ABSTRACT

The paper presents design of the MERTIS POInting Unit of the Bepi Colombo mission. Demanded technical, environment and performance brought us to described design. The description is focused on the stepper motor concept and highly integrated the pointing mirror with support made of ceramic material CeSiC. The technology of position control with hall sensors and other part of MPOI are shortly described. The stepper motor description presents design and test results of pre-qualification models of MPOI with different type of lubrications: grease-based (Braycote 601EF) and dry lubricated (Wolfratherm). Results of test are discussed and final solution for the flight model is presented.

1. INTRODUCTION

The Mercury Radiometer and Thermal Imaging Spectrometer (MERTIS) of the Bepi Colombo mission is dedicated to global mineralogical mapping and measurements of surface temperatures and thermal inertia in the spectral range of 7-14 µm. The Pointing Unit (MPOI) as one of the spectrometer modules is situated in front of MERTIS to orient the optical entrance of the instrument to 4 different targets sequentially. These targets are the Mercury surface for scientific data take, the look into deep space (space view) for low temperature calibration, the 300 K black body for thermal calibration, and the 700 K black body for thermal calibration.

Besides strong needs for miniaturization environmental conditions are key for design details: operational temperature range -30°C to +70°C, random vibration loads around 40g rms and high level of radiation. The required performance is characterized with a pointing accuracy of 0.8 arcmin for the main targets and a pointing mirror flatness of better than 0.4 µm for sufficient wave front quality.

Referring these severe conditions the design is described in common including the basic outline, the stepper motor concept and the technology of position control with hall sensors and magnets. The relatively wide operational thermal range with small optical tolerances asks for ceramics material for the pointing mirror. Here a highly integrated design has been selected based on CeSiC. Test results and experiences with the technology are discussed finding the final solution for the flight model.

The stepper motor is described in detail regarding the needs of modification to cope with the vibration loads, the level of radiation and the requirement of long life vacuum operation based on motors commercially delivered by PHYTRON. The stepper motor design is described highlighting the bearing systems used. A special section is spent on the test results of pre-qualification models of MPOI with different type of lubrications: grease-based (Braycote 601EF) and dry lubricated (Wolfratherm). These have been manufactured in parallel and simultaneously tested. Vibration test, thermo-balance test and long life tests were carried out. After tests, REM inspection at bearing level was done and discussed. The full qualification model of stepper motor with recommended ball bearing was manufactured and the radiation test results presented.

2. MPOI DESCRIPTION

The Pointing Unit (MPOI) is situated in front of the MERTIS instrument. The main objective of the Pointing Unit is to orient the entrance of the instrument to 4 different targets sequentially. These targets are:

- the Mercury surface for scientific data take,
- the look into deep space (space view) for low temperature calibration,
• the 300K black body for spectrometer temperature reference calibration,
• the 700 K black body for mercury temperature reference calibration.

It is essential for frequent views to the calibration targets and the cold space for temperature referencing. There are requirements to see targets of 300K, 700 K and cold space within the Mercury observation.

This is realized by implementing a single rotary mechanism with a 45° tilted mirror. Its rotation axis is oriented in optical axis direction thus efficiently reaching the necessary targets. Also across track scanning would be possible in this configuration, but due to thermal design restrictions the resulting wider cone of the baffle is not acceptable, even for the spacecraft thermal control.

The MPOI consists of: counter bearing assembly (1), pointing mirror assembly including screen tube(2), stepper motor (3), magnetic sensors with electronics (4), drive power electronics (5), cross pointing structure including 4 target ports (6), emergency pointing actuator(7).

General view of MPOI are shown in drawing of cross section Fig.1 and in photo Fig.2.

The operation concept is defined by sequence of rotation between positions. The mechanism starts to rotate the pointing mirror in a start/stop manner from the default position at the 300K Black Body. This is the launch/rest and the initialization position. The measurement cycle start from Mercury position, so it means that a rotation about 180 deg from 300K Black Body position should be done before start of measurements. The Mercury position is “zero” position for ICU counter. The pointing mirror stay in this position around 13 sec. Next the mirror orients the instrument line of sight to the 700K calibration target. From there after taking the data the 300K BB target is reached and finally open space port of the instrument is approached for deep space observation before the Mercury position is reached again. The stepper motor can be rotated in both directions. The movement from deep space position to Mercury position is done in reverse direction. Direct movement between deep space and Mercury view is mechanically block. The mechanical element which block the movement is used for precise fixing Mercury and Deep Space positions according pointing requirement.

The pointing system is motorized with the stepper motor specially design for the MPOI based on commercial VSS 25.200.0.6 E (Phytron). Control commands are sent by ICU via drivers of the motor. For validation of the mirror position, a system of magnetic sensors (4) is applied (see fig.3).

Magnetic Hall effect sensors are used for defining zero position (sensor Z) and validation of calibrations positions (sensors V1, V2). Scheme of positions of magnetic sensors (red rectangulars) and magnetic pins (grey small cylinders) is shown in fig.4 (view from top after removing the mirror with the cylinder).

The 5 magnetic pins are fixed in the bottom part of the cylinder of the pointing mirror assembly. Four pins are dedicated for validation sensor, one pin for the zero position sensor.
Fig. 4 Positions of magnetic pins

The zero position provides initialisation for step counting and start of measurements. Every new position is achieved by sending command with number of steps. Standard micro-processors usually used for ICU are equipped in counters, what simplifies the driving electronics. This motor can be operated to work in a micro step mode with a standard step of 1.8 deg or half step of 0.9 deg with accuracy better then 3% according technical note delivered by producer.

The rotation of the mirror is done with step 90 deg or with its multiple. In case of right position two validation magnetic sensors see magnetic pins. Both validation sensors work in logic configuration „or“. In case of failure one of them a signal from second is sufficient for validation. The sensors deliver a confirmation that commanded position is reached. Number of steps is calculated by ICU. Moreover every position of the motor has own binary code which can read by ICU s/w.

The zero position sensor is used at the beginning of every measurement cycle. The zero position pin shall stop in front of magnetic sensor only for Planet view position. The magnetic pin for this position and zero position magnetic sensor are situated higher then pins and sensors for validation position to avoid any interference between them. After switched on the MPOI, the mirror is rotated from position of 300K BB to the Mercury position. The counter is reset. The measurement can be run.

Positions of Mercury and deep space require a high accuracy 0.8 arcmin of positioning. From this reason mechanical limiters are applied. For these two positions two or more additional steps are done to be sure that the mirror reach the right position.

To keep these positions stable the 3 additional magnets are install. One is in structure (Fig.5) and 2 are placed at the bottom of the mirror support. When the mirror reach position Planet View or Deep Space the magnet from structure is close to the magnet from cylinder. Magnetic forces keep the position stronger to avoid any microvibration influences, which can move mirror when power is off during measurement for these two positions.

For temperature measurements, four temperature sensors (green pieces) are fixed to the structure. Main and redundant sensors are placed close to the stepper motor and next pair is fixed to the structure close to the counter bearing assembly (fig.5). The temperature is read by ICU.

The motor control logic and procedures is integrated into the ICU as FPGA VHDL code. The motor controller works in two modes: closed loop and open loop.

Counter bearing assembly at the instrument entrance port is designed for guided mirror rotation at its interface ring (see fig.6). It should enhance the pointing accuracy and minimise launch load effect. Four element made of Peek pushing by regulated springs keep the cylinder with proper force.

Figures 6 Counter bearing assembling

Emergency pointing actuator (EPA) shall be used in case of electronic failure. It can rotate the motor shaft with pointing mirror to the Mercury view position and keep this position all the time. The mechanism is based on rolled springs which will be released on command. The actuator will be situated on the back shaft of the stepper motor what is shown on photo 1. The reverse rotation of rolled spring is blocked by special fiber (made by DSM Dyneema) Dyneema SK65 Φ 0.3 mm. One end of the fiber is fixed in hole of the top cover, next it
embraces the resistor and it goes under the spring box to the second resistor and finally is fixed using second hole in top cover like is shown on fig. 4.8. Every resistor needs 3.2 W (voltage 28) to burn fibers during a few seconds. There are powered independently. Every resistor can burn the fiber and run release mechanism.

Pointing Unit Electronics consists of three separated parts:
- stepper motor, coil’s drivers and position sensors located in MPOI and delivered by SRC as the real hardware, and
- MPOI Autonomous State Machine (MPOIASM), used for control of the mirror rotation, located inside Main Instrument Control and delivered by SRC as VHDL code. MPOIASM uses 3 input FPGA lines for position sensors interface and 8 output FPGA lines for controlling the current in four separated coils in stepper motor.
- Identical MPOIASM located inside Redundant Instrument Control and connected to MPOI hardware in OR with Main MPOIASM.

Both, Main and Redundant MPOIASM parts work at the same scenario. In Normal Mode (so called Closed Loop) of operation the rotation is initialized by setting internal register values to desired values and then performed by sending operation command (go to a certain position). This is realized as write cycles to MPOIASM’s internal registers. Then MPOIASM performs, in autonomous way, the proper number of phases for stepper motor according to previously defined timings. MPOIASM chooses the left/right rotation and counts the number of steps. The bit READY in output register is cleared by MPOIASM during movement and set by MPOIASM when the required position is stabilized. Then the confirmation that the position of the mirror is achieved can be done by MERTIS Instrument Control by checking the signals acquired from position sensors.

3. STEPPER MOTOR

The stepper motor plays a fundamental role in the complete unit with a high reliability.

Hard environmental condition must be fulfilled:
- high random loads
- hard radiation
- long life
- thermal environment
- low shaft run out and high accuracy
- compact and stiff structure

It was clear at the beginning that the standard VSS 25.200.0.6-E stepper motor for ground based vacuum applications cannot perform the hard requirements without a complete redesign for the MPOI requirements.

The stepper motor has been integrated as a fundamental component in the pointing unit and combines the suspension and also the drive.

To present a small and lightweight support for the CSiC pointing mirror assembly we made the essential structural components out of a titanium alloy. Diameter of the shaft and size of the bearings were significantly strengthened expected to the forces. A closely aligned duplex bearing system stabilizes the inner rotor system.

To limit the technical lifetime risks and the consequences to a project delay we decide to test two different pre-qualification models (PQM’s) configurations simultaneously:
PQM-1: bearings lubricated with BRYCOTE 601EF and VESPEL SP3 cages.
PQM-2: hybrid bearings with siliziumnitrid (Si₃N₄) balls and a dry lubrication coating (5um wolfratherm coating inside the rings) and stainless steel cages.
The rest of the stepper motor construction was identical.
Environmental tests of PQM’s were carried out according ESA procedures and specifications for the mission at qualification leveles.
Following the normal test sequence we start at assembly level with the qualification vibration test.

Figure 10  vibration test

A thermo balance test was done to measure the thermal characteristic of the stepper motor and the reactions to the mirror position accuracy.

Figure 11 thermal test chamber at SRC PAS

The long life test scenario follows over nearly 6 month under vacuum conditions and temperature cycling with the two PQM systems (see fig.12, fig.13 ). The range of operational temperature was from -35°C to +55°C.
Around 2x10⁶ motor shaft rotations were done in this time.

After the tests both PQM versions were completely disassembled by PHYTRON for an end of life (EOL) inspection. In the focus of our interest were the bearing parts.

Figure 12  life time test facility DLR Berlin

Figure 13 PQM’s placement at the interface

4 LIFETIME RESULTS OF PQM-1 (WED LUBRICATION)

Lubricated bearing system with BRAYCOTE 601 EF were in very good conditions. Nearly no wear or other degradation aspects were found inside the disassembled bearings. The measured torque characteristic shows us only under lower temperature a significant torque decrease.

Unclear questions were :the friction inside the grease at lower temperature (approx 320 mA was necessary to start at -50°C at BOL = approx. 55 % of nominal current) and agglomeration effect. Degradation of BRAYCOTE due to hard radiation is well known effect. From this reason the application of the grease lubricant was carefully analysed.
The additional hard radiation test was decided after inspection.
5. LIFETIME RESULTS OF PQM-2 (DRY LUBRICATION)

For dry lubricated bearing system with 5 µm WOLFRATHERM coating on the rings, Si₃N₄ balls, stainless steel cage the degradation inside the coating was clearly visible. Produced plates and chips can block the bearings and a single failure can fail the complete mission.

Negative results of the test of the dry lubricated bearing, caused that the stepper motor with grease ball bearing was selected.

For checking proper work hard radiation test of a qualification version of the stepper motor was made. The intention of the test with a γ-emitter (1,17 MeV and 1,33 MeV) was to get an impression of the negative torque influence depending on the aging affects of the bearing lubrication during radiation. The cobalt 60 as a source was used for test.

No visible and measured changes were observed after the test and this type of the stepper motor with selected ball bearing is used for qualification and flight models of MPOI. Qualification model of MPOI was fully tested and no problems with the stepper motor were noticed.

6. POINTING MIRROR ASSEMBLY

The Pointing mirror assembly is a suite of the pointing mirror itself and interface parts to the motor and a screen tube for shielding unwanted radiation from outside the FOV. This is most effective by having an aperture in a cylinder surrounding the assembly sharing all movements applied according figure 19. Usually the design approach is to separate the mirror and the support structure as different parts.
with well defined interface technology. The 45° tilted mirror is simply specified to be plane. However the thermal loads at the instrument front are significant and the pointing mirror is a stand-alone 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 dedicated to the positioning like magnets in 5 positions to initiate hall sensor signals and 2 more for end position capture (see fig.19, fig.20). Counter balance masses (fig.18 point 1-space for mass) are added to keep the angular position of the mirror assembly balanced during launch loads avoiding any locking device. The strategy of reaching a high pointing accuracy for at least two of the targets by mechanical limiters is also implemented by providing the necessary mechanical interfaces.

Additionally, to avoid stray light, the cylindrical shield inside is coating by Kepla-coat. The tube interface ring to the counter bearing assembly is covered by the layer of AHC hardcoat filled by teflon (fig.19 point 2) to reduce friction and to improve hardness of the ring surface.

The material of choice is CeSiC which is inherently thermally stable by low CTE and provides sufficient thermal conductivity for gradients depression against deformation. Since CeSiC technology is basically different from metal machining not allowing complicated contours is it necessary to apply shared pre-manufacturing to be glued together before Si-infiltration getting into one-body system. As a result the basic ceramics form according fig. 21 is created.

In a following step the final geometry is reached with eroding processing followed by preparation of the mirror surface with Si-layer for optical quality polishing. The typical result is provided in figure 22.
Fig. 22 interferometric image of the mirror surface

Gold coating with Yttrium-oxide safety coating on top ends up the mirror manufacturing.

After assembling and adjusting in QM MPOI a qualification tests were carried out including thermal balance test in a temperature range of -55 C to +85C. Deformation of the surface of the mirror with the present design was brought down to less than 1µm which is corresponding to λ/10.

To cope with the demanding dynamic loads of the application defined it was necessary to have extended FE-analysis to find the appropriate structure design. In the case of this outstanding material there is intermediate testing necessary to verify the parameters use in models Figures 23 shows improvements of the design towards homogenous stress distribution inside the integrated mirror.

Fig. 23 stress distribution in integrated mirror

7. CONCLUSION

Presented design of the Pointing Unit of the MERTIS after full qualification tests fulfilled technical assumptions. The flight and spare flight models will be assembled according presented solutions.