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COMPACT BLACKBODY CALIBRATION SOURCES FOR IN-FLIGHT CALIBRATION OF SPACEBORNE INFRARED INSTRUMENTS

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ABSTRACT

High-emissivity blackbodies are mandatory as calibration sources in infrared radiometers. Besides the requirements on the high spectral emissivity and low reflectance, constraints regarding energy consumption, installation space and mass must be considered during instrument design. Cavity radiators provide an outstanding spectral emissivity to the price of installation space and mass of the calibration source. Surface radiation sources are mainly limited by the spectral emissivity of the functional coating and the homogeneity of the temperature distribution. The effective emissivity of a “black” surface can be optimized, by structuring the substrate with the aim to enlarge the ratio of the surface to its projection.

Based on the experiences of the Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) calibration source MBB3, the results of the surface structuring on the effective emissivity are described analytically and compared to the experimental performance. Different geometries are analyzed and the production methods are discussed. The high-emissivity temperature calibration source features values of 0.99 for wavelength from 5 μm to 10 μm and emissivity larger than 0.95 for the spectral range from 10 μm to 40 μm .

I. INTRODUCTION

Existing and future instruments for earth observation satellites as well as for exploration missions for planetary research are focused on the precise spectral characterization of the earth’s or planet’s surface radiation. In addition to imaging instruments for application wavelengths in the visible spectrum (VIS), the infrared (IR) spectrum is of elevated scientific and application-oriented interest.

The spectrally resolved radiometry data in the atmospheric windows in the range $3 \mu\text{m} \leq \lambda \leq 13 \mu\text{m}$ is used for Earth Observation (EO) and allows the characterization of earth’s ocean, land or ice surface temperatures [1]. The addition of dedicated spectral channels is used to analyze the distribution of aerosols, including water vapor and clouds, in our atmosphere as well as their distribution and movement [2].

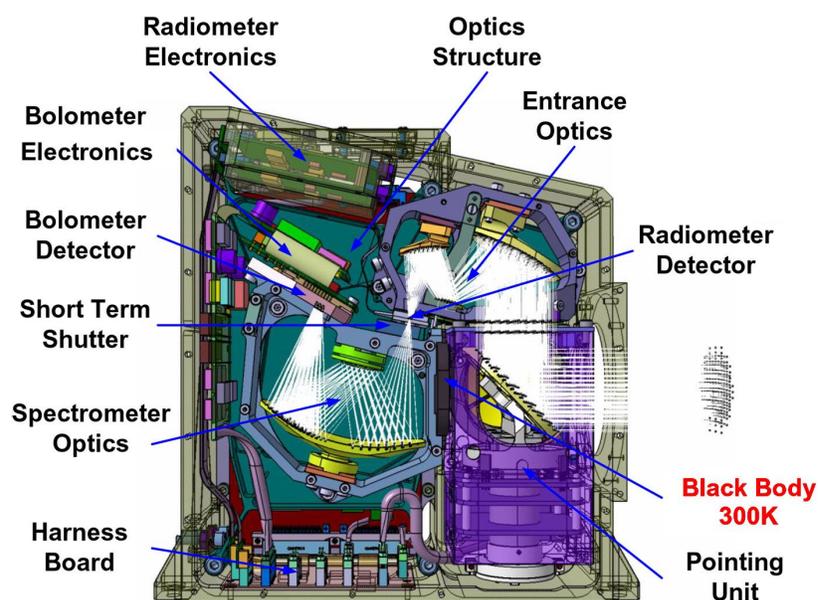


Fig. 1. Functional configuration of MERTIS (Courtesy DLR) [4].

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In case of extra-planetary missions, the spectral range is adjusted to fit the radiating spectrum of the object's surface that is to be monitored [3]. Here, besides the surface temperature, also the mineralogical composition is of interest to the scientific community. A prominent example of such an instrument is the Mercury Radiometer and Thermal Infrared Imaging Spectrometers (MERTIS), which is a contribution to ESA's BepiColombo mission that will be launched in 2016 to its journey to Mercury. The instrument combines a pushbroom IR grating spectrometer for the application wavelength between $7 \mu\text{m} \leq \lambda \leq 14 \mu\text{m}$ with a micro-radiometer, sensitive for IR-radiation in the range between $7 \mu\text{m} \leq \lambda \leq 40 \mu\text{m}$ [4]. The functional configuration is shown in figure 1.

Changes in the optical performance of such devices are caused by offsets, gains and drifts of the optical elements (such as the degradation of the infrared detector). In-flight calibration of the optical path using high emissivity on board calibration sources is therefore a necessary requirement for the absolute radiometric acquisition of the spectral radiance. The precise radiometric calibration of any instruments for the above mentioned missions using a sophisticated and space qualified blackbody is mandatory for an absolute measurement and the comparability of different results over time and over various devices.

II. BLACKBODY CALIBRATION SOURCES

An ideal blackbody is a physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence [5]. It emits electromagnetic radiation according to Planck's law, meaning that it has a spectrum that is determined by its temperature alone, not other physical properties. By definition, a blackbody in thermal equilibrium has an spectral emissivity of $\epsilon(\lambda) = 1.0$.

Any technical blackbody is limited in its physical properties. These limitations are caused by the limited spectral emissivity as result of the residual reflectivity and the limited isothermality. A well designed technical blackbody has a spectral emissivity of $0.97 \leq \epsilon(\lambda) < 1.0$.

Technical blackbodies are designed as surface or cavity radiation sources. Cavity radiation sources provide the advantages of the independence from the energy density, as well as the independence from the thermo-optical properties of the radiating surfaces within the cavity. The emitted radiation of a well developed cavity radiation source depends on the temperature of the thermodynamic equilibrium. Due to the required diameter-to-length ratio, the small aperture as well as overall volume and the energy requirements, the use of pure cavity radiators is mainly limited to earthbound calibration sources as part of the Optical Ground Support Equipment (OGSE).

A compact design is offered by surface radiation sources. The advantages are the small volume, the low mass and low energy consumption of the subsystem. The thermo-optical properties of a radiating surface are used to emit a predictable spectrum in the instruments application wavelength. The surface of the emitter shall feature an emissivity ϵ and absorption close to 1 in the application's spectral range. Any reflections on the blackbody surface contribute to the uncertainty of the calibration source.

Although the thermo-optical properties of different black surface treatments are optimized by functional coatings, micro structuring or surface modifications and their combinations, the spectral emissivity $\epsilon(\lambda)$ is limited fundamentally. The emissivity of typical high emissivity coatings are ranging from $0.85 \leq \epsilon_0 \leq 0.97$ in the spectral range $5 \mu\text{m} \leq \lambda \leq 40$. Prominent examples are summarized by [6, 7, 8, 9, 10]. Since the instrument's performance requirements are in many cases above these values, a simple coating of the emitter surface is not sufficient. An enhancement of the spectral emissivity is necessary to improve the precise radiometric calibration of infrared radiometers.

III. ENHANCEMENT OF THE EFFECTIVE SPECTRAL EMISSIVITY

A significant increase of the effective emissivity over the spectral range is achieved if the radiating surface area is increased, while the projected surface area is maintained. This relation is describes in equation (1) and can be found in [11].

$$\epsilon_{\text{eff}} = \frac{1}{\left(1 + \left(\frac{1}{\epsilon(\lambda)} - 1\right) \cdot \frac{A}{A_{\text{proj}}}\right)} \quad (1)$$

Figure 2 shows spectral emissivity of a plane aluminum surface, which is coated with a functional high emissivity black coating subsequent to a conventional machining and cleaning procedure. In the wavelength range $5 \mu\text{m} < \lambda_0 < 10 \mu\text{m}$, the spectral emissivity is $\epsilon_0 > 0.97$. The black optical coating is optimized for the near and mid-infrared spectrum up to a wavelength of $10 \mu\text{m}$. In the spectral range $10 \mu\text{m} < \lambda_0 < 40 \mu\text{m}$, the spectral emissivity is reduced to values $\epsilon_0 > 0.85$.

Figure 2 also contains two plots of the simulated effective emissivity of the same black coating on the aluminium substrate. Equation 1 is applied to the measured profile with the assumption of a surface ratio of 1/2 and 1/5. The surface area is enlarged, while the projected surface is kept equal. As result of the simulation, the effective emissivity ϵ_{eff} is enhanced. The surface enlargement by factor two raises the effective emissivity to $\epsilon_{\text{eff}} > 0.92$. The surface enlargement by factor five would result in an effective emissivity $\epsilon_{\text{eff}} > 0.996$ with an average emissivity of 0.999.

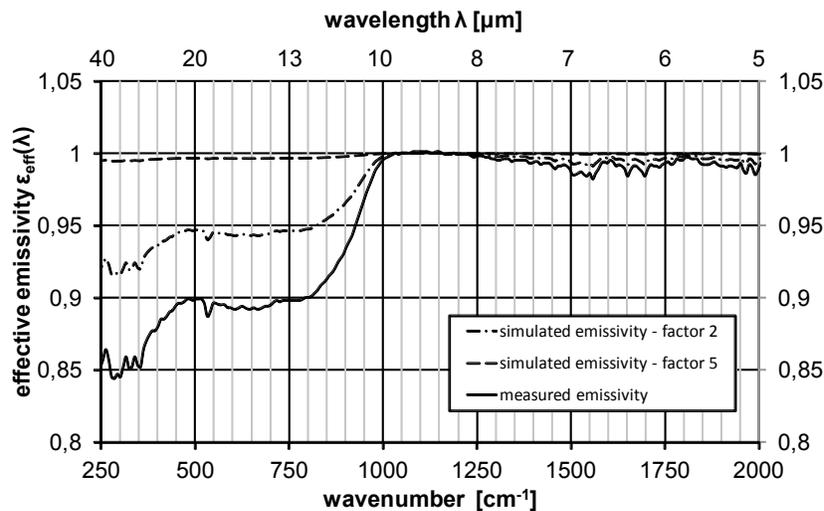


Fig. 2. Directional spectral emissivity of a plane surface with a functional high emissivity black coating and simulations of the directional effective emissivity as result of an increased surface area.

The simplifications of the chosen model have to be considered, to assess the quality of the above made prediction. The simulation is based on the assumption of an isothermal blackbody. A larger radiating surface would lead to a thermal gradient within the emitter and hence to an uncertainty of the blackbody radiation source. Therefore a trade-off between an optimized effective emissivity and the surface structures to enlarge the radiating area has to be found.

Figure 3(a) illustrates a possible example geometry for a blackbody surface structure in perspective. The radiator is composed of macroscopic pyramids. In this example, the structures have a base length of 0.5 mm and an apex height of 0.433 mm. The base area of 0.25 mm^2 is magnified by the factor of approx. two.

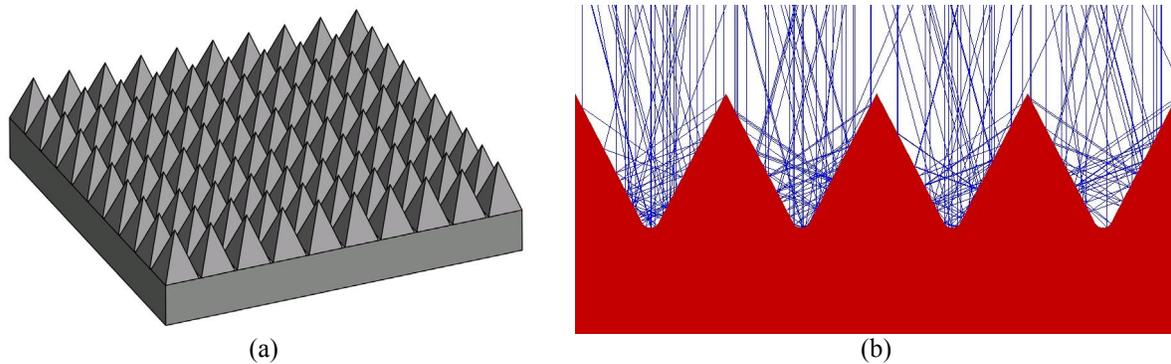


Fig. 3. Enhancement of the effective emissivity by macroscopic surface structuring
(a) CAD-Model of a pyramid structure to enlarge the surface (b) Ray-tracing of beams for a multiple reflection on the low reflectance surface

In contrast to a plane surface, where an incident beam is reflected once and might enter the optical system, the macroscopic surface structuring forces a multiple reflection before the beam propagates in direction of the receiver, as shown in figure 3(b). With each reflection on the surface with a low reflectance and high absorbance, the power of the reflected beam will be reduced to only a fraction of its original power. For example, in the considered coating in figure 2 at a wavelength of $\lambda_0 = 12 \mu\text{m}$ the emissivity of the smooth surface is $\varepsilon_0 = 0.95$. The surface's coefficient of reflection is $\rho(\lambda_0) = 5\%$. Since the beam is reflected twice by the surface structure, the remaining power of the incident beam would be 0.25%.

By combining a suitable high emissivity black coating with a well developed macroscopic structure, the incident radiation power is reduced to a fraction, so that the spectrometer detects almost exclusively the radiation of the calibration source, and only a very small part of the reflected radiation from the environment. As consequence the uncertainty of the spectral emissivity of the coating is significantly reduced. This principle can be found in the patent literature [12, 13].

Possible imperfections are the radii of the grooves between the pyramidal faces due to the limited edge radius of the cutting tools. Incident rays might be reflected in these valleys and thus contribute to the error budget. Also the heat distribution in the pyramid structure has to be considered in the design phase.

IV. CALIBRATION SOURCES WITH ENHANCED SPECTRAL EMISSIVITY

The MERTIS instrument design, introduced in section I, is based on a highly integrated and miniaturized concept, featuring low mass of only about 3 kg and a sophisticated design. The instrument calibration is achieved with two technical calibration sources and the view into the cold space. The onboard infrared calibration sources are the active MERTIS blackbody at 700 K (MBB7) [14] and the passive MERTIS blackbody at 300 K (MBB3). The surface radiation source MBB3 is highlighted in the functional configuration of the instrument in figure 1. Both infrared calibration sources were developed, produced and space qualified by Astro- und Feinwerktechnik Adlershof GmbH.

The blackbody radiators have to fulfill the mass, volume, and power restrictions of the extraterrestrial mission. The passive calibration source MBB3, has a mass of 18 g, incl. two PT100 temperature sensors and the harness. The aperture size is 42 mm x 34 mm. The high emissivity of the MBB3 is based on a structured surface with a qualified coating. The enhancement of the effective emissivity of the surface radiator is achieved using the above introduced approach of surface enlargement and reflectance reduction.

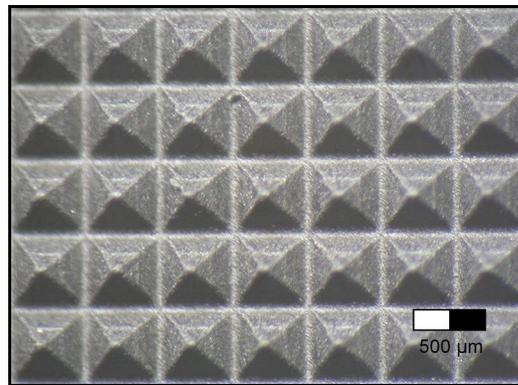


Fig. 4. Microscope Image of the bare aluminium surface of the MBB3 calibration source substrate

Figure 4 shows the microscopic image of the surface structure of the uncoated MBB3 calibration source. A variety of different structures, including groves and pyramids with different opening angles were analyzed prior to the final design. All geometries have been manufactured using cutting edge machining technologies. The evaluation of the surface quality in terms of homogeneity, burrs and functionality lead to the conclusion that the pyramid structure as outlined in section III is best suited for the use as surface structure for the calibration source MBB3.

The radiometric characterization of the calibration sources was achieved in cooperation with the Physikalisch-Technische Bundesanstalt, Infrared Radiation Thermometry working group. The measurements of the MBB3 were performed with the setup for the determination of the directional spectral emissivity [15]. The applied measurement principle is based on a radiometric comparison of the spectral radiance of the MBB3 to a cavity blackbody as described in section II. The setup and the procedures for the measurement and evaluation of the emissivity were described in detail by MONTE AND HOLLANDT [16].

Figure 5 illustrates the enhancements of the effective emissivity as result of the pyramidal structure of the emitting surface. The surface enlargement by pyramidal structuring of the substrate before the coating yields an increased emissivity. The effective emissivity ϵ_{eff} of the blackbody is 0.99 in the spectral range from $5 \mu\text{m} < \lambda < 10 \mu\text{m}$. Thus the calibration source is well suited for earth observation missions, where the requirements on mass, volume and power consumption are demanding. In the range from $10 \mu\text{m} < \lambda < 30 \mu\text{m}$, the effective emissivity ϵ_{eff} is well above 0.96. The emissivity drops to 0.9 for the spectral range $30 \mu\text{m} < \lambda < 40 \mu\text{m}$. Values of $\epsilon_{\text{eff}} > 1$ in figure 5 are not reasonable and a result of the uncertainty of the measurement. The uncertainty is illustrated as shaded area.

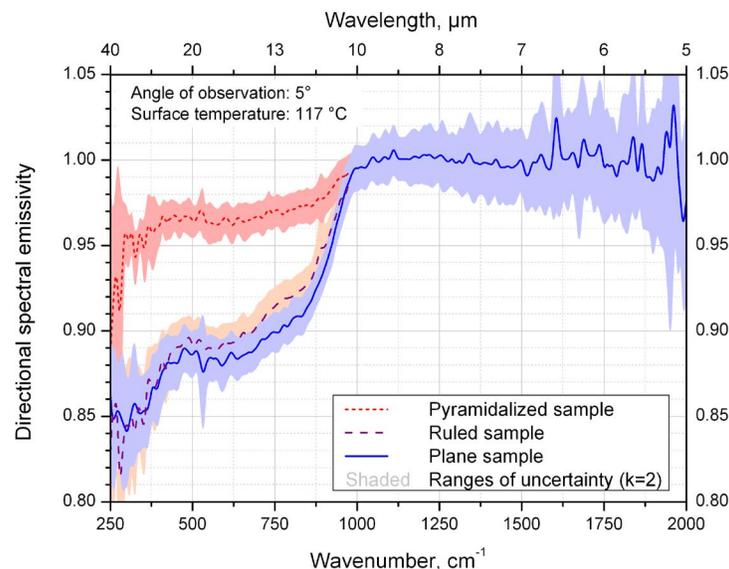


Fig. 5. Directional spectral emissivity of a plane, a ruled and a pyramidalized sample of the MBB3 coated with the high-emissivity space qualified surface coating intended for the MBB3 [15]

The measured directional spectral emissivity $\epsilon_{\text{eff}}(\lambda)$ is in good compliance to the simulated effective emissivity with a surface enlargement of factor two as shown in figure 2. The deviations between the two profiles are assumed to be a result of the surface roughness of different machining processes and a contribution of the measurement uncertainty, illustrated as shaded area in figure 5.

The high-emissivity passive IR-calibration source MBB3 is shown in figure 6. When operated as a reference blackbody, the temperature of the MBB3 is determined by two PT100 sensors mounted in two cylindrical bores close to the emitting surface. The absolute temperature measuring accuracy is 30 mK. The data processing is achieved using an external electronic board. The performance parameters of the MERTIS calibration source MBB3 are summarized in table 1.

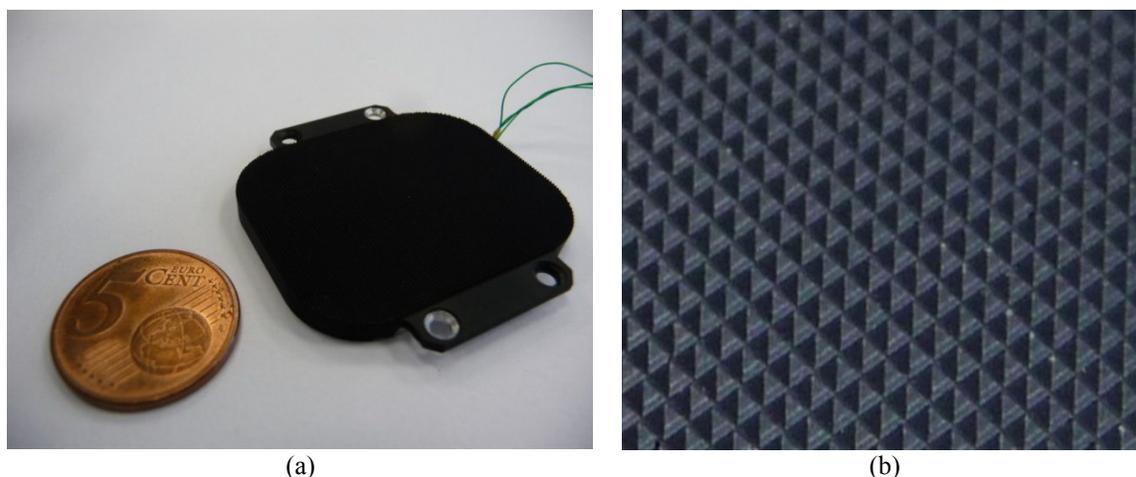


Fig. 6. High-emissivity in-flight passive IR-calibration source MBB3 for MERTIS
(a) Completely integrated Flight Spare incl. PT100 temperature sensors and harness, (b) surface structure of the coated MBB3 radiation source

Tab. 1. Performance parameters of MBB3

Spectral range for calibration measurements	$5 \mu\text{m} < \lambda < 40 \mu\text{m}$
Nominal radiation temperature	$300 \text{ K} \pm 20 \text{ K}$
Emissivity:	
$5 \mu\text{m} < \lambda < 10 \mu\text{m}$	0.99
$10 \mu\text{m} < \lambda < 30 \mu\text{m}$	0.95
$30 \mu\text{m} < \lambda < 40 \mu\text{m}$	0.90
Homogeneity of the temperature over the aperture	$< 0.4 \text{ K}$
Knowledge of radiation temperature	$\pm 0.1 \text{ K}$
Mechanical properties	
Mass (without electronics)	18 g
Dimension (without electronics)	42 mm x 34 mm x 4 mm
Electrical properties	
Nominal supply voltage	7.2 V (-0.2 V ... +0.3 V)
Power consumption	$\sim 0.7 \text{ mW} / \text{channel}$
Data Interfaces	analog interface (2 PT100 sensors) to external electronics (also space qualified)
General	
Operation temperature range	$+10^\circ\text{C}$ to $+30^\circ\text{C}$
Non-operation temperature range	-30°C to $+50^\circ\text{C}$

Further examples for the successful use of IR calibration sources, according to the principle described above, are the calibration source of the Planet Fourier Spectrometer (PFS) of the Venus Express mission and the in-flight calibration source of MASCOT radiometer (MARA) DLR Institute of Planetary Research.

The MARA blackbody calibration source, which in contrast to the MERTIS calibration source is actively thermally controlled, is shown in figure 7. The surface is homogeneously heated by a thermoelectric conversion to a dedicated radiation temperature. The blackbody emitter is based on an aluminum alloy with an elaborated thermal conductivity. The direct integration of mounting and mass reducing features of the flight hardware allows minimizing the mass to approx. 100 g with a radiating aperture of approximately 90 mm x 75 mm. The integration of the calibration source and the principle of the sensor head are described by GROTT ET AL. [17].



Fig. 7. MARA active in-flight IR-calibration source

V. CONCLUSION

Space qualified high-emissivity coatings with a broad spectral range and high performance are still under development. To enhance the thermo-optical performance of commercially available space qualified coatings, a surface enlargement with pyramidal structures is proposed. Simulations and experimental results prove the enhancement of the effective emissivity of compact blackbody calibration sources for in-flight calibration of spaceborne infrared instruments.

The developed blackbody calibration sources can be temperature controlled passively or actively. Therefore the precise radiometric calibration of infrared radiometers for earth observation and extra-planetary observation missions is ensured. An absolute measurement and the comparability of different results over time and over various devices are achieved using such calibration devices.

The ongoing development addresses the further improvement of the calibration source emitter geometry in combination with the enhancement of the emissivity coating. Astro- und Feinwerktechnik Adlershof GmbH provides customized solutions including the development, manufacturing, verification and space qualification of compact blackbody calibration sources for in-flight calibration of spaceborne infrared instruments.

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