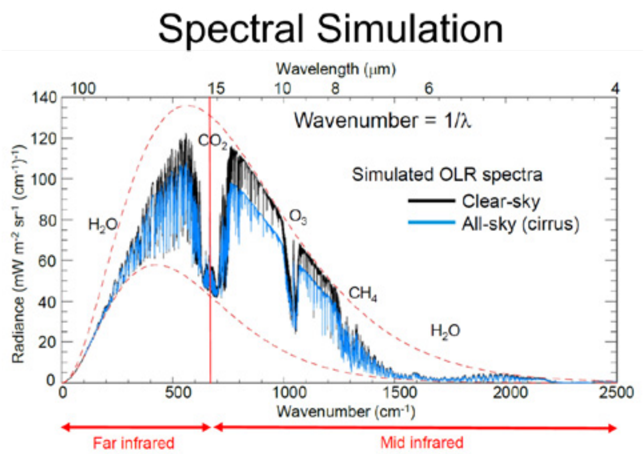

Figure 1. Spectral Outgoing Longwave Radiation (OLR) at TOA in clear sky (black line) and in the presence of a cirrus cloud (blue line) for a mid-latitude scenario. The red dashed curve is the black body emission at the surface temperature of 26°C which approximates the surface emission.

Challenge

Global warming is a direct consequence of changes to the Earth's radiation balance. However, disruptions to this balance are relatively small and difficult to detect, while sources of change are difficult to attribute.

Anything that increases or decreases the amount of incoming or outgoing energy may disturb Earth's radiative equilibrium. So, new knowledge of levels of radiation in the far infrared (wavelengths ranging from 15 to 100 micrometres) would be particularly valuable for establishing the earth's energy balance, as objects emit radiation in the far infrared range (FIR) as a result of Planck's law.

Globally averaged, model simulations suggest about half of the total energy emitted by the Earth is in this wavelength range, so may significantly disrupt the planet's energy balance. Nevertheless, FIR has never been measured spectrally, in its entirety, from space, mainly due to technical difficulties associated with achieving necessary instrument signal-to-noise ratios. To date, outgoing radiation has been measured in the IR spectral range up to 17 micrometres (17 µm) omitting longer FIR wavelengths which contribute about half of the outgoing flux.

However, advances in detector and optical technologies look set to open new opportunities.

Several satellites directly measure the energy absorbed and radiated by the Earth, and by inference its energy imbalance. NASA's CERES instruments have operated since 1998. In early 2020, NASA selected the follow-on Libera mission to operate on the NOAA JPSS-3 satellite from 2026.

The ESA Earth Explorer Mission 9 FORUM (Far-infrared-Outgoing-Radiation Understanding and Monitoring) mission, set for launch in 2027, will measure Top-Of-Atmosphere (TOA) emission spectrum in the mid- to FIR spectral range of 6.25 µm to 100 µm using an on-board

Fourier-transform spectrometer (FTS). For the first time, FORUM will observe most spectral features of the FIR contribution, including in the 15 µm to 100 µm spectral region.

This new data will help evaluate the influences of FIR on climate and is likely to reduce uncertainties of predictions of future climate change. Insights are also likely into water vapour concentrations, particularly in the upper troposphere/lower stratosphere, and the radiative impacts of ice clouds. The mission will also measure the role of FIR surface emissions in determining the rate of change of surface warming.

A black body housed at the entrance of the instrument will serve as an onboard calibration mechanism to periodically adjust for biases of infrared measurements post-launch. An ideal black body emits radiation according to Planck's law, meaning it has an emitted spectrum determined by temperature alone, not by shape or composition.

The absolute radiometric accuracy demanded for FORUM is challenging, particularly in the 'fingerprint region' at mid-infrared wavelengths and at the lower end of the dynamic range (190 K), where an accuracy of less than 0.1K is required. The consequent uncertainty requirements of the mission are for spectral radiance temperature of 33 mK in the spectral range from 9 µm to 33 µm and 66 mK in the spectral range from 33 µm to 50 µm.

Such challenging uncertainties require improved pre-flight radiometric calibration facilities and new reference 'black bodies'.

A large aperture FIR black body, will provide a suitable onboard reference source, while pre-flight characterisation, stability investigation, and calibration, require new ground-support equipment. Only one NMI in Europe was able to provide spectral radiance in a vacuum up to wavelengths of 100 µm. Uncertainty of the reference source was 40 mK in radiance temperatures, whereas FORUM requirements were for 20 mK across the full spectral range.

Critical to the uncertainty budget of a black body is the uncertainty of its effective emissivity, in this case, calculated using Monte Carlo simulations. These simulations depend on the availability of optical parameters of the cavity coatings and their associated uncertainty. The angular distribution of the reflected radiation of the coatings, the bidirectional reflectance distribution function BRDF, was not known with the required uncertainty in the FIR range between 25 µm and 100 µm, limiting the achievable uncertainty of reference black bodies.

Solution

PTB developed metrology for a new reference black body and an improved in-lab in vacuum reference black body, to provide spectral radiance from 3 µm to 100 µm in a temperature range of -50 °C to +50 °C with a standard uncertainty in spectral radiance of better than 20 mK.

In the EMPIR MetEOC-4 project (2020 to 2023), PTB developed two setups to measure and verify BRDF in the 25 µm and 100 µm spectral range.

A study of the Vacuum Reference Black body (VRBB) design as the reference source to calibrate the FORUM on-board reference black body showed a liquid-operated black body with a bifilar heat exchanger and copper body capable of achieving cavity temperature uniformities better than 20 mK.

Measuring the temperature of the black body with an uncertainty of less than 10 mK (necessary to achieve an uncertainty of the radiance temperature of the black body of less than 20 mK) was demonstrated using in-liquid mounting. Monte-Carlo ray-tracing simulations showed that with the cavity geometry of the VRBB and the expected temperature gradient in the cavity under operating conditions, a sufficiently high effective emissivity was achievable with two potential coatings.

Two independent approaches to obtaining BRDF data in the FIR spectral range up to 100 µm were developed: an in-vacuum FIR gonio-reflectometer for the BRDF measurements and an FIR integrating sphere for directional hemispherical reflectance measurements.

A Gonio-reflectometer was tested for applicability in the FIR spectral range and subsequently used to characterise the angular distribution of candidate Lambertian surfaces.

Using computer modelling, a candidate FIR integrating sphere for reflectance measurement was designed using optical ray tracing.

Any practical black body will have some small remaining radiance that needs to be calculated and considered in the uncertainty budget – and its environment controlled. To achieve this for PTB's new Reduced Background Calibration Facility 2 (RBCF2) a cold-screen was developed, made up of a large temperature-controlled plate and properties of high emittance and good temperature uniformity.

Outcome

By the end of the MetEOC-4 project, PTB met the specified calibration requirements for the FORUM on-board black body reference source, having reduced the uncertainty of its new facility from 40 mK to 20 mK in radiance temperature.

This was achieved by:

1. A new in-vacuum reference black body for the RBCF2, the VRBB, able to achieve an uncertainty in radiance temperature of 20 mK, procured for delivery by October 2023.
2. The design, build, and integration of a cold screen into the RBCF – characterised to demonstrate high-temperature uniformity, to ensure uncertainty in radiance temperature of the reference black body of 20 mK providing effective emissivity not worse than 0.999.
3. As an accessory to the existing Fourier-transform spectrometer, a FIR gonio-reflectometer, was tested. This can measure Bidirectional Reflectance Distribution Function (BRDF) in the FIR spectral range, enabling Monte-Carlo raytracing calculations of effective emissivities above 0.9995, enabling demonstration that the reference black body is less sensitive to instabilities and gradients from its surroundings.
4. A Lambertian surface in the FIR range of 25 µm to 200 µm was developed and incorporated into the design of a practical sphere. The integrating sphere was scheduled for completion and coating by September 2023. An associated optical setup was due to be completed by November 2023. The FIR integrating sphere will be used to measure FIR directional-hemispherical reflectances and provide independent verification of the FIR gonio-reflectometer reflectance and FIR emittance measurements to confirm emittance data used for effective emissivity calculations.

PTB's Reduced Background Calibration Facility 2 was thus on track to help realise radiometric traceability and characterisation within the challenging uncertainty demands of the optical components of ESA's Earth Explorer 9 FORUM mission and the NASA LIBERA mission.

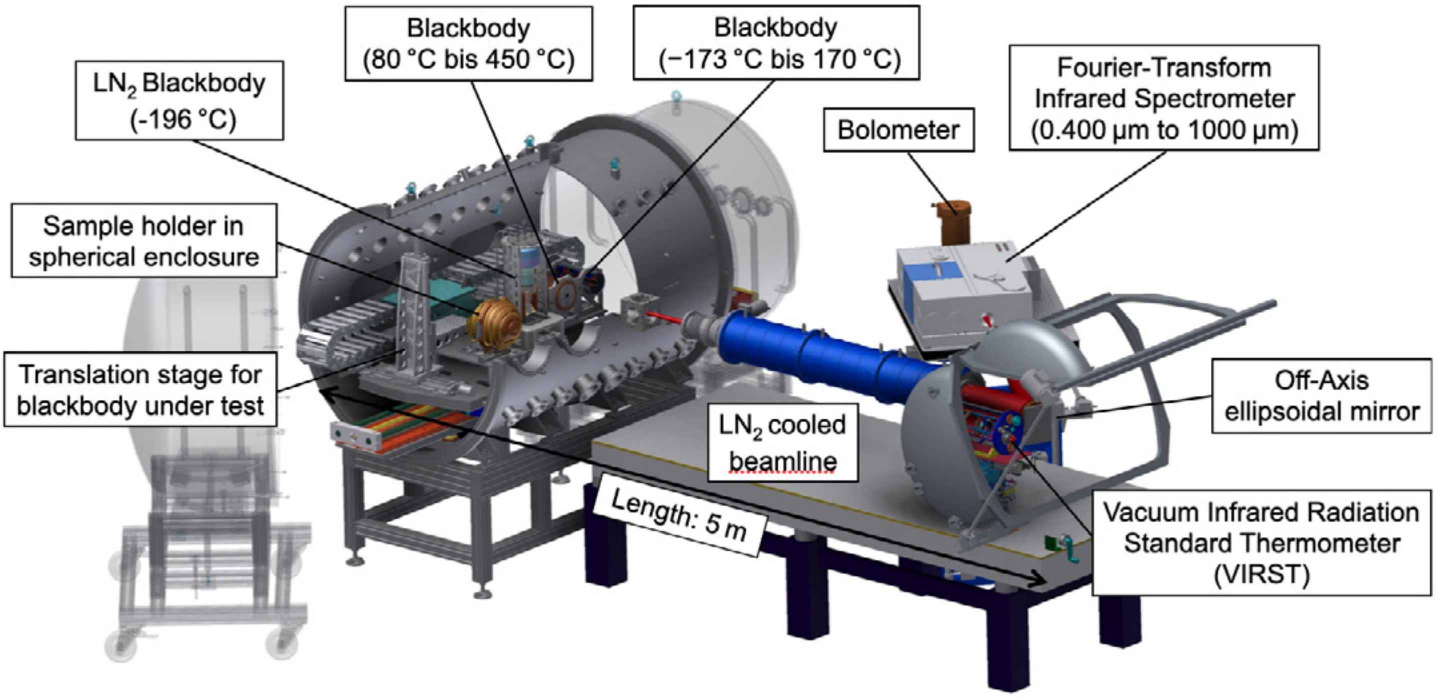

Figure 2. CAD image of PTB's Reduced Background Calibration Facility 2 (RBCF2).

PTB's new reference black body — the Hemispherical Black body

Complementary to the space measurements of Earth emitted radiation, MetEOC also supported the traceability of infrared radiation emitted by the sky towards the surface. As part of MetEOC 3 and 4 projects, a new reference black body, the Hemispherical Black body (HSBB) was developed at PTB in cooperation with Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center (PMOD/WRC).

Long-wave downward radiation is continually measured at stations around the globe, collecting data about climate change and the greenhouse effect. These measurements are typically carried out with pyrgeometers, which are spectrally broadband infrared detectors with a hemispherical acceptance angle.

To ensure the reliability and comparability of measurement data over the long term, pyrgeometers must be calibrated regularly. The HSBB was specially designed for calibrating pyrgeometers. The HSBB is traceable via the Radiation Temperature Scale of PTB to the International Temperature Scale ITS-90 and hence to the SI.

In MetEOC-4, results of comparison measurements between the measurement standard BB2007 at PMOD/WRC – a well-established reference for long-wave downward radiation measurements – and the new HSBB showed agreement within the target irradiance uncertainty of 0.5 W/m^2. Traceability of the BB2007 at PMOD/WRC to the SI provided a second independent path of traceability, while the low uncertainties associated with the HSBB raised prospects for measurements of long-wave downward radiation at lower uncertainties.

For more information visit www.meteoc.org

From 2011 to 2023, the NPL-coordinated MetEOC series of projects — supported by EURAMET's European Metrology Research Programme (EMPR) and European Metrology Programme for Innovation and Research (EMPIR) — encouraged collaboration between European National Metrology Institutes (NMIs) and partners in industry or academia. MetEOC combined ground, atmosphere, and space-based measurements to develop metrology tools and frameworks to support climate observation systems capable of increasing understanding of the drivers of climate change.

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