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MERTIS - The Thermal Infrared Imaging Spectrometer Onboard of the Mercury Planetary Orbiter

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Abstract — **The MERTIS instrument is a thermal infrared imaging spectrometer onboard of ESA's cornerstone mission BepiColombo to Mercury. MERTIS has four goals: the study of Mercury's surface composition, identification of rock-forming minerals, mapping of the surface mineralogy, and the study of the surface temperature variations and thermal inertia.**
MERTIS will provide detailed information about the mineralogical composition of Mercury's surface layer by measuring the spectral emittance in the spectral range from 7-14 µm at high spatial and spectral resolution. Furthermore MERTIS will obtain radiometric measurements in the spectral range from 7-40 µm to study the thermo-physical properties of the surface material. The MERTIS detector is based on an un-cooled micro-bolometer array providing spectral separation and spatial resolution according to its 2-dimensional shape. The operation principle is characterized by intermediate scanning of the planet surface and three different calibration targets – free space view and two on-board black body sources.
In the current project phase, the MERTIS Qualification Model (QM) is under a rigorous testing program. Besides a general overview of the instrument principles, the papers addresses major aspects of the instrument design, manufacturing and verification.

Keywords: MERTIS, BepiColombo, Mercury, Infrared Imaging Spectrometer, radiometer

I. INTRODUCTION

The recent knowledge about the infrared spectral emittance of Mercury's surface is limited to a number of ground-based telescopic studies e.g. [6], [7] or data from Mariner 10 [8] which flew past Mercury three times in 1974 and 1975. Several studies suffer from their restriction to the NIR-range, where pure feldspars have no specific spectral signature [9]. In the Thermal Infrared (TIR), however, feldspars can be detected by means of their diagnostic spectral signatures: Christiansen frequency, reststrahlen band, and transparency feature. In addition, pyroxenes and most other minerals can be detected and specified in this spectral range. Thermal infrared spectroscopy operating in the range between 7 and 14 µm will enable valuable mineral identification of feldspars and low-iron species that are expected to be prevailing on Mercury's surface.

Performing TIR measurements will make it possible to identify spectral features associated with the high radar backscattering efficiency of putative minerals and to differentiate between the proposed compositions (water ice, sulphur, and cold silicate glasses) for the high-latitude volatiles, something that cannot be done by ground based observing or near-infrared spectroscopy. [9]. In summary, MERTIS has four scientific goals: the study of Mercury's surface composition, identification of rock-forming minerals, mapping of the surface mineralogy, and the study of the surface temperature variations and thermal inertia. The instrument will provide detailed information about the mineralogical composition of Mercury's surface layer by measuring the spectral emittance in the spectral range from 7-14 µm with a high spatial and spectral resolution [1], [2], [3]. Furthermore MERTIS will obtain radiometric measurements in the spectral range from 7-40 µm to study the thermo-physical properties of the surface.

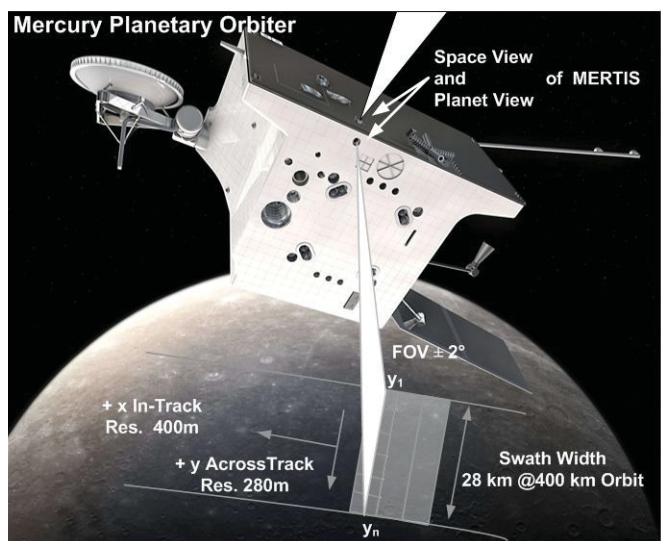

Figure 1: MERTIS space and planet view

II. INSTRUMENT OVERVIEW

The MERTIS instrument is an IR-imaging spectrometer and radiometer working on a high resolution push-broom principle. The spectrometer employs an un-cooled microbolometer array made from amorphous silicon, which yields a short thermal time constant as well as very low noise equivalent temperature difference NETD [10]. The array provides spectral separation and spatial resolution according to its two-dimensional shape. The operation concept principle is characterized by intermediate scanning of the planet surface and three different calibration targets - free space and on-board black body sources. Sharing the same optical path a push-broom radiometer is implemented according an in-plane separation arrangement.

The general instrument architecture comprises two separate parts - the Sensor Head including optics, detector and proximity electronics and the Electronics Unit containing the power supply with an interface to the primary bus, the sensor control and the driving electronics. This highly integrated and with 3.3 kg extreme light weighted measurement system is completed by a motor driven Pointing Unit device which orients the optical path to the planet and the calibration targets. Figure 2 gives an overview on the instrument configuration.

III. MERTIS INSTRUMENT MAIN PARAMETERS

	Spectrometer	***Radiometer***
Focal length	50 mm	50 mm
F-number	2	2
Optical efficiency	0.54	0.54
Detector technology	Bolometer matrix array	Thermopile line array
Number of pixel/size	160 x 120 / 35 µm (100 spatial, 80 spectral)	2 x 15 / 250 µm
Spectral range	7-14 µm	7-40 µm
Spectral channel width	90 nm/pixel	Line array 1: 7-14 µm Line array 2: 7-40 µm
Spectral resolution (λ/Δλ)	78-156	-
Detectivity	NEP < 15 pW	NEP ~ 150 pW
FOV (field of view)	4°	4°
Ground sample distance (400 km)	280-1400 m	2000 m
Dwell time	109 msec	775 msec
Swath width	28 km	28 km
Instrument dimensions	180 x 180 x 130 mm^3	
External baffles	200 mm x Ø75 mm (planet baffle) 90 mm x Ø75 mm (space baffle)	
Mass	3.3 kg (margin 5%)	
Power consumption (cold case heating)	8-13 W (< 19 W)	

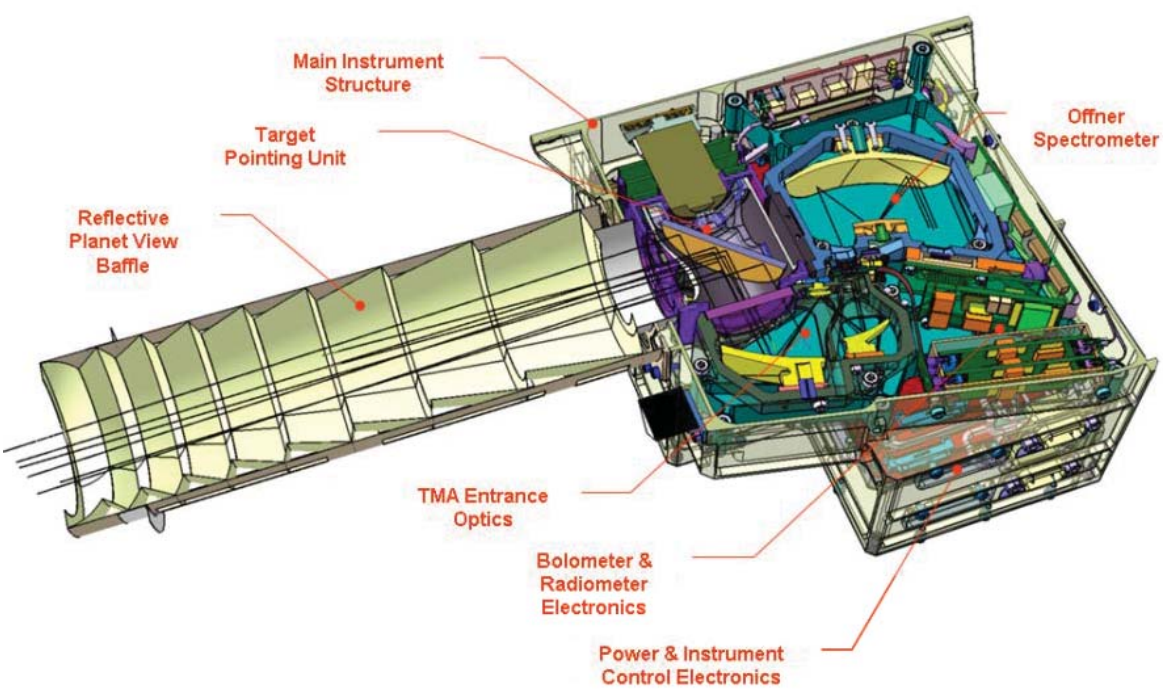

Figure 2 MERTIS instrument overview

IV. OPTICS SETUP

The instrument optics combines a Three Mirror Anastigmat (TMA) with a modified Offner grating spectrometer. The TMA consists of three off-axis asperical 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.
This suite is completed by the detector electronics as well as the pointing unit placed centered within the optical axis between IR entrance window and on-board calibration targets.

Optics performance simulation and results

The optical path difference of the dual focal plane concept does not exceed $\lambda/4$ which characterizes a diffraction limited design although the f-number is two. This is true for the image plane and at the slit where the detectors are intended to be placed. Tolerances are typically set to 5 to 30µm for radii, form irregularities of 0.1 to 1 µm P/V and a surface roughness of typically 5 nm. Figure 3 shows calculation results of the tolerances affecting the optics performance.

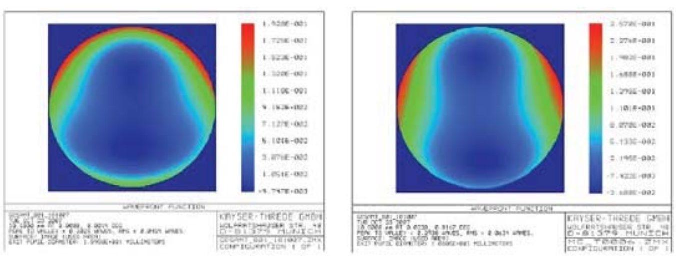

Figure 3: Wave front deformation analysis at the bolometer array from the designed (left) to the as-built toleranced status

Based on this analysis single point diamond turning has been applied for manufacturing of the mirror. Due to the lightweight and thin walled design deformation under rotation as well as vibrations required special simulations for the optimization of the cutting parameters. Measurements with interferometer and 3D-profilometer and following correction loops leads to a final figure deviation. For TMA alignment also an interferometric approach in the VIS (633 nm) was applied to bring the TMA into the desired status. Figure 4 provides the results of the wave front performance which meets the characteristics of the theoretical simulations very well [2].

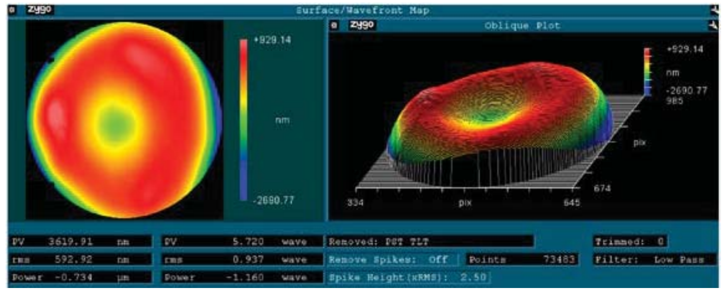

Figure 4: Measured TMA focus wave front shapes

The grating is the optical key part of the instrument. The challenge is to combine the functions of the spherical mirror as part of the Offner imaging path and of the blazed grating for the diffraction of the incoming radiation. From their several orders of diffraction the first is used for the spectrometer. The parameters are:

- grating period 11.5 lines/ mm
- groove depth 5.6µm,
- blaze angle 3.7°.

Dependent on the wavelength the efficiency is optimal around 10 µm.
For diamond turning the tooling is a combination of the off-axis rotation of the part and the tool path control perpendicular to this. During the development process the material has been optimised such that a fine grained AA6061 aluminium alloy is used with a highly reflective gold coating.

Order	Wavelength		
	7 µm	9.4 µm*	14 µm
0	3.9%	$6.9 \cdot 10^{-4}$	17.0%
1	64.1%	93.8%	61.5%
2	2.5%	$1.4 \cdot 10^{-3}$	4.4%

*: Maximum wavelength of 1st order diffraction efficiency

Figure 5: Cut grating profile and efficiency analysis

MERTIS optics is based on an all-aluminium design approach for all mirrors and the grating as well as for the connecting structure parts. This was decided with respect to the harsh

thermal environment causing temperature changes which have to be minimised by highest possible thermal conductivity within the optics.
Even though the displacements of individual elements are quite large the surface deformations are small about a few µm and are mostly rotational symmetric. Fitting all elements parameters considering de-center and tilt as well as the surface deformations the remaining errors are very small and causing negligible performance degradation. This is shown in the next figure comparing spot diagrams for a nominal and 40 K thermal loaded TMA.

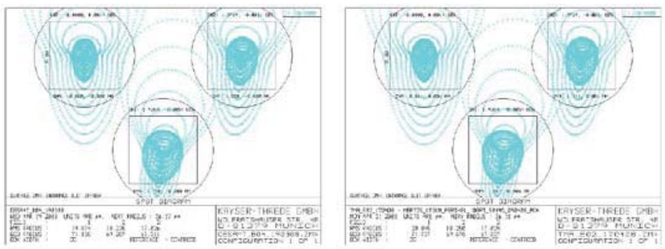

Figure 6: Spot diagrams of TMA nominal (left) and at Mercury perihelion (right) at 10.5 µm, box is pixel size, circle is airy disc

V. OPTICS MANUFACTURING AND VERIFICATION

A. Manufacturing Goals

The MERTIS reflective infrared optics for the spectral range from 7-14 µm can be ideally implemented as diamond turned aluminium mirrors coated with a thin gold layer. Single Point Diamond Turning (SPDT) offers the possibility to manufacture both, the optical surface and mechanical references in close tolerances and in respect to each other. From the manufacturing point of view the MERTIS optics consists of three different mirror types:

- On-axis mirrors: M2, Offner mirror
- Off-axis mirrors: M1, M3
- Spherical grating: Offner grating
-

For all elements mechanical simulations were carried out for an optimization regarding:

- Minimizing mounting forces during manufacturing and assembly.
- Minimizing centrifugal forces during SPDT.

The usage of identical reference planes on the mirror bodies for alignment during manufacturing, measurement and system assembly was an essential approach.

B. On-axis Mirrors

The on-axis mirrors M2 and the Offner mirror can be fabricated using the traditional diamond turning process. Due to interferometric measurements and following correction loops the figure deviation of the M2 mirror is reduced to around 100 nm p.-v.. Due to the usage of a novel aluminium alloy with refined grain size the surface roughness is less than 4 nm RMS (measurement area 315 µm x 235 µm) [4].

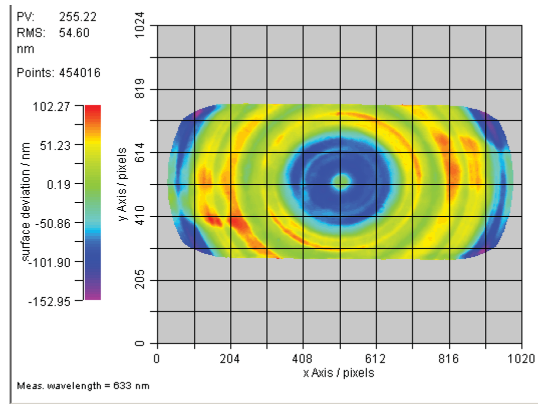

Figure 7: Interferometric measurement of a Offner mirror

Considering the simulation results of the light weight structure regarding the deformation under rotation, the spindle speed was reduced to 400 rpm for the Offner mirror. By turning the mirror with the calculated spindle speed a typical figure deviation of less than 300 nm p.-v. has been achieved for the Offner mirror. The radius of curvature and the vertex height can be manufactured in a tolerance of 0.01 mm.

C. Off-axis Mirrors

The M1 and M3 mirrors are similar excepting their size and will be fabricated in the same manner. The mirror bodies are mounted on a fixture, well referenced using a central dowel pin and clamps. After SPDT the guide edges of the fixtures are measured with a coordinate measuring machine. Together with the Z-position of the last cut this data provides the position (X,Y,Z) of the optical surface with respect to the mirror reference planes. This knowledge is essential for a deterministic alignment on the TMA optics.

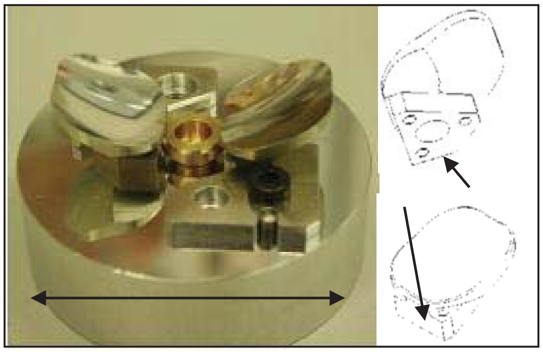

Figure 8: M3 mirrors on manufacturing fixture

Because of the deviation of the M1 and M3 aspheres from the best fit sphere it is not possible to measure the M1 and M3 interferometrically without a Computer Generated Hologram (CGH). An alternative solution is the usage of a tactile 3-D profilometer to measure the
surface shape. Because of the risk of scratches due to the cantilever the final tactile measurements has to be done before the last cut.

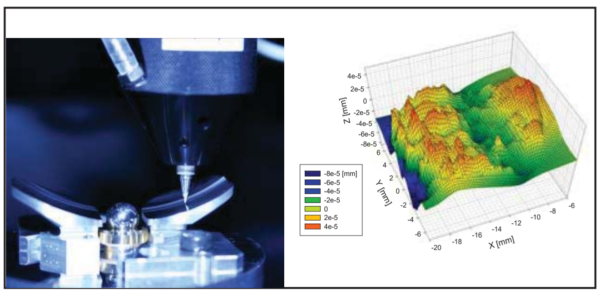

Figure 9: Measurement of M3 with tactile 3D-Profilometer (Panasonic UA3P), p.-v.: 256 nm

D. Spherical Grating

Rotationally symmetric microstructures like blazed gratings can easily be cut into flat, spherical or aspherical substrates by diamond turning. Cutting a linear grating in a spherical substrate is more difficult – but possible as well. In case of the Offner grating the substrate is mounted in an off-axis position with a distance equal to the radius of curvature of the desired sphere. This technique is typically used for the manufacturing of toroids. In case of the Offner grating the toroid has two identical radii. One radius of curvature is built by the off axis distance and the second radius of curvature is built by the tool path. The tool path can include a grating structure and other shaped elements.

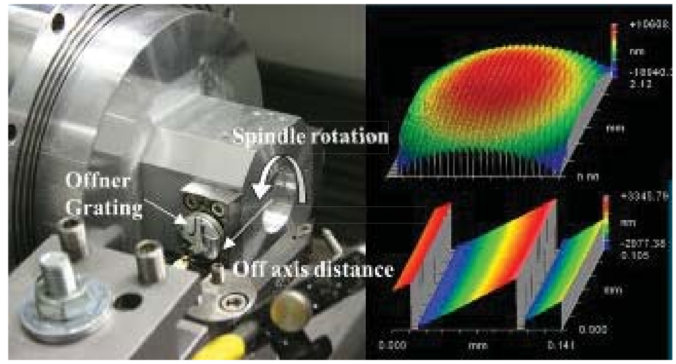

Figure 10: SPDT of Offner grating, White light interferometer image

E. Coating

After a cleaning procedure the mirrors were immediately coated with gold. The thin film deposition is a sputtering process to achieve a good adhesion and durability of the coating. The gold coating withstand requirements accordingly to

– Adhesion test, Procedure:Tapetest DIN 58196-6
– Humidity, Procedure:MIL-M-13508C 4.45 (49°C / 95% RH/ 24 h)Temperature change, Procedure:ISO 9022-2-14-04 (-50/+60 °C, 5 cycles, 30% humidity)

The reflectance of the gold coating on the diamond turned mirrors rises up from 97.5 % @ 1000 nm to more than 98.5 % fore wavelength above 2000 nm.

F. TMA Assembly Principle

Figure 11 illustrates the assembly principle of the TMA optics. The TMA-housing contains a central hole representing the optical axis. The M2 mirror and a dowel pin are fixed in this hole. The adjustment of M1 and M3 is done by gauge blocks in X- and Y- direction and by assembly plates in Z-direction (respectively in Rx and Ry). Furthermore well-known are:

- The position of the mirrors reference planes in respect to the aspheres
- The vertex positions of M1, M2, M3
- The mirror radii

The manufacturing of the housing is done according to these measures values from the mirrors. The outcome is an initial TMA assembly, which creates a wave front image that can be improved by interferometric observation.

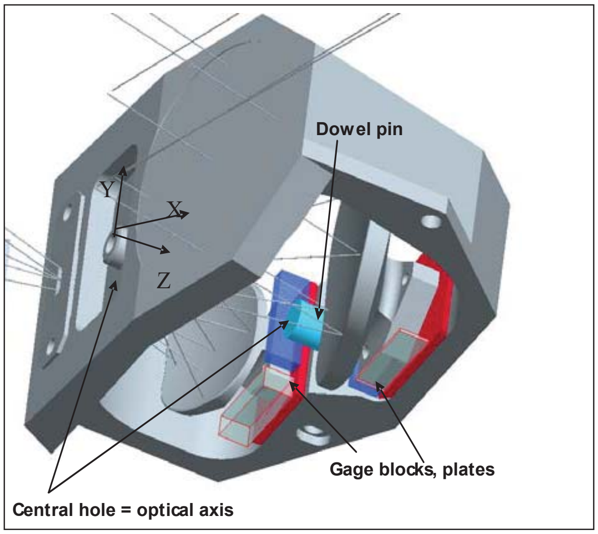

Figure 11: TMA assembly principle

G. *TMA verification*

The optical alignment of the TMA is done by an iterative process. Based on the initial wave front data new positions and tilt angles of M1 respectively M3 are calculated with optical design tools. These movements are realized by custom gauge blocks and plates. In this way the TMA was aligned close to the theoretical wave front.

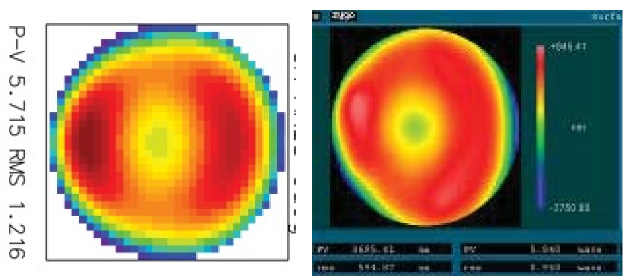

*Figure 12**:** Theoretical (left) and measured (right) wave front with 25 mm TMA-aperture*

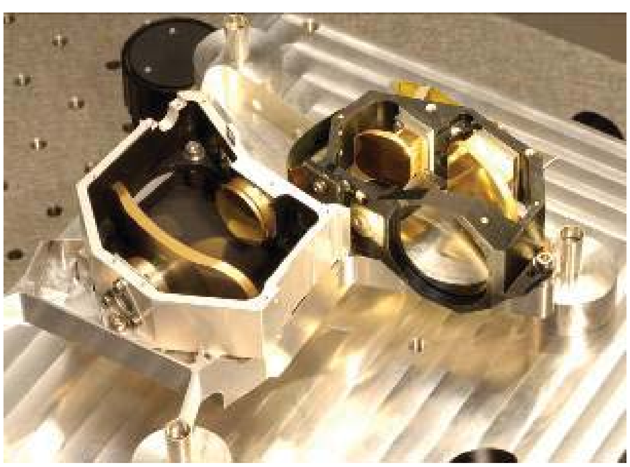

*Figure 13**:** Assembled MERTIS Spectrometer Optics*

VI. MERTIS RADIOMETER

A. *Technical Concept and Design*

The basic concept of the proposed MERTIS radiometer channel is to place a 2x15 elements thermopile double line array sensor chip with integrated optical slit for the spectrometer at the focal plane of the TMA entrance optics. The small signal voltages of the order of µV to mV generated by the thermopile sensors are transmitted differentially via a starr-flex interface PCB to a proximity electronics, where the signals are multiplexed, amplified, converted to digital units and transmitted to the MERTIS ICU.

The unusual solution of incorporating the optical slit into the radiometer chip was driven by the very small space available which is mainly a consequence of the MERTIS requirement to minimize the heat input through the entrance optics. This design requires a modification of the standard thermopile design where a self-supporting membrane containing the thermoelectrically active layers is spanned over a surrounding Si frame. Here, an additional central bridge is added to the Si frame which provides additional mechanical support (see figure below), thereby allowing to cut the slit into the centre of the membrane. Furthermore, the thermopile pixels are only weakly coupled to this central Si bridge by very narrow V-shaped bars to reach the maximum possible sensitivity.

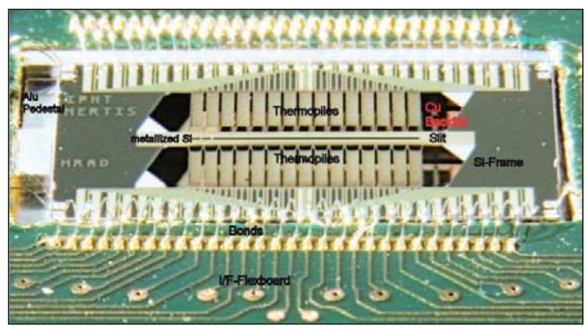

*Figure 14**:** MRAD detector chip and part of I/F flexboard (without IR filter)*

Each thermopile pixel of 200 x 1100 µm size consists of 14 thermocouples connected in series using $Bi_{0.87}Sb_{0.13}/Sb$ as thermoelectric materials. The pixels are coated by a thin layer of black silver smoke, a material with nearly constant high absorption from the visible to the far infrared. The pixel width of 200 µm is close to the diffraction limit of the optics at 40 µm wavelength, a small gap of 50 µm width between the pixels is necessary for technological reasons and also effectively eliminates thermal crosstalk between neighbouring pixels (under vacuum).

One infrared 8-14 µm band pass filter is mounted directly above the thermopile array on 50 µm high standoffs which are micro machined directly onto the chip. The other array uses only the MERTIS entrance filter to realize a 7-40 µm broadband IR channel which is aimed at measuring low object temperatures down to 100 K.

The electrical interface of the thermopile arrays is provided by direct wire bonding of the sensor signals to a rigid-flex PCB, the ends of the two flex wires are equipped with a Nano-connector to feed the signals into the radiometer electronics. Chip and PCB are mounted inside a dedicated Aluminium housing comprising of a baseplate and a cover. The whole detector unit is then fixed to the TMA structure by Shapal spacers which are providing an excellent thermal coupling but electrical insulation.

B. Manufacturing and Verification

For the manufacturing of the detector chips 300 µm thick wafers of <110> Si equipped with a 1 µm thick Si_3N_4 membrane were chosen. The process starts with the anisotropic deep etching of the Si to create the support frame and the staircase structure in the centre. The next steps are devoted to the micro structuring of the thermopile functional layers ($Bi_{0.87}Sb_{0.13}$, Sb, isolation and passivation layers) into the membrane. After cutting the wafer into individual chips the processing continues on single chip level with the manufacturing of the 80 µm wide optical slit by reactive ion etching. The last step to finalize the detector chip is the deposition of the black silver smoke absorber through a micro machined aperture.

The necessary backside cover which is required to prevent stray light (note that the detector chip is partly transparent to infrared light) to enter the spectrometer part of MERTIS is realized as a 10 µm thick copper foil glued onto the rear side of the detector. Into the central part of this foil a 500 µm wide slit of 4 mm length is etched to guarantee an unobstructed field-of-view for the radiation passing the optical slit (the 80 µm wide slit etched into the thermopile membrane) of the spectrometer.

The whole chip ensemble is glued to an Aluminium baseplate of 0.8 mm thickness which acts as a heat sink. To allow reliable bonding from the thin detector chip (300 µm) to the thicker (800 µm) PCB a pedestal of 500 µm height is added to the central part of the baseplate. Furthermore, the pedestal is equipped with two mounting edges which allow the positioning of the chip (especially the slit) to a few micron accuracy, a requirement which stems from the optical alignment strategy. All Aluminium parts of the housing are coated with *Fractal Black* [11].

The performance of the thermopile arrays was verified by mounting the detector inside a vacuum chamber and looking through a KRS-5 window onto an external blackbody. By varying the temperature of the blackbody between 5°C and 95°C an average sensitivity of about 440 V/W could be derived (see Fig. 5-2). The inhomogeneity of the array is less than 2%, except for the two outermost pixels because they are slightly better coupled to the Si frame which acts as a heat sink. With thermopile resistances in the range of 23-24 kOhms these numbers correspond to an average detectivity of about $1.1\ 10^9$ cm $Hz^{1/2}$ W^{-1} , a value which is 10% better than the design goal.

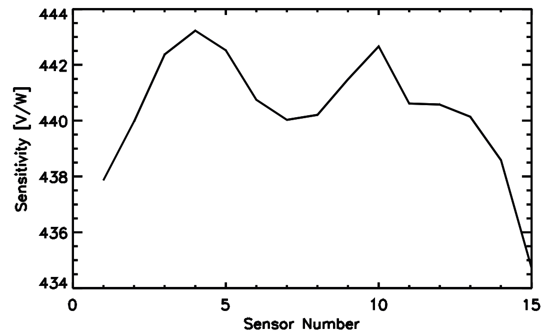

Figure 15: MERTIS Radiometer sensitivity

ACKNOWLEDGMENT

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