Mercury radiometer and thermal infrared spectrometer—a novel thermal imaging spectrometer for the exploration of Mercury

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Abstract: The MERTIS instrument is a state of the art imaging spectrometer in the TIR range onboard ESA's Bepi Colombo mission to the planet Mercury. MERTIS has four science goals: the study of Mercury's surface composition, identification of rock-forming minerals, mapping of the surface mineralogy, and the study of surface temperature variations and of the thermal inertia. The instrument is designed to achieve a signal-to-noise-ratio above 100 in the 7-14 µm range with a spectral channel width of 90 nm and a nominal spatial ground resolution of 500 m within the complex thermal and radiation environment of Mercury.

Keywords: Infrared spectroscopy, infrared space observatory, remote sensing, imaging systems, emission, optical systems.

1 INTRODUCTION

Telescopic measurements have shown that the surface composition of Mercury, the planet closest to the Sun, can be derived from mid-infrared observations (1). They show heterogeneous composition, the presence of intermediate and basic soil types, and pyroxenes (2). However, the observation conditions from the Earth are difficult. Up to now only very few spectra of Mercury are available. The ESA mission BepiColombo, to be launched in 2013 will explore the planet from a short distance, orbiting Mercury in 2019/21 (3). The spacecraft houses a state of the art mid-infrared spectrometer. MERTIS is the first thermal imaging dispersive spectrometer for planetary deep space missions and the first thermal infrared imaging spectrometry for a mission to Mercury. It covers the range from 7-14 µm with 80 spectral channels. The instrument is designed to study the global mineralogical composition and the local and daily temperature variation at the surface of Mercury. With SNR of about 100 the instrument will make it possible to resolve and map low contrast mineral bands at even higher nominal spatial resolution of 500 m. About 5-10% of the surface will be analyzed even at higher spatial resolution. The instrument design is completed by a radiometer covering the range from 14 to 40 µm for thermal surface studies. MERTIS is one of the key instruments of the Mercury Planetary Orbiter (MPO) onboard the ESA cornerstone mission BepiColombo, and will contribute to a better understanding of the actual state and the evolution of the planet Mercury.

2 SCIENCE GOALS

Understanding the evolution of Mercury is crucial for the comparative analysis of the development of the inner planetary system bodies including the Earth. As Mercury is closest to the Sun, it has been inadequately explored. It is the smallest and densest of the planets in the Solar system. Its unusual high density is indicative of a large metallic core. Different models have been proposed to explain the evolution of the planet. Some of them focus on the enrichment of metal by accumulation or by the breaking away of significant portions of the silicate crust. Others suppose strong evaporation processes during planet formation. Actually high daily temperature variations and strong space weathering processes characterize Mercury's environment.

The spectral radiance on Mercury's day side shows that the thermal emission starts to dominate over reflectance at wavelengths longer than 1.2 µm (at 725 K) depending on the surface albedo. The range between 0.8 and 2.8 µm is a transition region characterized by overlapping of the reflected solar radiation and the thermal emission. This makes near-infrared spectroscopic techniques difficult, but enables emissivity studies in the mid-infrared range. This range is usable for mineral identification; therefore the specific goal of MERTIS is the analysis of the surface mineralogy by measuring the spectral emissivity between 7 and 14 µm. Diagnostic signatures of relevant minerals are: Christiansen frequency, reststrahlen bands and transparency bands (Fig.1). The Christiansen feature is an emissivity maximum resulting from a rapid change in real part of the refractive index of the material. Its wavelength position is indicative for the mineral composition.

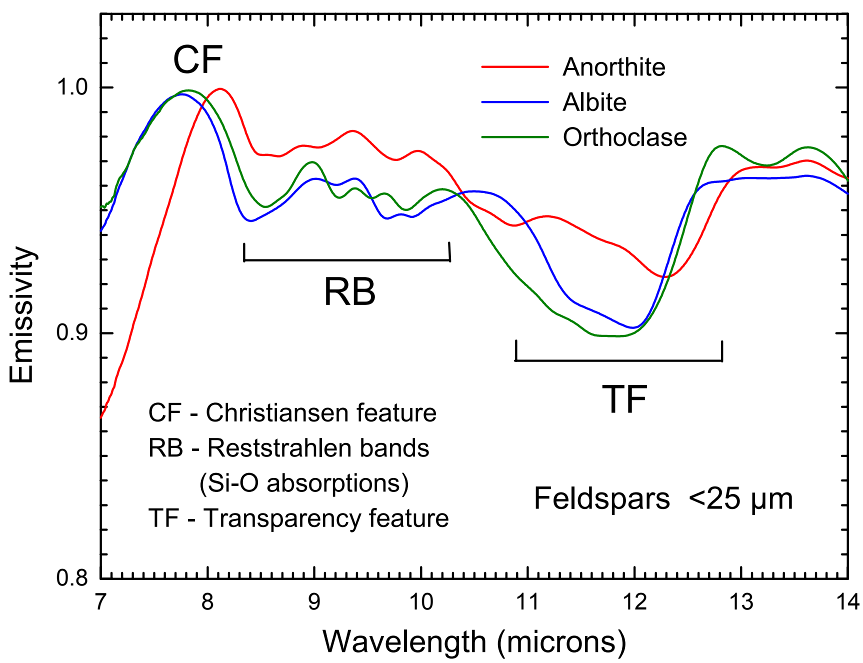

Fig. 1. Diagnostic mineral features, from ref. 4.

Detailed laboratory studies of mid-infrared spectra of the minerals have been published in the past (4, 5, 6, 7, 8, and 9). Recent laboratory analyses of Mercury's analog materials are presented by Helbert et al. in preparation of the BepiColombo mission (10). They obtained emissivity spectra as a part of the Berlin Emissivity Database (BED) for different, relevant mineral classes at various particle sizes within the measurement range of MERTIS.

Comparative ground-based studies of Mercury are difficult due to the small angular separation from the sun. A subset of comprehensive spectra has been obtained by Sprague and Roush (11, Fig. 2). The spectra appear to be common with feldspar, mixtures of feldspar and pyroxene and, in two cases to igneous nepheline-bearing alkali syenite. The wavelengths of the thermal emissivity maxima (Christiansen features, CF) indicate an intermediate or slightly mafic rock type. The surface composition is heterogeneous. Heterogeneous composition of Mercury's surface is indicated by the mid-infrared spectra (12). On Mercury there is little evidence for Fe-bearing basalts or Ti_2O in significant abundance. Spectral telescopic and albedo observations indicate a FeO content of only 3% and a Ti_2O content of only 1% based on the color-ratio analysis methods developed for the Moon by Lucy et al. in the Herman soil (13). These ground-based spectra have been discussed in comparison with laboratory spectra of terrestrial analog materials. Plagioclase feldspar $(Ca,Na)(Al,Si)AlSi_2O_8$ is a candidate mineral that seems to fit the measured spectral behaviour (14). Variations in the albite abundance in the feldspars and in the composition and abundance of pyroxenes have been observed. Plagioclase feldspar is formed both at high and low temperatures. Na-rich plagioclase feldspar can be comprised mainly of albite with a minor content of anortite ($Albite_{95}Anorthite_5$). The emissivity maximum in the spectra of Mercury is located near 8 µm; therefore the spectra obtained by Sprague et al. seem to be better matched by laboratory spectra in the Ab_{50} to Ab_{30} range indicating labradorite rather than anorthite which are common on the surface of the Moon. This supports the model that Mercury has a thick anorthositic crust (15, 16, and 17).

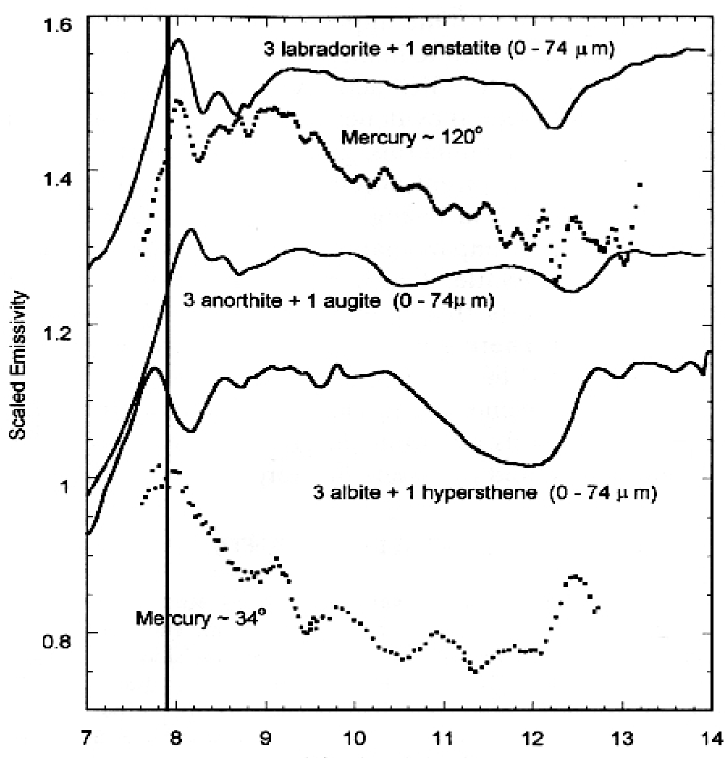

Fig. 2. Telescopic data of Mercury's surface from ~ 34° and ~ 120° longitude compared with calculated emissivities of mixtures of feldspars and pyroxenes according to Sprague and Roush (11).

Members of the pyroxene group are ortho- and clino pyroxenes. Spectra of Mercury taken in the equatorial region (~240° - 250°) show similar mid-infrared spectra compared to laboratory spectra of mixtures of plagioclase feldspars and the orthorhombic pyroxene enstatite ($MgSiO_3$). Other spectral features indicate the presence of clino-pyroxenes as well at longitudes of ~ 335 – 340°. They are similar to the lunar spectra. This was supported by the discovery of the 5-µm-emission in the spectra 275 ° - 315 ° E longitude. This would denote the pyroxene diopside ($CaMgSi_2O_6$).

Extraction of more detailed information about the surface composition of Mercury' is difficult or impossible with ground-based data. The close-range spectral analysis with MERTIS at Mercury will provide mineralogical data on small, global spatial scales. This knowledge will help to establish new fundamental boundary conditions for models of the origin and evolution of Mercury. Additionally, information about the texture and physical properties of the soil can be derived from the particle size dependence of spectral features (9).

The detection and specification of feldspars, pyroxenes, and other minerals, the expected surface characteristics of the regolith and the thermal conditions have driven the design of this state of the art instrumentation.

3 INSTRUMENT DESIGN AND PERFORMANCE

MERTIS uses an integrated instrument approach combining an IR-spectrometer based on a push-broom principle (18, 28) with heritage from the Mercury Radiometer (MRAD) (19), the Planetary Fourier Spectrometer (PFS) for ESA Mars Express (20), the Visual and Thermal Imaging Spectrometer (VIRTIS) for the ESA Rosetta and Venus Express missions (21), and the DLR Bispectral InfraRed Detection (BIRD) mission (22).

The MERTIS instrument design (Fig. 3) is driven by the call for miniaturization and a modular combination of the functional elements. It represents a modular concept of the sensor head, electronic units and power/calibration systems within a mass budget of 3.4 kg and 8 – 13 Watts average power consumption. The spectral resolution of the imaging spectrometer can be adapted depending on the actual surface properties to optimize the signal-to-noise ratio (SNR) (20). This allows us to resolve even weak spectral bands of the regolith (≤1-% contrast). The instrument achieves the requirements listed in table 1.

Table 1. Main performance requirements.

Spectral coverage	***7-14 µm***
Spectral channel width	***90 - 200 nm***
SNR for spectral range 7-14 µm	***>100***
Spatial resolution for global mapping	***500 m***
Target observation with better than 500 m	***5-10% of the surface***

The flexibility of the instrumental setup will allow a study of the composition of the radar-bright polar deposits with SNR >50 for an assumed surface temperature of 200 K. The development of the instrument is in the design phase.

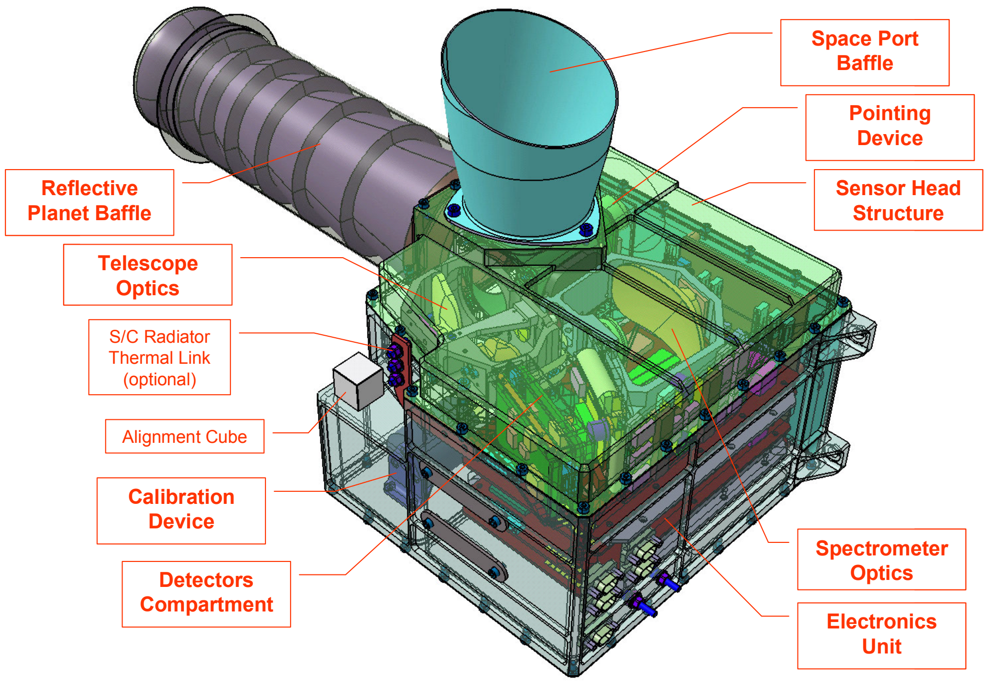

Fig. 3. MERTIS design, dimensions: 180 x 180 x 130 mm^3, baffles: 200 x 90 x Ø 75 mm^3.

The instrument's functional concept is based on a sequential illumination of four targets – planet, deep space, 300 K and 700 K black bodies as Mercury target references. A single rotary mechanism with 45° tilted mirror in front of the MERTIS instrument enables frequent views of the in-flight calibration targets and cold space as well as of the planet. The pointing system is motorized with a stepper motor and magnetic sensors for zero position identification. A cylinder shields the mirror and closes the opposite ports of the instrument against incoming radiation. The pointing device is shielded by an aluminum cover that is thermally decoupled from the optical structure. This shield is the interface to the instrument reflecting baffle.

The electronics architecture is driven by a modular concept for the instrument subsystems and cold redundancies for the instrument controller and the power electronics as the core parts. Due to the limited resources, detectors and their front end electronics as well as the black body drives, are unique. Therefore, in the whole system cross-trapping electronics have been added to establish the connections needed. This strategy is a result of the implementation of a highly integrated digital logic by integration into a single FPGA (27). Among others the main tasks of the instrument electronics are:

- Acquisition and processing of science data
- Independent control of MERTIS sub-systems (pointing mirror, black bodies and optional shutters)
- Provision of internal voltages and interfacing the +28V S/C power bus
- Telecommand and -control management and interfacing to the spacecraft providing housekeeping and status information
- Detector control and temperature stabilization

The final optical design of MERTIS is based on a telescope with a focal length of 50 mm and a F-number of 2. The FOV will be 4° and the grating of the spectrometer combines diffractive and imaging tasks in one element. MERTIS will use the push-broom principle where a 1D-FOV is imaged on the whole detector array and where a line corresponds to the spatial information and a column to the spectral information of the object scanned.

The spectral splitting will be accomplished by using a reflective diffraction grating. The 1D-FOV lies perpendicular to the orbiter track and each frame will be recorded after the movement of the obiter over a certain spatial distance or time. This way MERTIS will gather 3D-information for each scanning step including spatial, spectral and radiometric properties of the observed area.

The optical design (Fig. 4) combines a Three Mirror Anastigmat (TMA) with a modified Offner grating spectrometer. The TMA consists of three off-axis aspherical mirrors with the second one as aperture stop. The Offner spectrometer uses two concentric spherical elements where the small convex one is the grating opposed by a large concave mirror. The grating is placed about midway between the slit and concave mirror. Additionally, on both sides of the entrance slit the detector elements of the radiometer are situated using the same TMA fore optics.

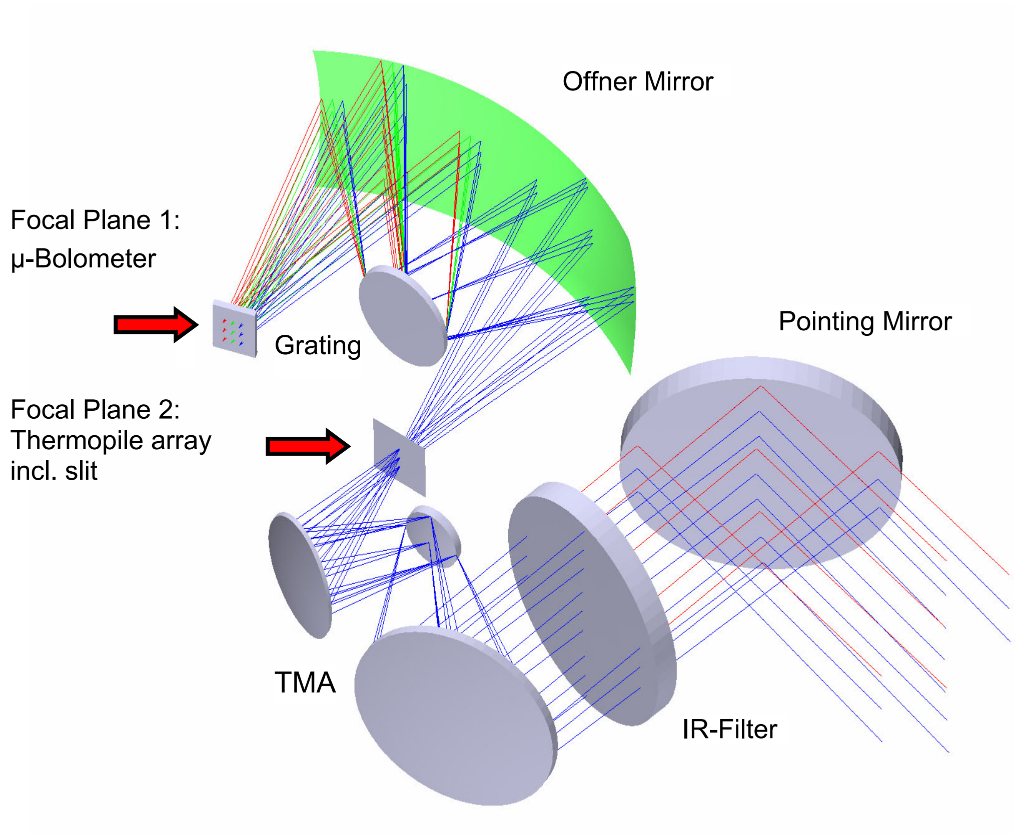

Fig. 4. Optical design for the MERTIS spectrometer after Hirsch (25).

This grating concept was first introduced by Bittner and is described by Reininger et al. and Fink et al. (21, 24). It opens a higher level of spectral imaging quality. The system is well corrected to be diffraction limited and it is of moderate field curvature (< 1.2 mm spectral; < 0.24 mm spatial) and distortion (< 3.7% spectral; < 0.8 % spatial) as is usual for off-axis systems.

Aberrations due to the spherical surfaces of grating and mirror have to be considered. The TMA allows us to correct these effects by using three off-axis aspheres of higher order. The optical path difference (OPD) of the beams focusing on the slit and on the detector only insignificantly exceeds the diffraction limit of λ/4 only insignificant.

The diffraction Modulation Transfer Function (MTF, Fig. 5) demonstrates the high contrast below the physical limit of diffraction.

Manufacturing the grating for longer wavelengths between 7 and 14 µm based on a holographic method did not work. For this reason a diamond point turning technique was successfully applied. An optical filter for discriminating the 7-14 µm wavelength regions is situated in front of the detectors and acts as hermetical window of the dewar housing.

The optical design is athermalized. Due to the expected head load the design is based on aluminum mirrors each mounted in the centre on 3 points for alignments and access for external adjustment elements. The uniform use of aluminum for the optical bench as well as for the mirrors and their mounts provides a practically perfect athermalisation at a wide range of temperatures.

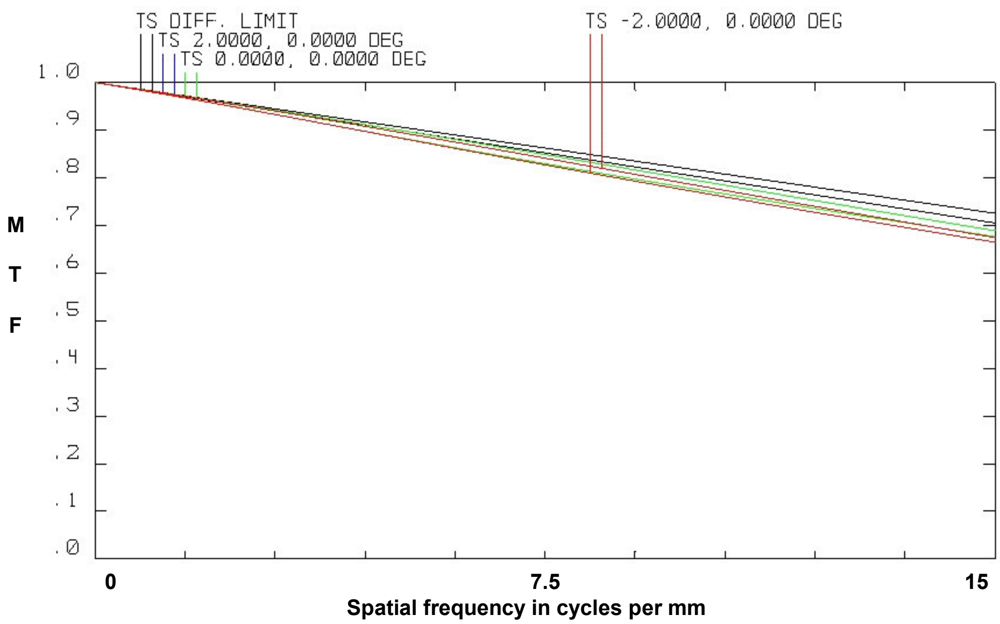

Fig. 5. Modulation Transfer Function (MTF) of MERTIS' OTF spectrometer after Hirsch (25). The MTF is the modulation as a function of spatial frequency for a sin wave object of ideal unity contrast (ideally bright to totally dark). Any optics transforms this object into an image of decreasing contrast (bright grey to dark grey) with increasing spatial frequency. A practical limit is the Nyquist frequency where a one-cycle object is imaged on to just one pixel pair, here 14.3 cycles per mm due to 70 µm per pixel pair.

The functional principle of an imaging spectrometer requires the application of a matrix array. The candidate for the spectrometer detector in the thermal region of 7 – 14 µm which can be used in the hot environment of Mercury is the micro-bolometer technology. However, the highest sensitivity is offered by semiconductor quantum detectors but the necessary cooling power is not available on this mission. For the measurements of Mercury's surface radiation an uncooled micro-bolometer array, similar to the Mars 2001 Odyssey THEMIS instrument detector (23) will be used due to the mission budget restrictions. This ULIS array is a 160 x 120 pixel bolometer with a pixel size of 35 µm to realize a spectral channel width of 90 nm/ pixel and a spectral resolution of $\lambda/\Delta\lambda$ 78-156. The array is the best compromise in terms of swath coverage, radiometry resolution and data rate requirements. The amorphous silicon based resistive micro-bolometer is connected to a ReadOut Integrated Circuit (ROIC) and is stored mounted on a thermoelectric cooler in a miniaturized package. The thermal control of this Micro Electro Mechanical Device (MEMS) has a key function for the measurement accuracy and it's specified as 10mK for stability.

A technology program has been started to reach the required detectivity of NEP = 15 pW.

The central part of the radiometer is a customize thermopile detector chip composed of two 15-element line arrays. These are situated in the intermediate focus of the spectrometer optics thus sharing the same entrance optics and calibration targets. To reach a maximum of sensitivity the pixel size is 200x200µm² and the wavelength range is extended to 40µm. The proximity electronics here has to be optimized for the small signal voltages in the order of µV.

The first Radiometric Analysis Breadboard (RAB) has been configured. First spectral and radiometric calibration procedures and algorithms have been tested. The linear performance of the detector depends on its temperature; therefore a Thermo Electric Cooler (TEC) regulation algorithm is integrated to stabilize the detector temperature at 10 mK within an interval of 10-30° C. The spectral alignment is done using a visible laser source at the output slit of a monochromator.

In order to minimize the error of the response function a spectral offset coefficient and IR-long-pass filters were introduced to the system (26). Currently, radiometric performance testing of the MERTIS spectrometer bread board is being continued and the spectral-radiometric bread boarding is in progress as well as the complete instrument design.

4 CONCLUSION

MERTIS combines a push-broom TIR imaging spectrometer in the range from 7 – 14 µm with a thermal radiometer for exploration of the surface composition, the temperature, the thermal inertia and texture of Mercury's surface. The spectrometer operates with a telescope focal length of 50 mm (F-number 2), a FOV of 4°, and, with a spectral channel width of 90 nm. The all-reflective, diffraction limited, very fast, and miniaturized optical design together with very small tolerances of the manufactured elements promises an excellent optical performance. Moreover, it enables applications in other spectral ranges. One of the key features is the combination with a micro-bolometer matrix detector without any cooling due to the stressed thermal concept of the entire spacecraft and so also for MERTIS.

The composition can be studied on spatial scales of 500 m and less with an SNR of 100 up to 1000. Composition analysis and the study of physical properties of Mercury's surface will contribute to a better understanding of the planet's formation processes.

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References

[1] A. L. Sprague and T. L. Roush, "Comparison of laboratory emission spectra and Mercury telescopic data," *Icarus* **133**, 174-183 (1998) [doi:10.1006/icar.1998.5929].

[2] A. L. Sprague, J. P. Emery, K. L. Donaldson, R. W. Russel, D. K. Lynch, and A.L. Mazuk, "Mercury: mid-infrared observations show heterogeneous composition, presence of intermediate and basic soil types, and pyroxene," *Meteorit. Planet. Sci.* **37**, 1255-1268 (2002).

[3] http://sci.esa.int/science-e/www/area/index.cfm?areadid=30

[4] C. Wagner, "Thermal emission spectroscopy of laboratory regoliths," in *Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths* **196**, 233-247, Proc. Astronomical Soc. Pacific (2000).

[5] L. M. Logan and G. R. Hunt, "Emission spectra of particulate minerals under simulated lunar conditions," *J. Geophys. Res*. **75**, 6539-6548 (1970)

[6] G. Arnold, "Measurements of the spectroscopic emttance of particulate minerals and some remote sensing applications," *Vib. Spectroscopy* **2**, 245-251 (1991).

[7] J. W. Salisbury, A. Wald, and, D. M. D'Aria, "Thermal infrared remote sensing and Kirchhoff's law 1. Laboratory measurements," *J. Geophys. Res.* **99**, 11897-11911 (1994) [doi:10.1029/93JB03600].

[8] B. G. Henderson and B. M. Jakosky, "Near-surface thermal gradients and mid-IR emission spectra," *J. Geophys. Res.* **102** (E3), 6567-6580 (1997) [doi:10.1029/96JE03781].

[9] G. Arnold and C. Wagner, "Grain size influence on the mid-infrared spectra of the minerals," *Earth Moon Planets* **41**, 163-171 (1988) [doi:10.1007/BF00056401].

[10] J. Helbert, L. V. Moroz, A. Maturilli, A. Bischoff, J. Warell, A. L. Spraque, and E. Palomba, "A set of laboratory analogue materials fort he MERTIS instrument on ESA BepiColombo mission to Mercury," *Adv. Space Res.* **40**, 272-279 (2006) [doi:10.1016/j.asr.2006.11.004].

[11] A. L. Sprague and T. L. Roush, "Comparison of laboratory emission spectra with Mercury telescopic data," *Icarus* **133**, 174-183 (1998) [doi:10.1006/icar.1998.5929].

[12] A. L. Sprague, J. P. Emery, K. L. Donaldson, R. W. Russell, D. K. Lynch, and A. L. Mazurk, "Mercury: mid-infrared (3-13.5 μm) observations show heterogeneous composition, presence of intermediate and basaltic soil types, and pyroxene," *Meteorit. and Planet Sci.* **37**, 1255-1268 (2002).

[13] P. G. Lucy, D. T. Blewett, and B. L. Jolliff, "Lunar iron and titanium abundance algorithms based on final processing of Clementine," *J. Geophys Res.* **105**, 20297-20305 (2000) [doi:10.1029/1999JE001117].

[14] A. L. Sprague, D. B. Witteborn, and F. C. Chruikshank, "Mercury's feldspar connection – Mid-Ir measurements suggest plagioclase," *Adv. Space Res.* **19**, 1507-1510 (1997) [doi:10.1016/S0273-1177(97)00363-3].

[15] P. Spudis and J. Guest, "Stratigraphy and geologic history of Mercury," in *Mercury,* pp. 118-164, F. Vilas, C. R. Chapman, and M.S. Matthew, Eds., Univ. Arizona Press, Tucson (1988).

[16] A. L. Tyler, R. W. H. Kozolowski, and L. A. Jakosky, "Determination of rock type on Mercury and Moon trough remote sensing in the thermal IR," *Geophys. Res. Lett.* **15**, 808-811 (1988).

[17] M. S. Robinson and G. J. Taylor, "Ferrous oxide in Mercury's crust and mantle," *Met. Planet. Sci.* **36**, 841-847 (2001).

[18] M. S. Scholl and G. Paez-Padilla, "Push-broom reconnaissance camera with time expansion for a (Martian) landing – site certification," *Opt. Eng.* **36**(2), 566-573 (1997) [doi:10.1117/1.601228].

[19] J. Helbert, E. K. Jessberger, J. Benkhoff, G. Arnold, M. Banaszkiewicz, A. Bischoff, M. Blecka, S. Calcutt, L. Colangeli, A. Coradini, S. Erad, S. Fonti, R. Killen, J. Knollenberg, E. Kuehrt, I. Mann, U. Mall, L. Moroz, G. Peter, M. Rataj, M. Robinson, T. Spohn, A. L. Sprague, D. Stoeffler, F. Taylor, and J. Warell, "MERTIS – A thermal infrared imaging spectrometer for the Bepi Colombo mission," **LPS XXXVI**, 1753 (2005).

[20] G. Arnold, R. Haus, H. Hirsch, "The Planetary Fourier Spectrometer: Studies of the Martian atmosphere and surface," **DLR-FB 18**, ISSN 1334 – 8454 (2000).

[21] F. Reininger, A. Coradini, F. Capaccioni, M. Capria, P. Cerroni, M. DeSanctis, G. Magni, P. Drossart, M. Barocci, D. Bockelee-Morvan, J. Combes, J. Corvisier, T. Encrenaz, J. Reess, A. Semery, D. Tiphene, G. Arnold, U. Carsenty, H. Michaelis, S. Mottola, G. Neukum, G. Peter, U. Schade, and the VIRTIS team, "VIRTIS: Visible and Infrared Thermal Imaging Spectrometer for the Rosetta mission," *Proc. SPIE* **2819**, 66–77 (1996) [doi:10.1117/12.258082].

[22] K. Briess, W. Baerwald, T. Gerlich, H. Jahn, and F. Lura, "The DLR Small Satellite Mission BIRD," *2nd IAA Symp. Small Satellites for Earth observation*, Berlin (1999).

[23] P. R. Christensen, B. M. Jakosky, H. H. Kieffer, M. C. Malin, H. Y. McSween, Jr. K. Nealson, G. L. Metall, S. H. Silverman, S. Ferry, M. Caplinger, and M. Ravine, "The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission," *Space Science Rev.* **110**, 85–130 (2004).

[24] U. Fink, H.-J. Rostalski, and H. Hirsch, "Applications of holographic gratings to two-dimensional spectroscopy," *Appl. Opt.* **35**, 1047-1052 (1996).

[25] H. Hirsch, "Optical design of MERTIS" in BepiColombo MERTIS-TIS, ESA-ref. MER-IFP_PP-001, 32-35 (2004).

[26] T. Saeuberlich, E. Lorenz, and W. Skrbek, "Conception and state of the radiometric analysis breadboard (RAB) for the Mercury Radiometer and thermal Infrared Spectrometer (MERTIS)," *Proc. SPIE* **6297**, 62970Y (2006) [doi: 10.1117/12.680335].

[27] I. Walter, H. Hirsch, H. Jahn, J. Knollenberg, and H. Venus, "MERTIS – a highly integrated IR imaging spectrometer," *Proc. SPIE*, **6297**, 62970X (2006) [doi:10.1117/12.679481].

[28] J. L. Bandfield, V. E. Hamilton, and P. R. Christensen, “A global view of martian surface composition from MGS-TES,” *Science* **287**, 1626-1630 (2000).