DESIGN, QUALIFICATION AND LESSONS LEARNED OF THE SHUTTER CALIBRATION MECHANISM FOR ENMAP MISSION

Tilo Schmidt, Silvio Müller, Arvid Bergander, Kai Zajac, Klaus Seifart

Hoch Technologie Systeme GmbH, Am Glaswerk 6, 01640 Coswig, Germany, Email: Tilo.Schmidt@htsdd.de; Silvio.Mueller@htsdd.de; Arvid.Bergander@htsdd.de; Kai.Zajac@htsdd.de; Seifart@htsdd.de

ABSTRACT

The Shutter Calibration Mechanism (SCM) Assembly is one of three mechanisms which are developed by HTS for the EnMAP instrument in subcontract to OHB System AG Munich. EnMAP is the Environmental Mapping and Analysis Program of the German Space Agency DLR.

The binary rotary encoder of the SCM using hall-effect sensors was already presented during ESMATS 2011. This paper summarizes the main functions and design features of the Hardware and focuses on qualification testing which has finished successfully in 2014. Of particular interest is the functional testing of the main drive including the precise hall-effect position sensing system and the test of the fail safe mechanism. In addition to standard test campaign required for QM also a shock emission measurement of the fail safe mechanism activation was conducted.

Test conduction and results will be presented with focus on deviations from the expected behaviour, mitigation measures and on lessons learned.

REQUIREMENTS AND APPROACH

General requirements

Table 1 comprises a choice of requirements which drove the development and verification effort.

Table 1 Requirements

Time for mirror wheel position change	≤ 10 s
Position accuracy of the wheel interface	≤ 0.1 mm
Accuracy of the stop positions	± 5 arcmin
Stability/repeatability of stop positions	± 1 arcmin
Move-stop cycles for qualification	322,060
Operational temperature range	0°C / 40°C
Non-operational temperature range	-40°C / 80°C

Functional requirements

The SCM is facilitating switching between three precise positions (+/- 5arcmin) of a multifunctional mirror wheel. This enables activation of a calibration source optical beam, an obscuration of the light path for dark calibration and a free passing of the observation optical beam. For the QM phase a dummy of the intended mirror wheel was furnished by the customer.

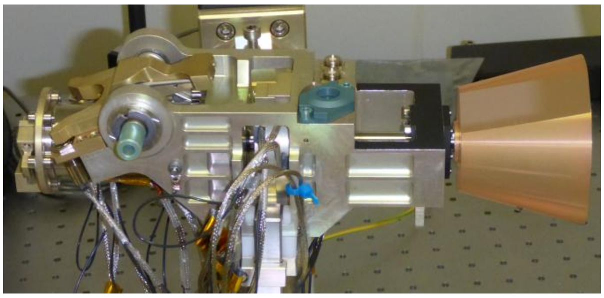

Figure 1 SCM with dummy wheel (right), cone and axis mechanical interfaces

To fulfil this requirement a drive chain (Figure 2) with strong motorization and sufficient precision was implemented. It consists of a stepper motor, a harmonic drive (ratio 1:100) and a long Ti-alloy shaft which has a locating duplex bearing close to the harmonic drive gear and a soft preloaded bearing close to the mirror wheel interface.

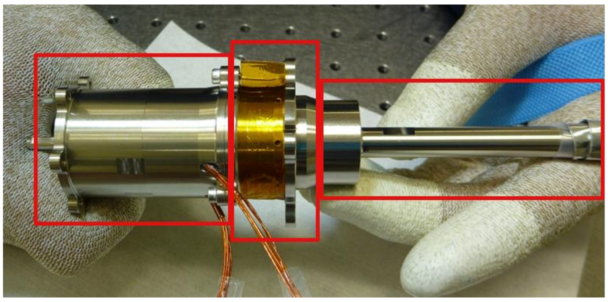

Figure 2 SCM drive unit (motor, gear, bearing&shaft)

The second mechanical function required was to bring the whole SCM assembly in such a position that ensures the undisturbed light path from telescope in case of a malfunction (wheel stuck). For this the mechanism can be folded away by 20 degree motorized by redundant rotary springs. Rotation is facilitated between an axis and the housing applying redundant bush bearings. The motion is triggered by a Frangibolt® actuator releasing the tightened cup-cone interface to the instrument structure (Figure 1).

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The definition of the mechanical interfaces to the instrument optical structure turned out to be unfavourable. Since the cup part of the cup-cone I/F and also the brackets where the fail safe axis is mounted was under customer responsibility, testing requires provision of these parts by the customer. On the other hand the functional surfaces of this I/F, the screw thread sizing and material had to be determined by HTS to ensure the needed performance and reliability of the mechanism. Fig. 1-3 shows the SCM QM including transparent I/F parts for the fail safe axle and the cup-cone I/F

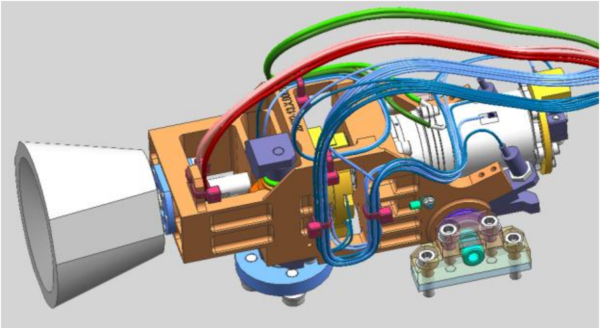

Figure 3 CAD Design of SCM QM

Structure and Material

The housing which forms the main structure of the SCM assembly is made of aluminium. The structure was designed basically as two side walls with several interconnections. It contains nearly all interfaces for subsequent components of the mechanism. Lightweighting was done by pockets at all outward faces, what could be modified according to structural analysis needs quite easily.
Because of the significant length of the actuator shaft and the CTE mismatch to the housing a soft preloaded duplex bearing was used close to the mirror wheel interface to take the radial loads. The dry lubrication was applying PGM cages, which performed well during environmental and life time testing. Lubrication of all bearings housed inside the stepper motor was Braycote 601 EF and for the HD gear RHEOLUB 2000 was used.

Positions verification

In principle the positioning of the mirror wheel was done by counting steps from a reference position. To encode the three operational positions, three hall sensors are used. A coarse position detector, consisting of two redundant magnet/ hall-sensor-pairs (two bit), is mounted on the gear shaft and recognizes that the correct configuration is approached. A fine position detector, consisting of one redundant magnet/ hall-sensor-pair, is mounted on the motor shaft and facilitates the necessary resolution by a 1:100 HD gear ration. For more details on the position verification development please refer to paper presented during 14th ESMATS [1].

INTEGRATION

Besides a moreover common integration process the mounting of the QM mirror wheel was the most challenging step. The interface comprised a rather close fit from shaft to mirror wheel because of high accuracy requirements under all thermal conditions and after enduring mechanical loads.

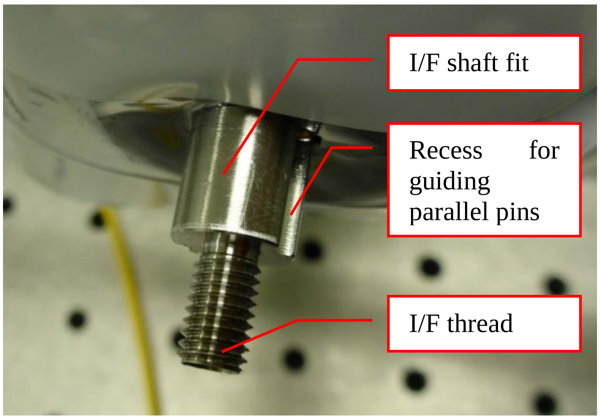

Figure 4 Mirror wheel interface

A mounting jig was used which clamped the actuator shaft and prevented load transfer to other components. The assembling was supported by heating the wheel, but this showed no perceptible effect. The handling of the hot component by hand was one detrimental point. Second the relative large surface of the part favoured a rapid cool down. The problem was that partial mounting could get the wheel stuck in a wrong position. A first mounting attempt failed exactly for that reason. But the wheel could be removed without damage fortunately. The investigations after this failed assembly step delayed the further integration. The size of the fit was revised on mirror wheel side. Changes on shaft side would have led to a complete disassembling of the SCM. A shaft dummy was manufactured to test the effectiveness of the design change. Finally the wheel could be mounted successfully, however with waiving the two guide pins and filling the gaps with adhesive.

TEST

The qualification test campaign started with performance testing focused on verifying the functionality and accuracy of the SCM assembly. A test frame was used allowing for operation under different spatial orientations. Also the procedures for refurbishing the Frangibolt® Actuator were checked.
First difficulties occurred during test of the fail safe function. The heating and the subsequent breaking of the Frangibolt® worked well, however the final fail safe position was not reached and hence the detection by end switches failed. The root cause was quite obvious the bending stiffness of the harness. First harness fixation point on system level was defined late in the course of

the project, so that the corresponding harness bridge (Figure 5) was introduced in the test setup without prior investigations. Small modifications on the routing and the free length of the cables led to successful deployment, which was also verified during life time testing of this function.

Figure 5 Test of the fail safe function of the SCM QM assembly

Another point to mention concerns the release by Frangibolt® actuator. The principle is breaking a bolt with a rated break point by expansion of a shape memory alloy. The maximum operation temperature (meaning save of unintended release) of the actuator given in the datasheet is +80°C. During testing release temperatures were recorded with the actuator internal sensor and varied in the range of +79°C to +109°C. For the same actuator type in the other EnMAP Mechanism under HTS responsibility the measured release temperatures reached even down to +72°C. This had consequences for the thermal testing which was planned to verify non-operational temperature of +80°C. A revisit of the thermal requirements by the customer allowed for reduction the max. non-operational temperature to +60°C. However the resulting qualification temperature of +70°C was still critical in terms of unintended release and any overshooting in the temperature control had to be prevented.

One objective of the QM testing was to evaluate the cleanliness procedures and measures. The SCM environmental testing campaign foresaw a hermetical sealing under foil. For that reason the application of acceleration sensors was done in cleanroom environment prior transport to the test facilities. However two weak points in the contamination control were identified. The health check requires a release of the fail safe mechanics and consequently a refurbishment in laboratory environment. Second the TV testing requires a venting of the foil cage. These events were tracked with specific witness samples. The unplanned issues which worsen contamination budget were the need to exchange one of the sensors during vibration testing and the questionable outgassing behaviour of the covering foil under TV test conditions. The decision to remove the foil tent in the chamber turned out to be a great portion of the overall particular contamination gained during testing. Afterwards a material test of the used foil showed that outgassing would have been compatible to TV environment and removing the foil tend was unnecessary.

The design of the FM mirror meanwhile evolved and deviated from the QM design. That's why in terms of vibration testing the load at mirror wheel level was of major interest and a three axis sensor was mounted in the middle of the wheel.

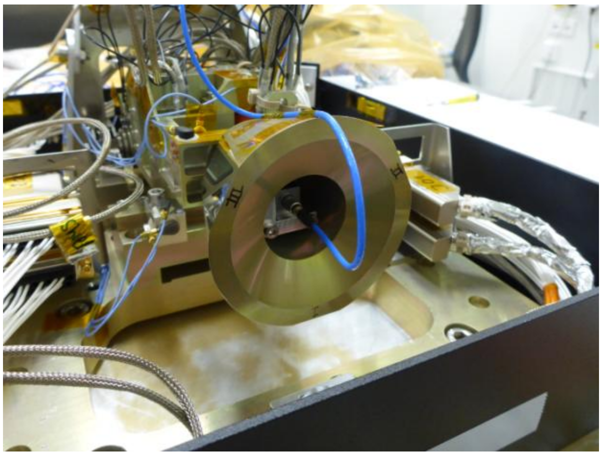

Figure 6 Central acceleration sensor at mirror wheel interface

This particular sensor recorded a signal which was compared to others excessively noisy for all three channels. In the resulting non conformance process investigations were first focused on checking the measurement system. Loose connectors were excluded by exchanging the channel cables. After replacing the sensor itself signal noise improved to some extend but was still too high. In addition the measured first modes frequency dropped to about 54% of the predicted one. It became evident that the noise was system inherent, meaning there is gapping occurring in the bearing. The following activities should answer the questions: Is the SCM build according to design (tolerances, preload, etc.)? Is the FEM model the prediction is based on adequate? Is the mechanism, respectively the actuator location bearing, able to stand the vibration loads? The results were: Yes, the MAI was done correctly; no, the FEM is modelling the bearing seat too stiff; yes, the loads are acceptable. By cost of a full testing day the campaign could proceed. Later life time tests showed that the gapping did influence neither the overall accuracy nor the health of the bearing.

The environmental test program included an additional shock emission recording while the Frangibolt® fastener breaks. The mechanism was fixed on the ringing table in such a way that the release direction of the breaking bolt is perpendicular to the mounting plane.

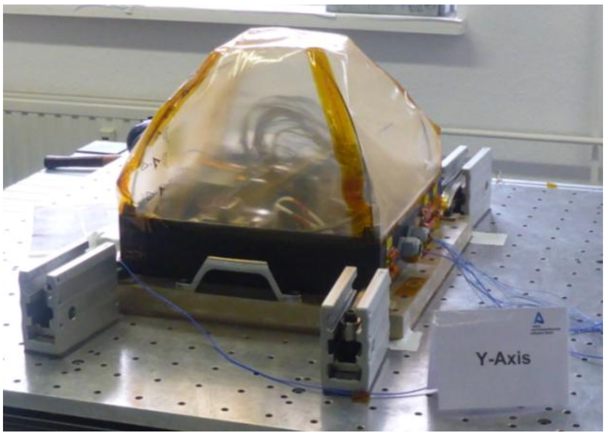

Figure 7 SCM on ringing table (shock test)

The shock levels at SCM interface, which is close to the Frangibolt® actuator position, reached values of about 1500g. Currently the reduction of the shock is further investigated by reducing the bolt preload. In parallel the rated break force of the bolt has been decreased to still guarantee safety of the release of the fail safe function.

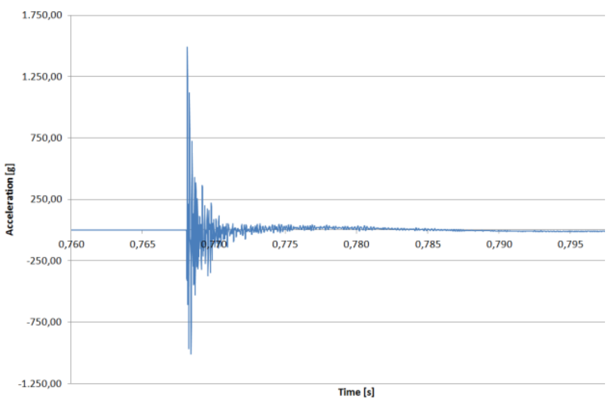

Figure 8 maximum emitted shock at I/F

The life time test was performed automated for 350,000 start-stop cycles in batches of 3x120° and 3x240° mirror wheel rotation. A number of autonomous stop criteria were included such as:

- Identification of jamming of actuator
- Temperature limit for windings exceeding
- Data acquisition anomalies/failures

The test period was approximated to be 35 days with 29 days (24 hours) rotation plus breaks for cool down and intermediate checks. Soon it was realized that the cool down time was drastically underestimated. A rotation batch of 6 position changes took 25 s. After exceeding the upper limit temperature of 40°C a cooling down below that limit took about 55 s. In result the lifetime testing was – although automatic performed – very time-consuming. After 64 days it was successfully completed without degradation of required mechanism performance.

RESULTS

Table 2 summarizes some of the achieved results from the qualification.

Table 2 Qualification results

Time for mirror wheel position change	≤ 10 s
Position accuracy of the wheel interface (comparison before and after test)	≤ 0.05 mm
Accuracy of the stop positions	± 3.45 arcmin
Stability/repeatability of stop positions	± 0.7 arcmin
Move-stop cycles for qualification	350,000
Operational temperature range	0°C / 40°C
Non-operational temperature range	-50°C / 70°C

To close the qualification successfully all non conformances were revisited. Again the interface between mirror wheel and actuator shaft raised questions. By the mentioned omission of the parallel pins the load had to be borne by the gap filling adhesive. The soundness of this connection was checked by an additional investigation. One Nm torque was applied to the mirror wheel while the shaft was clamped. Laser distance sensors at the circumference of the wheel and the shaft measures the distortion. Several measurements revealed that the distortion is fully elastic; meaning the connection between wheel and shaft is firm.

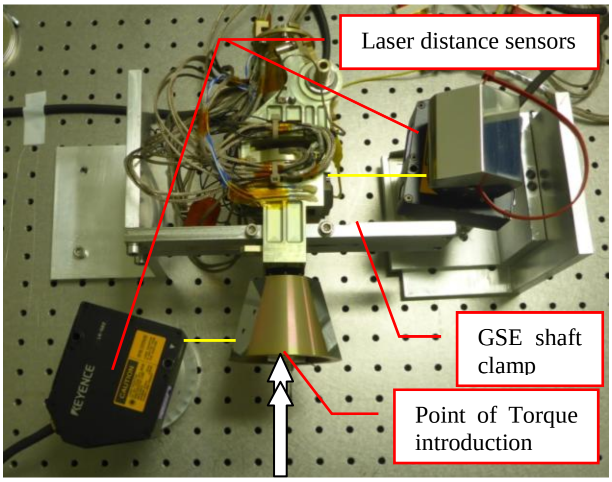

Figure 9 setup to investigate soundness of interface wheel to shaft

LESSONS LEARNT

Interface definition and reasonable sharing of responsibilities is a major concern to be regarded during requirement elaboration, but also during tender considerations. Besides others attention should be paid to:

- Separable mechanical contacts
- Moveable harness
- Interfaces to subcomponents with limited possibility of dismounting

Even if not required for QM the verification of cleanliness procedures during MAIT gives valuable inputs for later FM phase and reveals leaks like for instance:

- Material compatibility and usability
- Possible unforeseen events in contamination control planning
- Underestimated contamination contributors and their approximate quantification

Bearing preload is always a tricky point not only for structural reasons, but also in predicting testing behaviour. Soft preloading may result in unexpected noise during vibration tests.

The transient thermal behaviour of a specific actuator/motor should be assessed preferable on a comparable EM or other early model in order to predict lifetime test time. This data is also important for the operation instructions of the mechanism.

REFERENCES

1. Kottmeier, S., Müller, S., Schmidt, T., Zajac, K., Schmalbach, M., (2011). *A high precision, high reliability binary rotary encoder using hall effect sensors*,14th ESMATS 2011, ESA SP-698