Pointing and Spectral Assignment Design and Control for MERTIS

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ABSTRACT

The development of MERTIS, a miniaturized thermal infrared imaging spectrometer onboard of ESA's cornerstone mission BepiColombo to Mercury has been completed. Qualification of the design is followed by the calibration of the instrument showing up first results of the technology used.
Based on subsequent viewing of different targets including on-board calibration sources the push-broom instrument will use a 2-dimensional bolometer detector to provide spatial and spectral information.
Here repetition accuracy of pointing and spectral assignment is supported by the design of instrument components under the restriction of limited resources. Additionally a concept of verification after launch and cruise phase of the mission was developed.
The article describes how this has been implemented and what the results under environment testing are.

Key words:
Thermal infrared imaging spectrometer, micro-bolometer, pointing device, on-board calibration sources, qualification testing

1. INTRODUCTION

As one of the 11 scientific instruments of the BepiColombo Mission to Mercury onboard of ESA’s Planetary Orbiter MPO, MERTIS (Mercury Radiometer and Thermal Imaging Spectrometer) has been reached the qualification status of its design and the flight hardware is being built and calibrated presently.

Dedicated to the surface composition analysis, its minerals identification and temperature analysis MERTIS combines a push-broom IR spectrometer and a radiometer operating in the wavelength region of 7-14 µm and 7-40 µm respectively. The spectral channel width is 90 nm whereas the spatial resolution will be 500 m globally at Mercury.
The instrument optics 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 doubled-used spherical mirror. The grating is placed about midway between the slit and concave mirror. On both sides of the entrance slit the detector elements of the thermopile radiometer are situated using the same TMA fore optics.

Operating an uncooled bolometer technology avoiding actively cooled detectors is possible with respect to the target temperatures. This has to be combined with enhanced in-flight calibration essentially to achieve the desired signal-to noise ratio. MERTIS therefore is equipped with an integrated pointing mirror system allowing for intermediate scanning of two emitting targets as calibration sources and the open space as the background reference.

Recently for MERTIS every 40 seconds calibration is performed resulting in over 80 % availability of planet orientation.

2. DESIGN ASPECTS

2.1 Flight status reached

The instrument development as described in [1] is in its final stage and the qualification has been completed. Early results of measurements and analysis are able to be considered with regard to the mission constraints leading to an extremely miniaturized and straight-forward design approach.
The instrument ready to be flown is less than 3 kg in weight and consumes about 11 W of power. The flight unit under integration is depicted in Fig. 1.

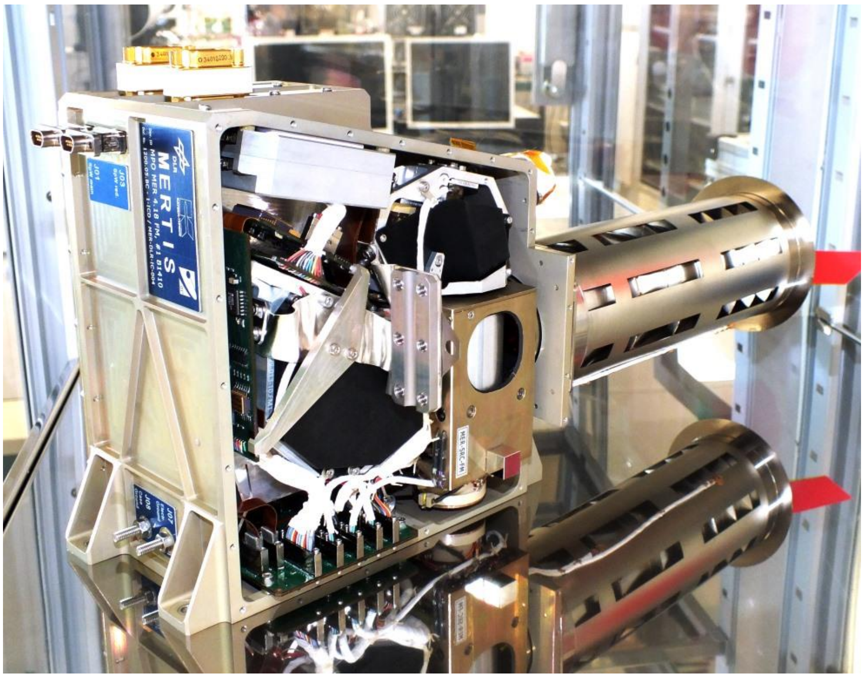


Figure 1. MERTIS Flight Unit before final closure

2.2 Pointing system

A stand-alone Pointing Unit is situated at the front of the MERTIS instrument optics with the main objective to orient the optical entrance of the instrument to 4 different targets sequentially:

- Mercury surface (planet view) for scientific data take
- Deep space (space view) for low temperature reference on-board calibration
- 300K black body for instrument internal temperature reference
- 700K black body for Mercury temperature reference simulation.

This is realized by implementing a single rotary mechanism with a 45° tilted mirror. Its rotation axis is oriented in optical axis direction of the entrance optics thus efficiently reaching the necessary targets.

Fig. 2 shows the MERTIS design, cut at the instruments baffles centrelines such showing the central location of the pointing mirror between the radiation entrance ports and the instrument optical entrance to the TMA. While opening for the dedicated instrument port the others are screened by a tube cylinder surrounding the mirror.

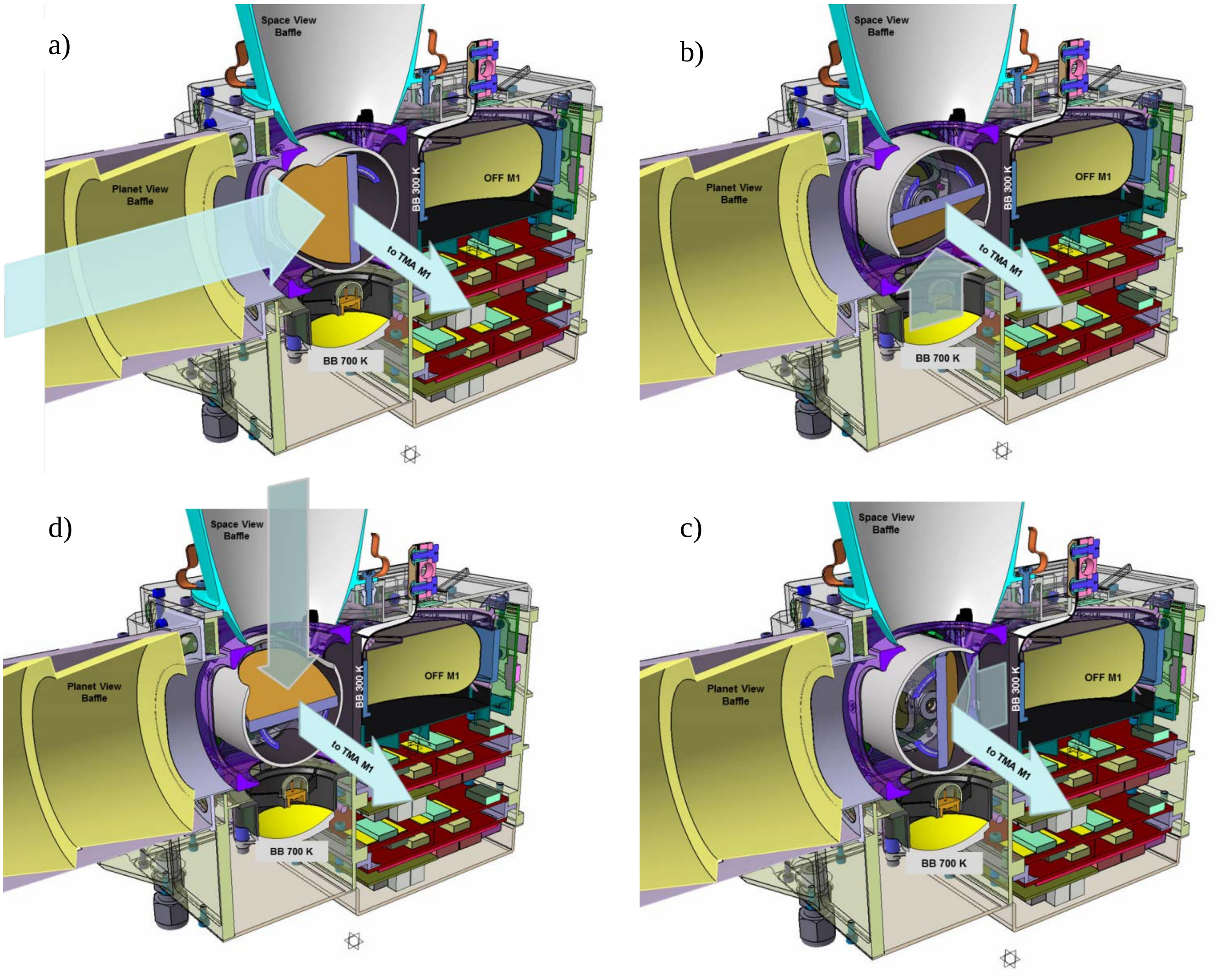


Figure 2. MERTIS Pointing Unit operations (clockwise): a) Planet view, b) Black body 700 K view; c) Black body 300 K view, d) Space view. Default position in off-mode is c)

2.3 Design for pointing accuracy and repeatability

The decision for a pointing system in front of the optics of an instrument allows fully coverage of all optical components in the calibration chain. But it automatically transfers pointing requirements to this unit in two ways – accuracy and repeatability. Overall Field of View (FOV) orientation is determined by thermal stabilities of structures and optics as well as the precision of replicating the state of the mechanisms included. Whereas the instrument overall pointing accuracy can cope with an aluminum structure design there are higher demands for the spectral assignment and repeatability of the target positions since these errors are not able to be recovered by ground truth considerations.

Hence the instrument orientation has to be recovered by 0.33 pixels IFOV which is 0.8 arcmin for the science targets and 20 arcmin for the calibration black bodies which are assumed to have flat field characteristics.
Micro-stepping control enhancing the step accuracy of the motor of about 3 arcmin (3% of 1.8° step width) was not an option because of the advanced electronics needs. Consequently a 270° reverse movement against mechanical end stops for planet and space view position has been chosen. The mirror rotation is provided by a stepper motor in open loop control mode which is supported by the instrument controller’s count functions.

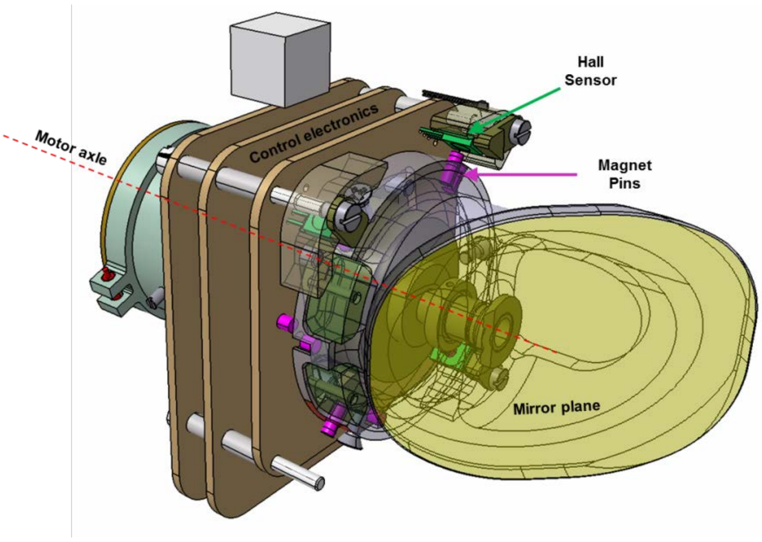


Figure 3. MERTIS pointing mirror on stepper motor incl. pointing control electronics and sensors

A simple sensor system with Hall Effect sensors combined with magnetic pins inside the rotating mirror base is situated such that a dedicated pin pattern identifies any position status. Additional magnets are supporting the adhesion at the mechanical end-stops suppressing bouncing effects. The main components of this concept are shown in Fig. 3, detailed described in [3].

2.4 Integrated pointing mirror – design and analysis

The 45° tilted pointing mirror is simply specified to be plane. However the thermal loads at the instrument front are significant and the pointing mirror is a standalone element and not included in the athermalisation concept of the main instrument optics. Consequently the original foreseen design based on aluminium suffered from interface problems at the mirror mounting structure. That is why a new concept has been implemented for integrating mirror and structure eliminating such interface in general. The integrated design gives the opportunity to implement elements beside the mirror mounting to the motor such as magnets for positioning and counter balance masses. Such designed base of the mirror carries also a screening tube cylinder for shielding the inactive view ports of the instrument.

After the principal design had been settled analysis helped to find the proper material. Even though small (mirror size 38 x 50 mm, elliptical) the FE model needed was 15k elements large with a mesh width of 2 and 0.5 mm at the mirror surface. The results of a deformation analysis are according Fig. 4 for the hot case and the cold case for aluminium against SiC.

At first a significant overall displacement difference occurs by about a factor of 10. Secondly the orientations of the tilted mirror plane differ although the designs are similar. That means the mirror structure integrated to the mirror should in general have a low CTE. Table 1 summarizes the values obtained by analysis. It compares starting from 20°C the overall thermal shift of the mirror centre w.r.t. motor interface (0,0), the mirror form deviation in X and Y, the thermal induced tilt of the mirror plane.
Whereas mirror shifts are not performance relevant and the plane tilt values are rather small compared to the budgets the form deviation with reached the tolerable limit of 1 µm with Al for this IR- instrument.
That is why the material of choice is CeSiC [2] which is inherently thermally stable by low CTE and provides sufficient thermal conductivity for gradients depression against deformation.

Table 1. Comparison of thermal form deviations of the pointing mirror for different materials

	Mirror centre vs motor IF +70°C	**Mirror centre vs motor IF -10°C**	**Mirror form deviation ΔX -10 …+70°C**	**Mirror form deviation ΔY -10 …+70°C**	**Mirror plane tilt -10 …+70°C**
AA 6016	+10.30 µm	- 6.20 µm	0.95 µm	0.60 µm	4.5 arcsec
CSiC	+0.99 µm	- 0.60 µm	0.13 µm	0.07 µm	0.1 arcsec

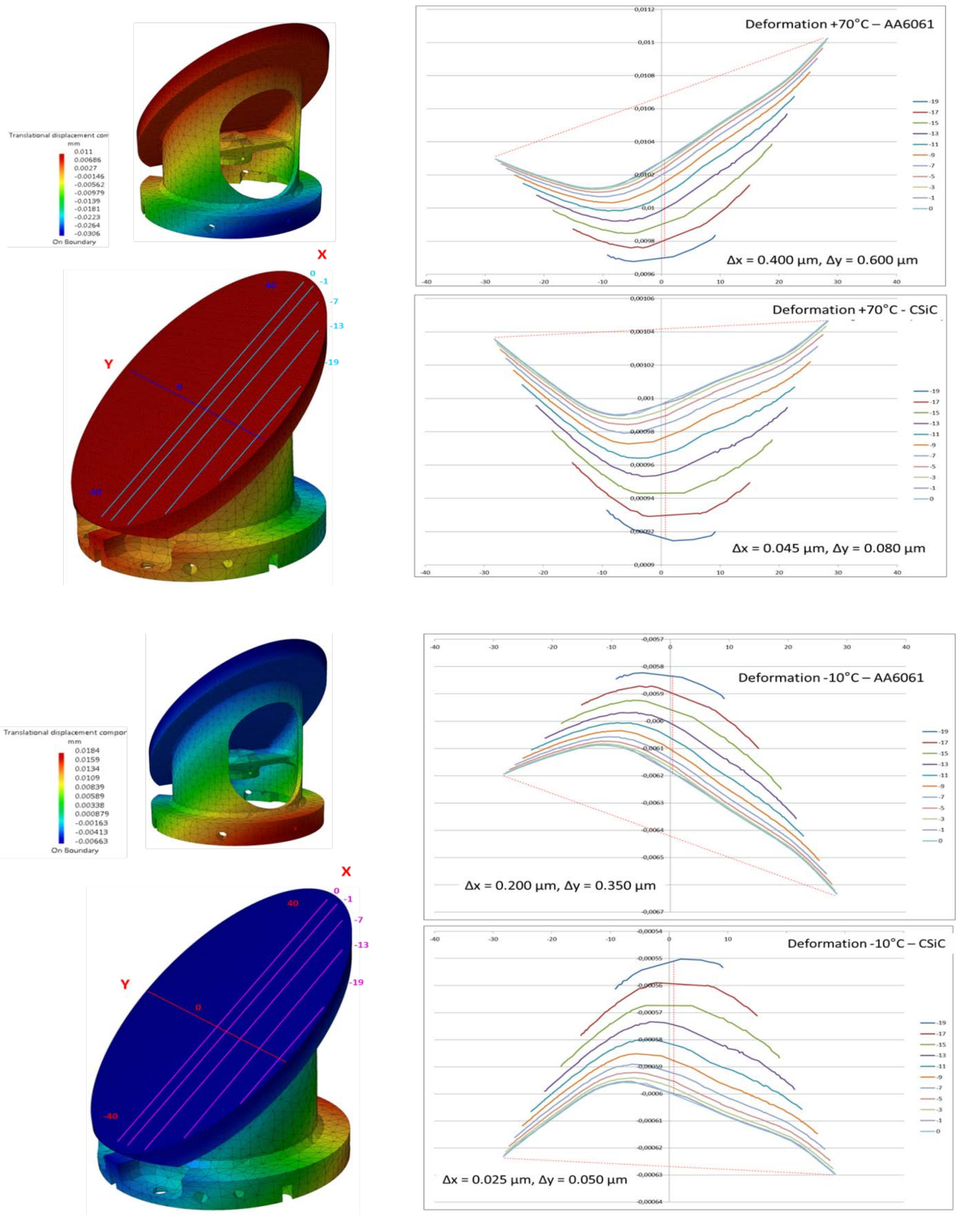


Figure 4. MERTIS Pointing mirror thermal FEA results hot (above) and cold (case) below, absolute displacements are scaled in the left upper parts whereas deformation is displayed in the curves representing the mirrors surface.

3. EXPERIMENTS RESULTS

3.1 Unit qualification results

During qualification the units i.e. were tested under vacuum to verify function and principle performance under thermal load. Pointing and repeatability of positioning had been checked by a laser, illuminating from outside into the chamber to the unit which was equipped with reflective mirrors at all view ports. A reference was derived via a beam-splitter to separate effects of the set-up. The back-reflected beams were captured on a screen at certain distance for pointing visualization.

The results showed pleasant results for hot case temperatures but significant thermal shifts for low temperatures of the same kind independent from the unit operational modes. Here deformation effects of the set-up could not be covered by the reference system. So the merit of these experiments was mainly to verify the unit functionality including different motor control modes, main and redundant coil operation etc.

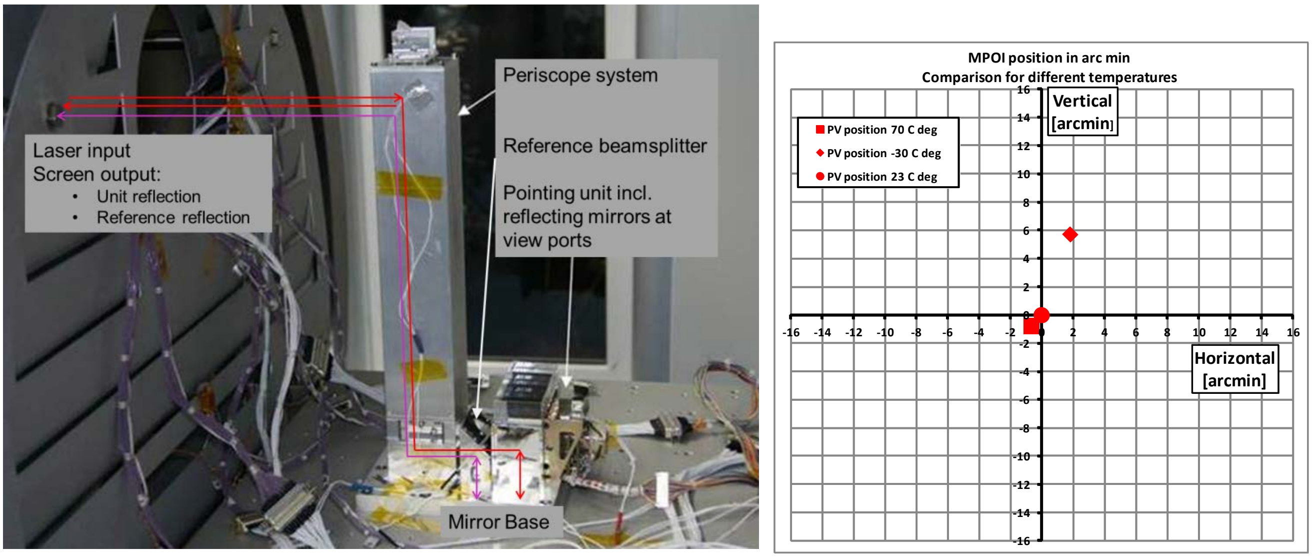
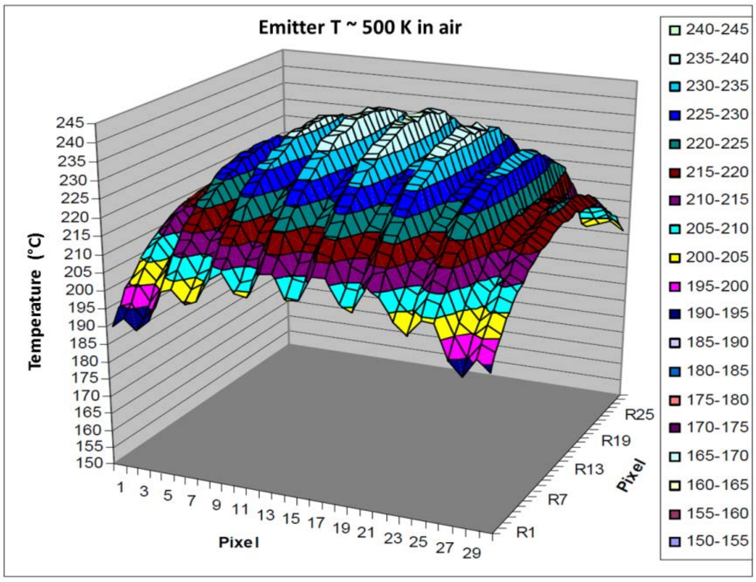


Figure 5. MERTIS Pointing unit verification set-up in a vacuum chamber (left) and a typical result of the reflected beam orientation for temperatures at +23, +70 and -30°C (right).

3.2 Inflight calibration source – Black Body 700 K

Confronted with the difficulties of stand-alone unit testing regarding pointing a concept applying the MERTIS inflight calibration sources has been considered. Although these are designed for flat field illumination of the entire MERTIS apertures in the case of the 700 K Black body a feature-rich scene was obtained in early radiometric measurements. Designed with a point source in the focus of an aspheric reflecting mirror to widen the beam for the full aperture there is a remaining intensity drop from center to the border of about 10% which allows a spatial discrimination in the sub-pixel domain.



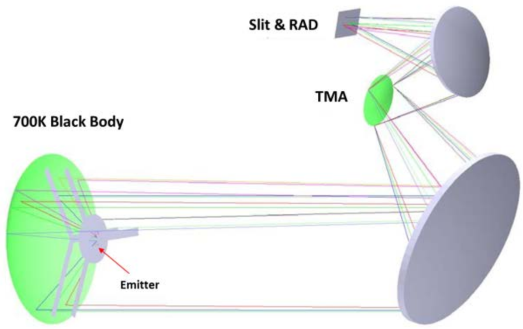


Figure 6. MERTIS 700 K Black Body system illumination principle

Figure 7 (left). Intensity plot of the emitter (grooves are limited by controlled mirror defocusing)

3.3 Determination of mirror position error

By means of operating series of 700 K Black body images with the full integrated MERTIS instrument pointing error determinations have been performed. In this application the Planet View is oriented to an IR-collimator providing a 700 K as well. Using the Black Body 300 K as background reference difference images are calculated from the two high temperature sources. Any image sequence (periods of 30 sec with 20 image frames taken from each target) is analyzed according its central position of the different scene and compared to the following one.

This method has been verified with recording 7843 images with the QM of the instrument first under thermal stable conditions after instrument integration. As a result the pointing accuracy of the Black body 700 K with respect to the external source, representing the open-loop controlled position could be derived (Fig. 8) as well as the Planet View pointing accuracy which was designed to be determined by mechanical end-stops for higher precision (Fig. 9).

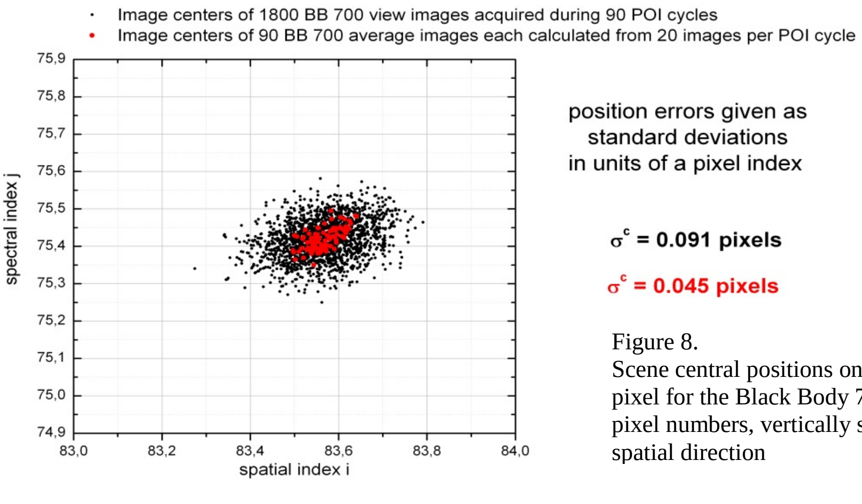


Figure 8.
Scene central positions onto a single μ-bolometer pixel for the Black Body 700K View. Indexes are pixel numbers, vertically spectral and horizontally spatial direction

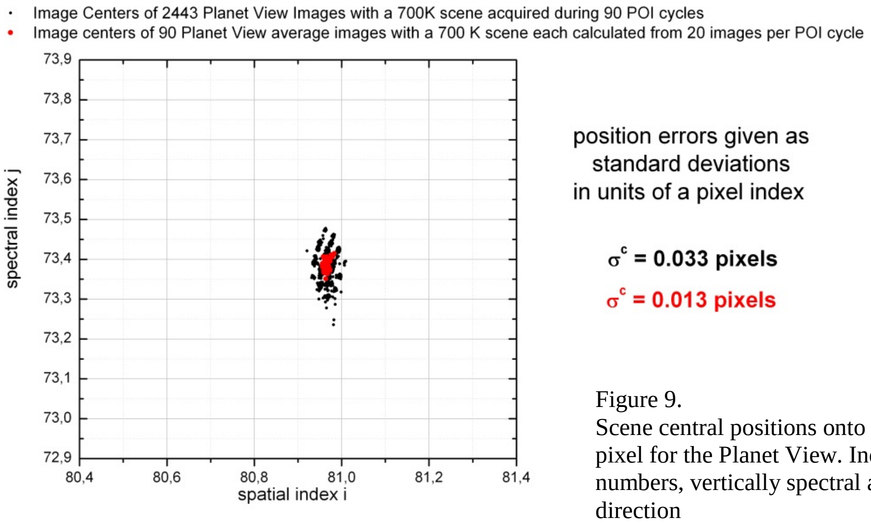
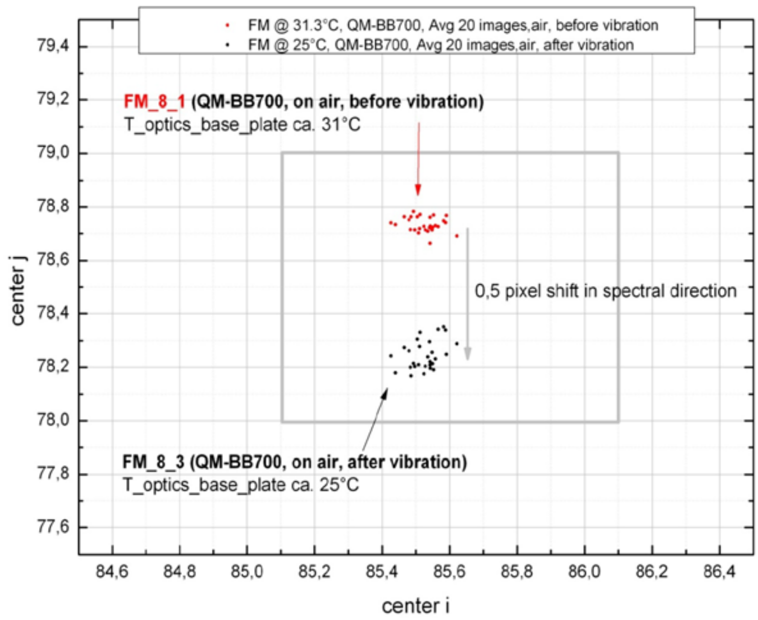


Figure 9.
Scene central positions onto a single μ-bolometer pixel for the Planet View. Indexes are pixel numbers, vertically spectral and horizontally spatial direction

3.4 Influence of environment conditions

With the Pointing Unit design confirmed the same method was used investigating the influence of the environmental loads to the instrument. First the status before and after the sinus and random vibration testing has been considered resulting in a 0.5 pixel settlement of the black body image in spectral direction. Referring to the instrument design this is the in-plane oriented structure which indeed is less rigid due to the mounting interfaces compared to the spatial orientation gaining from part stiffness over height.



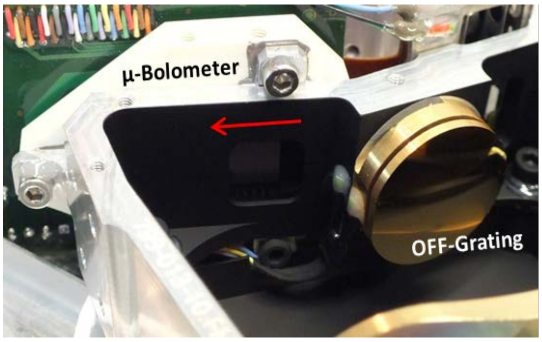


Figure 10.
Scene central positions onto the μ-bolometer pixel for the Black Body 700K View before and after vibration testing. 0.5 pixel shift are according the red arrow in the photograph along spectral direction.

However the temperature of the units compared were not exactly the same. So secondly the instrument under different temperature conditions has been analyzed. It is planned anyhow to operate the optical system within a range of 0 up to +40 °C to reflect to the orbit conditions at Mercury. MERTIS parameters must be adapted to that range such that the radiometric performance is optimized. Therefore calibration has been performed and also pointing data gained from this campaign.

Figures 11a, 11b and 12 give an impression of the temperature dependence of the spectrometer's image locations due to temperature variations of the instrument. In Figure 11a two thermal cycles in which the instrument temperature was driven between 0°C and 40°C are shown. The temperatures regarded are taken from sensors at the spectrometer's inner parts like the optical base plate, optical components and for comparison the BB300 temperature. These are relevant for the result of the imaging process since the sensor's image output strongly depends on the geometrical arrangement of the optical elements relative to each other and the bolometer matrix.

In order to develop an idea of the reason for the optic's displacement during thermal cycles a measure ΔT_t^{inst} reflecting the strength of the difference temperatures of the different spectrometer components is introduced as:

$$\Delta T_t^{inst} := \sqrt{\left(T_t^{BB300} - T_t^{SOP}\right)^2 + \left(T_t^{BB300} - T_t^{BasePlate}\right)^2 + \left(T_t^{SOP} - T_t^{BasePlate}\right)^2}$$

Herein T^{BB300}, T^{SOP} and $T^{BasePlate}$ represent the temperatures of BB300, the spectrometer optics and the optical base plate and t represents time. Including the time dependence ΔT_t^{inst} can express a relation between temporal and spatial (that is: within instrument) temperature gradients since this measure increases its value if strong temporal gradients of the different temperatures occurs and if these are individual to each spectrometer component. Figure 12 is illustrating this showing the corresponding temporal evolution of ΔT_t^{inst} for the first thermal cycle that has been shown in figure 11a. As it can be seen the spatial temperature gradient takes a maximum at the point where the maximum temporal gradient is observed. This point corresponds with the maximum image displacement which can be seen in figure 12. At the end of each heating or cooling process the systems returns slowly into a thermally stationary state. The corresponding temperature gradients for the cold (0°C) and warm (40°C) states differ as well as the image dislocations they cause. The maximum temporal gradient seen is ca. around 5-6 mK /s. For the MERTIS operation at Mercury <1 mK is expected. The image dislocations should therefore be much smaller than shown in figure 12 and it is suggested that they correspond more to a direct transition between the stationary state dislocations which are less that 0.5 pixels.

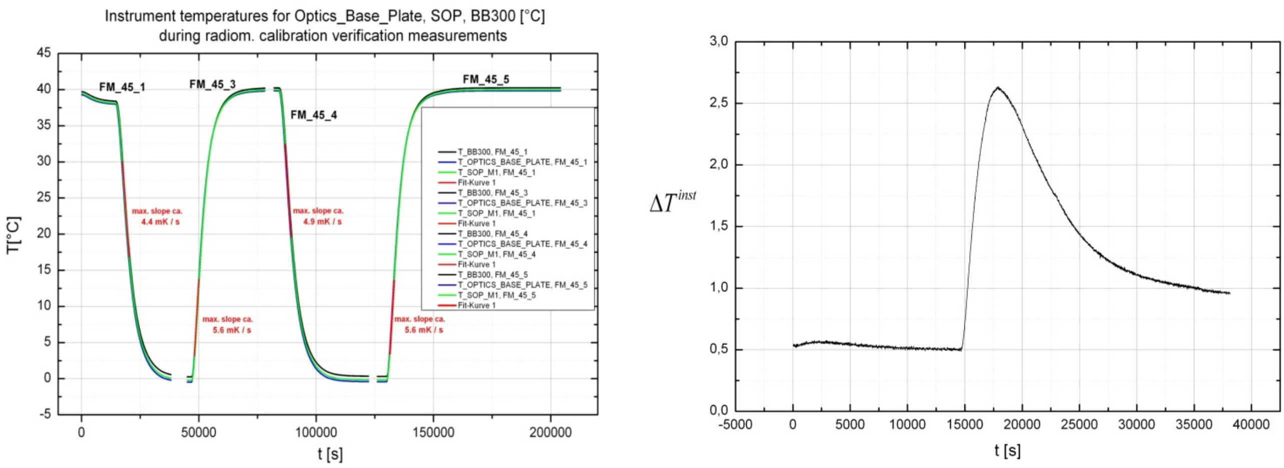


Figure 11: (11a – left): The MERTIS FM Instrument has been driven through two thermal cycles with instrument temperatures between 0°C and 40°C. The temperatures transients shown represent optically relevant parts like T^{SOP} and $T^{BasePlate}$. For comparison T^{BB300} is shown as well. A maximum temporal gradient of < 5 mK/s could be derived. (11b – right): During the first thermal cycle the instrument faces strong spatial gradients ΔT_t^{inst} which are supposed to cause image displacements. The gradient maximum corresponds to a maximum image displacement.

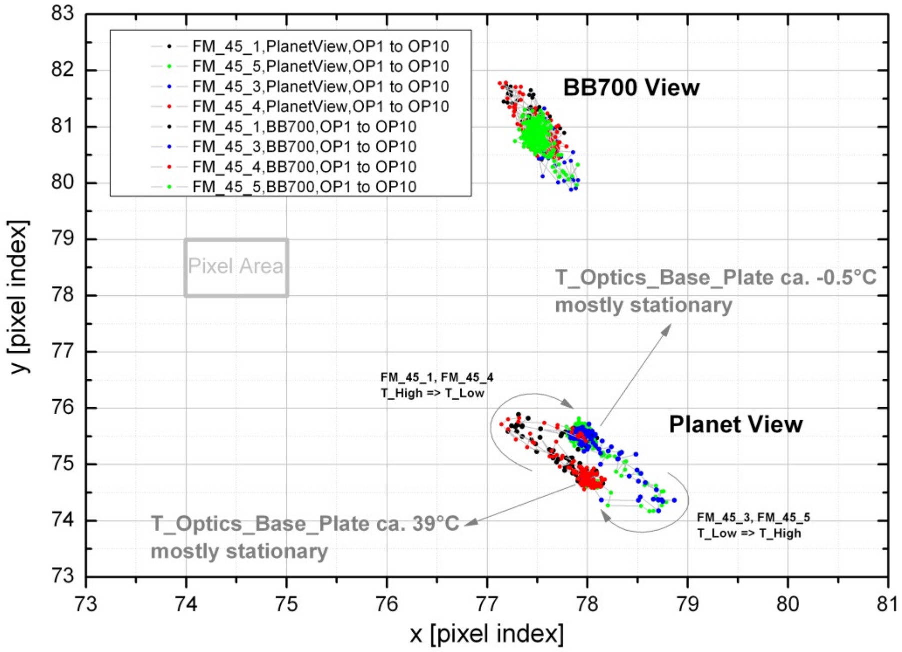


Figure 12: BB700 and Planet View image center positions during two thermal instrument temperature cycles giving the spectrometer components temperatures between 0°C and 40°C. An image displacement range of ca. 1.5 pixels in FOV-direction and 1 pixel in spectral direction can be seen for the hot scene at Planet View. The corresponding displacement for the BB700 scene is smaller with ca. 1 pixel in spectral direction and 0.5 pixels in FOV-direction and it has a different orientation compared to the Plant View. Between the thermally stationary instrument states (cool and hot) a displacement of <0.5 pixels is observed for Planet View, while none is seen for the BB700.

3.5 Conclusive remarks

The results shown are part of the ongoing instrument calibration. It could be shown that expected effects of the design become visible and strategies of retrieving the effective scientific spatial and spectral performance can be established. Facing long periods of storage and operation (Mercury approach is later than 2020) the implementation of on-board resources become even more important because permanent status determination of the instrument become realistic.

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