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Characterization of the 300 K and 700 K Calibration Sources for Space Application with the Bepicolombo Mission to Mercury

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Abstract The Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) onboard the European–Japanese space mission BepiColombo to Mercury will be launched in 2014. The MERTIS scientific objective is to identify rock-forming minerals and measure surface temperatures by infrared spectroscopy (7 μm to 14 μm) and spectrally unresolved infrared radiometry (7 μm to 40 μm). To achieve this goal, MERTIS utilizes two onboard infrared calibration sources, the MERTIS blackbody at 700 K (MBB7) and the MERTIS blackbody at 300 K (MBB3), together with deep space observations corresponding to 3 K. All three sources can be observed one after the other using a rotating mirror system. The leaders of the project MERTIS are the Westfälische University of Münster, institute for planetary investigation, Mr. Prof. Dr. H. Hiesinger (PI) and the DLR, Institute of Planetary Research Berlin-Adlershof, Mr. Dr. J. Helbert (CoPI). Both blackbody radiators have to fulfill the severe mass, volume, and power restrictions of MERTIS. The radiating area of the MBB3 is based on a structured surface with a high-emissivity space qualified coating. The relatively high emissivity of the coating was further enhanced by a pyramidal surface structure to values over 0.99 in the wavelength range from 5 μm to 10 μm and over 0.95 in the wavelength range from 10 μm to 30 μm. The MBB7 is based on a small commercially available surface emitter in a standard housing. The windowless emitter is an electrically heated resistor, which consists of a platinum structure with a blackened

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surface on a ceramic body. The radiation of the emitter is expanded and collimated through use of a parabolic mirror. The design requirements and the radiometric and thermometric characterization of these two blackbodies are described in this paper.

Keywords Calibration · Emissivity · Infrared spectroscopy · Radiation thermometry · Remote sensing

1 The BepiColombo Mission for the Comprehensive Study of Mercury

Mercury is the planet nearest to the sun. Its surface temperature reaches between 570 K and 725 K on its sunward side. These high temperatures and the small planet mass prevent it from having a permanent atmosphere. The few images of the hermian surface taken by Mariner 10 in 1972 show fissures due to volcanism and meteorite impacts. Mercury has a weak magnetic field of 0.4 μT which limits its sunward magnetosphere to 1000 km and in its direction away from the sun to 48 000 km. Extensive investigation into both the surface and the magnetic field will be an important scientific cornerstone regarding its geological structure, its chemical composition, as well as an understanding of the development of the solar system with its planets.

Up to now, Mercury is considered as one of the most unknown planets of our solar system. It is its proximity to the sun which makes Mercury unsuitable for any exact investigation by terrestrial telescopes. The European–Japanese mission to Mercury, called BepiColombo, is set to be launched in April 2014, by ESA (European Space Agency) and JAXA (Japan Aerospace Exploration Agency) [1,2]. This joint mission is concerned with the following aspects of investigation:

- the geological development of the planet
- the chemical composition of the planet's surface
- its internal structure and an investigation into its core
- the origin of its magnetic field and its interaction with the solar wind

The investigation of mercury with BepiColombo will be accomplished by two separate orbiters, the Mercury Magnetospheric Orbiter (MMO) developed by JAXA as well as by the Mercury Planetary Orbiter (MPO) from ESA. The interplanetary transfer from the earth to Mercury, that is to start from the earth orbit, will take a cruise phase of six years although a novel ion drive and several swing-by maneuvers at the earth, the moon, Venus, and Mercury will be applied. After a deceleration, the spacecraft will be injected into a polar elliptical orbit of 400 km × 12 000 km in the year 2020. There the MMO will be separated from the transfer module to investigate the solar wind as well as the magnetosphere. The MPO will pass into a deeper elliptical orbit of 400 km × 1500 km by further deceleration and investigate the planetary surface during 1 year with an optional extension of 2 years.

The Mercury Planetary Orbiter (MPO) of the ESA Bepicolombo mission is a platform for 11 instruments with different objectives: two X-ray spectrometers, a gamma-ray and neutron spectrometer, an accelerometer, a magnetometer, a radio science instrument, a particle analyzer, and four optical instruments. These instruments share a limited volume and limited energy resources resulting in low mass, low volume, and low power budget of each instrument.

Among the optical instruments, the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS), considered here, is an imaging spectrometer of the Offner type measuring the radiation of Mercury in the 7 μm to 14 μm region with a spectral resolution of 90 nm per pixel and a geometrical resolution of 500 m or better, complemented by an infrared radiometer for the wavelength region from 7 μm to 40 μm.

The scientific objective of the spectrometer is the study of Mercury's surface composition, especially the identification of rock-forming minerals and the mapping of the mineralogy of the surface, whereas the radiometer is designed to study the surface temperature and the thermal inertia.

2 MERTIS Principal Design

MERTIS uses an integrated instrument approach combining an IR-mapping spectrometer covering 7 μm to 14 μm based on a push-broom principle with a radiometer (Mercury Radiometer: MRAD) for 7 μm to 40 μm (Fig. 1). The instrument achieves the requirements listed in Table 1.

MERTIS uses all-reflective optics with an exquisite F-number of f/2 together with diffraction-limited imaging quality on the slit as well as on the detector. Corresponding to the usual extreme limitation of all resources in planetary missions, it is highly miniaturized, very lightweight, and sparing in power consumption.

3 Radiometric Calibration Concept

Besides geometrical and spectral calibration, each detector pixel will be calibrated radiometrically. To do this, two onboard blackbodies, the MERTIS blackbody at 700 K (MBB7) and the MERTIS blackbody at 300 K (MBB3), together with deep space

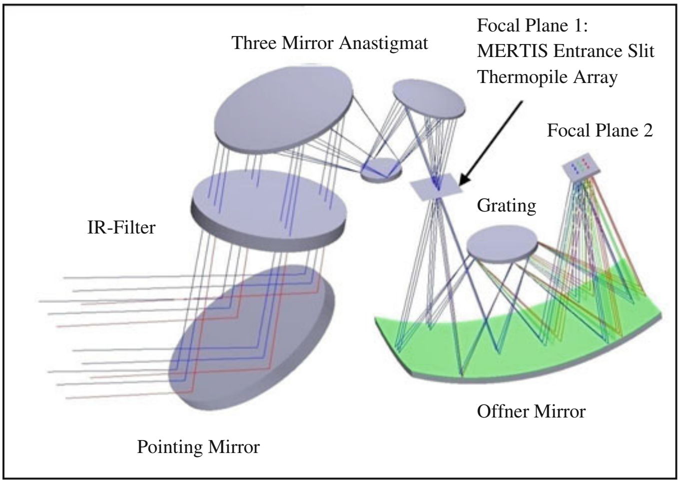

Fig. 1 Optical design of MERTIS (according to H. Hirsch)

Table 1 Main performance parameters of MERTIS

Spectral coverage	7 μm to 14 μm
Focal length	50 mm
Total field of view	±2°
F-number	f/2
Spectral channel width	90 nm to 200 nm
SNR for spectral range 7 μm to 14 μm	>100
Spatial resolution for global mapping	500 m
Target observation with better than 500 m	5 % to 10 % of the surface
Total mass (incl. margin 20 %)	3.4 kg
Average power consumption	8 W to 13 W

observation are used. They can be observed one after the other using a rotating mirror system. Therefore, a good calibration for the very high temperatures at the solar-illuminated side, but also for the low temperatures at the dark side of Mercury can be targeted.

The signal S_λ measured at a certain pixel is given by $S_\lambda = a_\lambda L_\lambda + b_\lambda$, where a_λ, L_λ, and b_λ are the spectral responsivity of the instrument, the spectral radiance (of Mercury or of the blackbodies), and a bias, respectively. To eliminate the two unknowns, a_λ and b_λ, at least two blackbodies of known spectral radiance at different temperatures, T_1 and T_2, are needed. Thorough investigations of the quality of the blackbodies (determination of emissivity and temperature) and of the rotating mirror system will lead to a good estimation of the uncertainty of the measured spectral radiance L_λ from the Mercury surface.

If sufficient mass, volume, and power would be available, precisely controlled isothermal cavities could be used as blackbodies and the uncertainty ΔL_λ could be kept very low. However, because of the severe mass, volume, and power limitations, other solutions must be chosen. To calibrate MERTIS with such non-ideal blackbodies, each blackbody itself must be calibrated as a function of its applied voltage and current using high-accuracy laboratory blackbodies of known radiance (see below).

3.1 Requirements for the In-Flight High-Temperature Calibration Source MBB7

The high-temperature calibration source MBB7 for the Mercury Radiometer and Thermal Infrared Spectrometer will be used for reference measurements with simulated Mercury day-time surface radiation temperatures. The spectral range, which is used for calibration measurements, extends from 7 μm to 40 μm. The mass of this calibration unit must not exceed 150 g. The operational ambient temperature is to be between −20 °C and +50 °C. The calibration source has an aperture of 32 mm × 38 mm and is actively heated and thermally controlled. The power requirement of the calibration unit is not to exceed 1 W. The spectral characteristics are not to change for the duration of the flight to Mercury and during the first year of the mission. The calibration source must be resistant to cosmic radiation, and the mechanical structure must resist the launch loads.

Whereas the aperture for the infrared calibration source is required to be 32 mm × 38 mm and the power requirements are restricted to a maximum of 1 W, only a comparatively small radiation source can be used. Therefore, the radiation from the source must be expanded and collimated with the help of a parabolic mirror.

3.2 The Applied Infrared Emitter EMIRS 200

Common search by the Astro- and the DLR MERTIS team world-wide revealed two infrared emitters with the same basic technology which fulfill the requirements regarding the high-spectral emissivity.

The selected emitter, of the Type EMIRS 200 (Fig. 2), achieves the required temperature for the radiating surface of 700 K in air with an electrical power of 450 mW and under vacuum with 120 mW. The emitter surface is 1.8 mm × 2.1 mm. Figure 3 shows its striped structure, made up of platinum on a special ceramic. To increase the radiating power, the platinum surface is blackened. The radiation source is an electrically heated resistor, which consists of a platinum structure. A particular temperature corresponds to a specific resistance. The temperature of the emitter surface is controlled via its electrical resistance. The regulation procedure uses a resistance bridge to keep the resistance of the radiation source constant. This procedure operates accurately under vacuum and keeps the surface at a constant temperature.

With variable ambient temperatures, however, the temperature distribution on the emitter surface changes. This must be taken into consideration, when the emitter is used as part of a calibration source.

3.3 Analysis of Temperature Distribution on the Emitter Surface of EMIRS 200

The absolute temperature and its spatial distribution over the surface of the radiator is a significant factor for the use of the emitter as a calibration source with an established spectral characteristic. The heated area of the emitter (1.8 mm × 2.1 mm) was

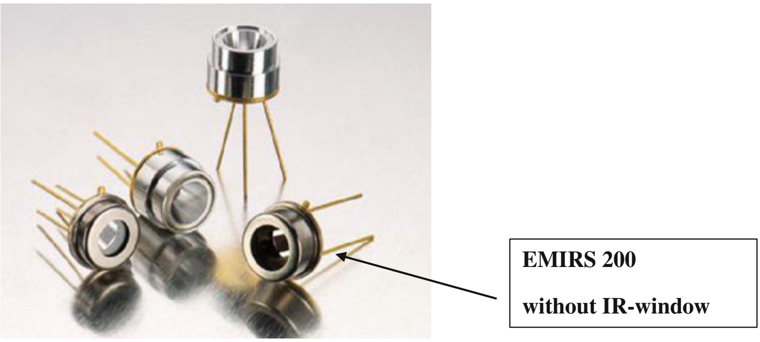

Fig. 2 Photo of the EMIRS 200 infrared emitter, taken from the prospect of the Swiss company LEISTER. The emitter is in a TO 39 standard housing; the housing diameter is about 8 mm

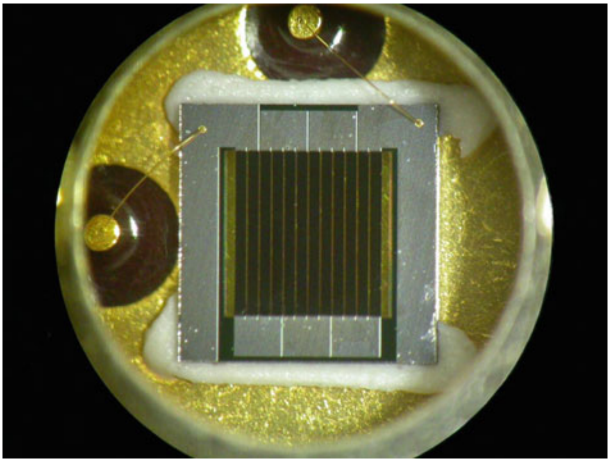

Fig. 3 Microscope photo of the radiating surface of the EMIRS 200 infrared emitter

observed with a calibrated infrared camera type Radiance PM from Amber, USA. The camera was used with a microscope objective, Type ASIO, with a magnification of 1:1 from Janos Technology, Inc. The camera is a mid-wave thermal imager working in a spectral range from 3 μm to 5 μm with an indium antimonide detector, with a linear split Stirling cooler. The pixel format is 256 × 256, and the NETD is given to 25 mK by the use of standard optics.

With the microscope objective, the resulting field of view is 9.7 mm × 9.7 mm. From this follows that the emitter surface is imaged onto 48 × 55 pixels. The distance between the objective and the emitter surface was 65 mm. The use of the microscope objective required a calibration of the thermal imager with this specific objective. This was accomplished against the heat-pipe blackbodies of PTB [3] equipped with apertures of 10 mm in diameter at different radiation temperatures in the relevant temperature range. With the help of an interpolation formula based on a physical model of the radiation thermometer and Planck's law [4], the calculation of any temperature value in this temperature range was feasible.

The temperature distribution on the emitter surface of EMIRS 200 was determined in air and under vacuum (Fig. 4) for different values of the supplied electrical power. Additionally two different holders, an aluminum holder and a Teflon holder, were used for mounting of the EMIRS 200 emitter. During all measurements, a reference blackbody was used to monitor the stability of the calibrated thermal imager.

For the measurements under vacuum, a vacuum chamber with a ZnSe-window of 100 mm in diameter and, as a reference blackbody, a cavity radiator type SR 10C with an additional aperture stop of 10 mm in diameter were used. The pressure of the vacuum was below 10^{-1} Pa. The transmission and radiation of the ZnSe-window in the spectral range of the Amber infrared camera were determined with the measured signals for different temperatures of the EMIRS 200 emitter with and without the ZnSe-window

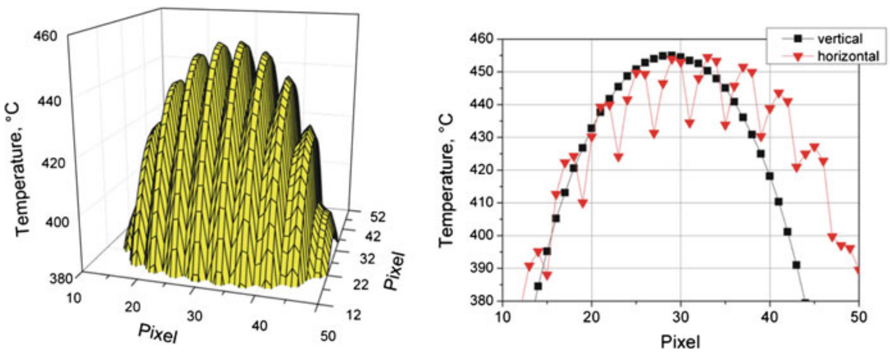

Fig. 4 *Left-hand side* temperature distribution of the EMIRS 200 infrared emitter mounted with a Teflon holder under vacuum. Shown is a surface area of 1.5 mm × 1.5 mm. The temperature varies from 455 °C to 380 °C in this area. *Right-hand side* horizontal and vertical temperature distribution cutting the center in the left-hand image

in the optical path in air. The ambient conditions during all measurements were kept constant.

3.4 Optical Design of the Calibration Source MBB7

For calibration of the MERTIS instrument, a special calibration source (MBB7) based on the EMIRS 200 infrared emitter with a collimating optics has been built. The MBB7 calibrating device combines the high-temperature EMIRS 200 infrared emitter with a parabolic collimator in an on-axis arrangement (Fig. 5). This design has been selected due to its superior imaging quality compared with an off-axis design. Furthermore, the on-axis design is much more compact than an off-axis one and saves volume and mass.

The focal length of the parabolic collimator is 15 mm and much shorter than the focal length of the "three mirror anastigmat" (TMA) of MERTIS with 50 mm so that only the central part of the emitter is imaged onto the focal plane 1 (Fig. 5). Because of this, the significant temperature decrease from the center to the boundary of the infrared emitter (Fig. 4) is limited to that of the decay inside the central area. Moreover, the emitter is slightly de-focused with respect to the parabolic mirror to smooth out the stripe structure of the emitter.

3.5 Temperature Distribution of MBB7

To investigate the MBB7 calibration, source measurements with a thermal imager working in a spectral range from 7.7 μm to 9.3 μm were accomplished. The thermal imager was of the Titanium 530L type from Cedip Infrared Systems with a spatial resolution of 320 × 256 pixels and with a noise equivalent temperature difference (NETD) of <20 mK. It works with a MCT detector with a Stirling cooler and with a 25 mm lens as standard optics. The Titanium 530L was calibrated at different temperatures

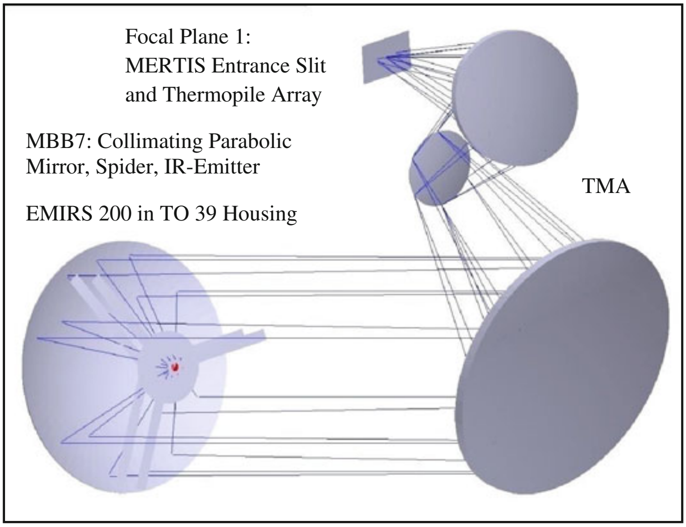

Fig. 5 Optical design of the MERTIS calibration source (MBB7) and the three mirror anastigmat (TMA) of MERTIS

against the heat-pipe blackbodies of PTB. The measurements were performed in air and with a fixed supplied electrical power to the EMIRS 200 emitter. The thermal imager was aligned on the optical axis of the collimated beam. The optics of the thermal imager were either adjusted to an infinite object distance or focused to different object distances between 19 mm and 320 mm.

The measurements with the optics adjusted to infinite object distance show the effective radiation temperature distribution of the emitter surface (Fig. 6). As the emitter is slightly out of focus of the parabolic collimating mirror, the striped temperature structure of the emitter surface is smoothed out (compare Fig. 6 with Fig. 4). The thermal image gained with the thermal imager focused to an object distance of 95 mm is shown in Fig. 7. This focused measurement shows the radiation temperature distribution of the backside of the EMIRS 200 emitter and the spider construction which holds the emitter in front of the collimating mirror (Fig. 7).

Since the MERTIS instrument is built to observe objects at an infinite object distance, the image of MBB7 on the MERTIS entrance slit will be smoothed out as is shown in Fig. 6. In fact, there is not a space qualified blackbody in a strict sense for higher temperatures complying with the rigorous limitations of low mass, volume, and power consumption typical for planetary missions. Therefore, the final step of the calibration procedure will be the spatially and spectrally resolved absolute calibration of the radiation temperature of the MBB7. It has to be performed by comparing the MBB7 to a blackbody radiator standard of the PTB with an optical system identical to the MERTIS system. Therefore, MERTIS itself will be used to perform this comparison. The result will be a library of calibrated MBB7 spectra of MERTIS taken under different ambient conditions.

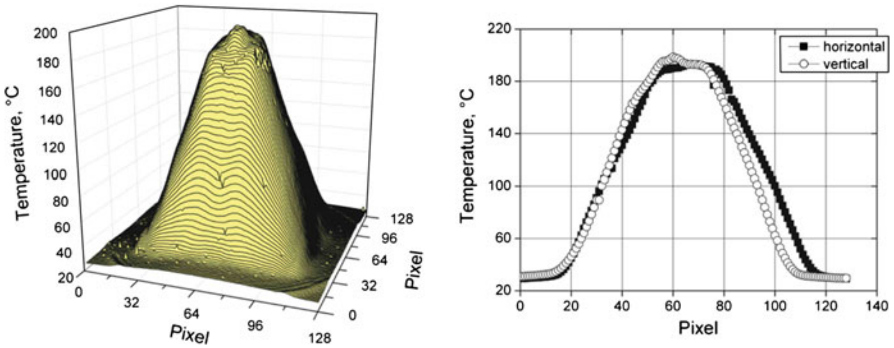

Fig. 6 *Left-hand side* effective radiation temperature image of MBB7 measured with a thermal imager adjusted to infinite object distance. As the EMIRS 200 emitter is slightly out of focus of the parabolic collimating mirror, the striped temperature distribution of the emitter is smoothed out. *Right-hand side* horizontal and vertical cross sections of effective radiation temperature distribution cutting the center in the left-hand image

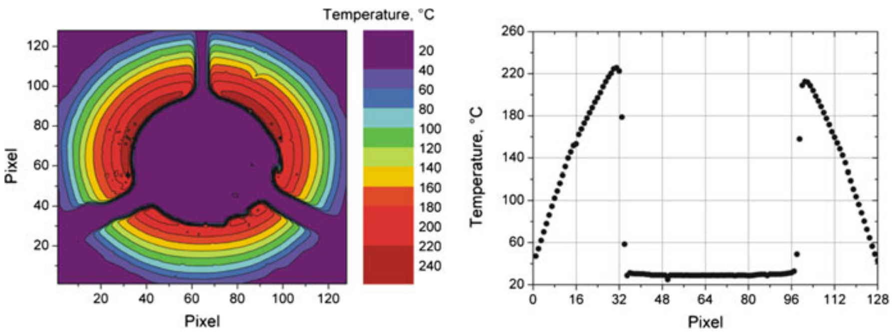

Fig. 7 *Left-hand side* effective radiation temperature image of the MBB7 measured with a thermal imager focused to an object distance of 95 mm. It shows the radiation temperature distribution of the backside of the EMIRS 200 emitter and the spider structure which holds the emitter in front of the collimating mirror. *Right-hand side* horizontal cross sections of effective radiation temperature distribution cutting the center in the left-hand image

3.6 Characterization of the MBB3

The measurements of the MBB3 reported here were performed with the setup for the determination of the directional spectral emissivity at PTB. The applied measurement principle relies on a radiometric comparison of the spectral radiance of the MBB3 with respect to a high-quality blackbody. This setup and the procedures for the measurement and evaluation of the emissivity were recently described in detail in [5] and the associated uncertainty in [6]. The final prototype of the MBB3 is shown in Fig. 8.

The requirement for the MBB3 was to provide a directional spectral emissivity above 0.97 in the range from 7 μm to 30 μm. To investigate and optimize the directional spectral emissivity of the MBB3, in a first step the directional spectral emissivity of a planar aluminum plate coated with the intended surface coating of the MBB3 was

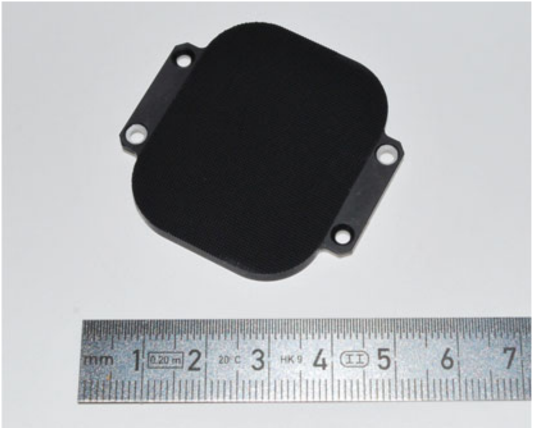

Fig. 8 Picture of the prototype of the MBB3 with pyramidalized surface

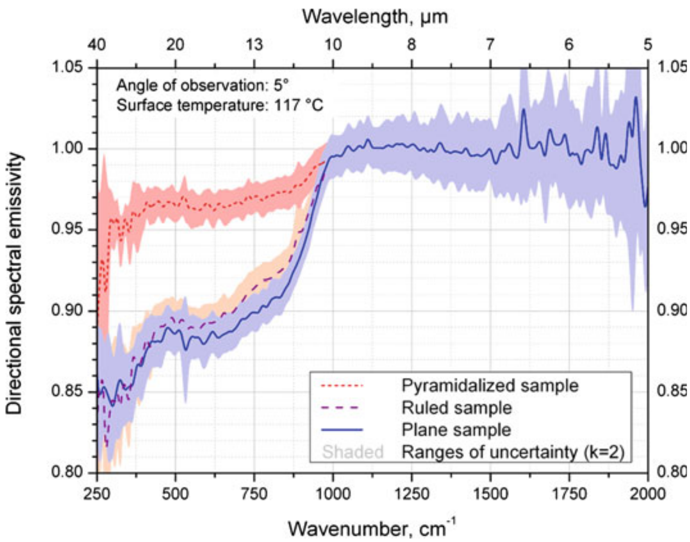

Fig. 9 Directional spectral emissivity of a plane, a ruled and a pyramidalized sample surface of the MBB3 coated with the high-emissivity space qualified surface coating intended for the MBB3

determined. The plane sample had to be heated to a temperature of 117 °C to perform the measurement with a reasonable signal-to-noise ratio. The result is shown in Fig. 9.

The measurements were repeated at 250 °C, and within the uncertainty of the measurement, no variation of emissivity with temperature could be found. This is a good indication that the directional spectral emissivity at 25 °C will show an identical shape as the obtained results at 117 °C. In the following, two prototypes for the MBB3 were investigated, one with a ruled surface and another one with a pyramidalized surface. The results are also shown in Fig. 9.

Already the plane surface shows a remarkable high emissivity in the range from 5 μm to 10 μm. Toward longer wavelengths the emissivity goes down to 0.85. Ruling the surface before coating leads only to a slight increase of the directional spectral emissivity in the wavelength range from 10 μm to 20 μm. Machining small pyramids in the surface before coating yields an increased emissivity of above 0.96 in the range from 7 μm to 30 μm.

With this surface treatment, the emissivity of the MBB3 nearly meets its requirement. When operated as a reference blackbody, the temperature of the MBB3 is determined by two PT100 sensors mounted in two cylindrical bores of dimension 1.6 mm by 20 mm drilled at a distance of 2 mm parallel to the emitting surface.

4 Summary

In cooperation between PTB, Astro- und Feinwerktechnik, and DLR, two high-emissivity temperature radiation sources (MBB3 and MBB7) have been designed and radiometrically characterized which meet the severe mass, volume, and power restrictions of the BepiColombo space mission. Both infrared sources will be applied for the in-flight radiometric calibration of the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) onboard BepiColombo.

However, further investigations are needed on the performance of both blackbodies with respect to meeting the design criteria, e.g., the temperature stability of the MBB7, influence of changing ambient temperature on the temperature distribution of EMIRS200, and the achievable overall uncertainty of the radiation temperature under flight conditions.

Note

References to commercial products are provided for identification purposes only and constitute neither endorsement nor representation that the item identified is the best available for the stated purpose.

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