ENVIRONMENTAL MAPPING AND ANALYSIS PROGRAM (ENMAP) MECHANISMS:
IMPACT ON INSTRUMENT PERFORMANCES

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ABSTRACT

The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission led by DLR whose aim is to monitor and characterize the Earth’s environment on a global scale. The space segment, which includes the Hyper Spectral Imager (HSI), is under OHB System AG responsibility. The HSI, main instrument on board, has two separated spectral channels in the VNIR and SWIR spectral range. Both spectrometers are designed as prism spectrometers and share a common telescope with a field splitter in the telescope focal plane.

The EnMAP HSI contains the following mechanisms:
- Shutter/Calibration Mechanism Assembly (SCMA)
- SWIR Switch Mirror Assembly (SSMA)
- Full Aperture Diffuser Assembly (FADA)

All three mechanisms have been developed, integrated and tested by RUAG Space Germany (RSG) according to specification of OHB. The SCMA (single DOF) positions a mirror wheel for internal calibration, obstruct and free the optical path. The SSMA (single DOF) moves a mirror and directs the light path to the redundant SWIR detector in case of failure of the nominal one. The FADA (two DOF) is positioned outside and at the main entrance of the EnMAP instrument. It allows the entrance of the light coming from the Earth and also the calibration of the instrument via sun.

The mechanisms (as also the instrument in the main functions) are fully redundant. The paper will outline the main mechanism design drivers with their impact on instrument performance. It will include the challenges on mechanism as well as instrument AIT (Assembly, Integration and Test). Particular attention will be given to describing the effect of the shock induced into the optical elements of the instrument and produced by the launch locking devices present in the mechanisms.

ENMAP MISSION DESCRIPTION

The goal of the German hyperspectral satellite mission EnMAP is to monitor and characterise the Earth’s environment on a global scale. Once operating, EnMAP will provide unique data needed to address major environmental challenges related to human activity and climate change. The mission’s main objective is to study and decipher coupled environmental processes and to assist and promote the sustainable management of the Earth’s resources. Figure 2 shows an overview of the EnMAP Satellite.

Mission outline
- Dedicated imaging pushbroom hyperspectral sensor mainly based on modified existing or pre-developed technology
- Broad spectral range from 420 nm to 1000 nm (VNIR) and from 900 nm to 2450 nm (SWIR) with high radiometric resolution and stability in both spectral ranges
- Swath width 30 km at high spatial resolution of 30 m x 30 m and off-nadir (30°) pointing feature for fast target revisit (4 days)
- Sufficient on-board memory to acquire 1,000 km swath length per orbit and a total of 5,000 km per day.

The main instrument on board is the hyperspectral imager (HSI, see Figure 4) with two separated spectral channels in the VNIR and SWIR spectral range. Both spectrometers are designed as prism spectrometers and share a common telescope with a field splitter in the telescope focal plane.

**Instrument Key Requirements and Mechanism's Impact**

The relevant top-level requirements for the HyperSpectral Imager are summarized in Table 1. The key design drivers are high optical throughput and low image distortion.

<table>
<thead>
<tr>
<th>Instrument Key Requirements</th>
<th>420-2450 nm</th>
<th>VNIR: 6.5 nm</th>
<th>SWIR: 10 nm</th>
<th>VNIR: 500:1 (@ 495 nm)</th>
<th>SWIR: 150:1 (@ 2200 nm)</th>
<th>14 bit</th>
<th>&lt;5%</th>
<th>&lt;2.5%</th>
<th>VNIR: 0.5 nm</th>
<th>SWIR: 1.0 nm</th>
<th>&lt;0.5 nm</th>
<th>&lt;0.2 pixel</th>
<th>&lt;0.2 pixel</th>
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</thead>
</table>

The instrument features a nearly diffraction limited three-mirror anastigmatic telescope (TMA) with an across-track field of view (FOV) of ±1.3°. The TMA has an 18cm entrance aperture and focusses the light from the earth’s surface onto a field splitter slit assembly (FSSA). The FSSA includes two separate micro slits for in-field separation of the light and a micro-mirror to redirect the SWIR field into the SWIR spectrometer. Both, VNIR and SWIR spectrometer optics have unit magnification and are derived from an “Offner” relay imaging concept and employ curved prisms in dual pass configuration as dispersive elements. Light from the spectrometer is finally focussed on VNIR and SWIR focal plane arrays.

All optical elements are mounted to a monolithic 3-dimensional Aluminium structure. For fulfilling the stringent requirements on overall pointing stability, the star tracker sensor assembly is directly attached to the optical unit. In the selected design, the required geometrical and spectral stability directly transfers to stringent requirements on thermal stability of the instruments optical unit. The thermal stability is achieved by heater control in combination with an actively controlled, sophisticated loop-heat pipe system.

In Figure 5, the calibration functional tree is shown. These functions are indirectly required to fulfill top level earth observation requirements and lead to the implementation of different hardware items. In terms of mechanisms, the Shutter Calibration and the Full Aperture Diffuser Mechanism play a key role during In-Flight Calibration of the HyperSpectral Instrument and in particular for radiometric calibration. They are providing the function to select between Earth observation, calibration via diffuser plate, calibration via internal integrating sphere or to block all incoming light in shutter.
mode for a “dark signal”. Therefore, the optical performance of the instrument is also dependent on the performance of the SCM and FAD mechanism.

The three EnMAP mechanisms SCMA, SSMA and FADA are shown in Figure 6. They are fulfilling different function and thus are located at different locations inside the instrument.

**Shutter Calibration Mechanism Assembly (SCMA)**

**SCMA key requirements**
- Mass: < 2 kg
- Temperature range: -40°C to +80°C non-operating (qualification level)
- Designed Life Time 8 years (5 years in orbit) and 120,000 start-stop cycles
- Cleanliness:
  - 300 ppm particulate
  - $1 \times 10^{-7}$ g/cm$^2$ molecular
- Position accuracy: ± 5arcmin or better
- Position repeatability: ± 1arcmin or better
- High reliability: 0.995 (EOL) or better
- Redirect light from calibration source
- Light tight interface to telescope

**MECHANISMS DESIGN DESCRIPTION**

In order to fulfil the calibration function, high position accuracy and repeatability are required for optical elements within the mechanisms. It also imposes high demands on light tightness of mechanical interfaces and stray light reduction which finally requires high cleanliness of all parts. High cleanliness is also required to minimize contamination of calibration sources which in turn means less degradation of optical references and therefore better performance of the instrument.

In sum all of this is derived from performance and reliability requirements on the instrument to provide high image quality during the mission lifetime.
In nominal mode the light coming from the telescope can pass unobstructed towards the field splitter. The on-board calibration source is blocked as well in this mode.

The SCMA is driven by a stepper motor controlled by the Instrument Control and Processing Unit (ICPU).

A malfunction of the SCMA actuator is a single point failure which would jeopardize the whole EnMAP mission. Therefore an emergency release of the SCMA is incorporated in the design. Once a release is triggered, the SCMA moves out of the optical path. Thus Earth observation can be continued but the calibration function via internal calibration unit as well as shutter function is lost.

**SWIR (Short Wave Infrared) Switch Mirror Assembly (SSMA)**

**SSMA key requirements**
- Mass: < 1.5 kg
- Temperature range: -40°C to +80°C non-operating (qualification level)
- Designed Life Time: 8 years (5 years in orbit) and 50 actuation cycles (qual.)
- Cleanliness:
  - 300 ppm particulate
  - $1 \times 10^{-7}$ g/cm$^2$ molecular
- Position accuracy: ± 10 arcmin or better
- Position repeatability: ± 1 arcmin or better
- High reliability: 0.998 (EOL) or better

![Figure 8: SSM Assembly overview. Credit RSG](image)

The main purpose of the SWIR Switch Mirror (SSM) is to do the selection between main and redundant SWIR detectors. In nominal operation, the switch mirror is outside of the light path and the optical beam passes to the nominal detector. Only in case of malfunction of nominal detector, the switch mirror is positioned into the light path with 45° angle (see Figure 9.) Now the light beam is redirected into the redundant SWIR detector.

This approach avoids the implementation of another fail safe mechanism in order to move the mirror out of the optical beam path.

![Figure 9: Schematic view of SSM position in front of EnMAP SWIR detectors. SSMA operating condition. Credit RSG](image)

The SSMA consists of the main structure, the actuator and the mirror as shown in Figure 8. The structure of the SSMA is providing necessary mechanical interfaces and carrying the actuator assembly which consists of
- Switch mirror supplied by OHB
- Releasing springs
- Latch locking device (protection against launch loads)
- Two position sensors (N+R) verifying release

After release of the Frangibolt®, the switch mirror rotates by 45° until the operational position is reached. The mirror is then kept in position by preloaded torsion springs. The end stop for the mirror is designed to be elastic to limit the deceleration loads on the mirror but also provides accurately defined surfaces for precise positioning. The mirror can be released via a one-shot mechanism, hence springs were used as actuators. The launch position can be recovered by refurbishment measures for on-ground tests.

**Full Aperture Diffuser Assembly (FADA)**

**FADA key requirements**
- Mass: < 19 kg
- Peak power consumption: < 10 W
- Temperature range: -65°C to +80°C non-operating (qualification level)
- Designed Life Time: 8 years (5 years in orbit) and 800 life cycles
- Cleanliness:
  - 300 ppm particulate
  - $1 \times 10^{-7}$ g/cm$^2$ molecular
- Diffuser surface normal position accuracy: ± 5 arcmin or better
- Diffuser plate position repeatability: ± 1 arcmin or better
- High reliability: 0.998 (EOL) Sun Diffuser Hatch
The FAD general design is shown in Figure 10. It consists mainly of the main structures, two hatches (Sun Diffuser Hatch – SDH and Diffuser Protection Hatch – DPH), the Spectralon diffuser plate used for calibration and the Inner Diffuser Baffle towards the instrument telescope. The overall dimensions of the mechanism are 690 x 495 x 474 mm.

The main purpose of the FADA is to provide stable, uniform and well characterised radiance needed for the EnMAP radiometric calibration, primarily for the absolute radiometric calibration. This is done by implementing a diffuser plate on the back side of the Sun Diffuser Hatch (SDH) which uniformly scatters solar light in front of the telescope entrance pupil. In general it is necessary to protect the diffuser surface from contamination and UV radiation since the Spectralon is very sensitive to degradation under sunlight. Therefore the Diffuser Protection Hatch (DPH) is implemented which protects the diffuser from sunlight during observation mode of the instrument and from contamination. Figure 11 shows a cross section of the launch configuration in which both hatches are closed such that no light nor contamination can enter the telescope.

The FADA is mounted in front of the telescope to the instrument cover structure (ICS) which is surrounding and protecting the EnMAP instrument.

The FADA provides three hatch configurations. In Earth observation mode the SDH is open and the DPH is closed, while in calibration mode, the DPH is open and the SDH is closed. During launch (if necessary also in orbit) both hatches are closed. The SDH features some baffles vanes on the opposite side of the diffuser. During earth observation they are complementing the inner diffuser baffle in order to reduce stray light. The interface between the inner diffuser baffle and the instrument telescope baffle forms a light tightened labyrinth without mechanical connection between the two baffles. Both hatches are driven by BLDC motors with gearheads and are equipped with rotational potentiometers for coarse position feedback. In addition, position and release sensors are implemented as well as heaters and temperature sensors.

In case of SDH actuator malfunction a Fail Safe Mechanism moves the SDH out of the telescope field of view. This is realised by a special coupler together with a preloaded spring and is released by a Frangibolt®. Frangibolts® from TiNi are also used for securing the hatches during launch.

**PLANNED AND ACHIEVED VERIFICATION AT MECHANISM LEVEL**

**SCMA**

Most important for a mechanism is to complete the life test successfully and at the same time it has still to meet the requirements on position accuracy and repeatability at end of life. On SCMA this verification was performed on the QM. The life test was done by alternating 3 short travel position changes (3 x 120° = 1 rotation) and 3 long travel position changes (3 x 240° = 2 rotations) with a temperature measurement. Only if the temperature measurement was within the specified range the test continued. The test was interrupted at 50% of the test cycles for a functional check, and a final performance test was done after the full number of 322060 start-stop cycles was reached. The mechanism completed successfully the life test and fulfilled position accuracy and repeatability requirements even at end of life test. In Table 2 the position accuracy measurements before, during and after the life test are listed. Position accuracy is the maximum difference of angle mirror to reference mirror.

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Position accuracy [arcmin]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verification before test</td>
<td>0%</td>
</tr>
<tr>
<td>First part life test</td>
<td>48%</td>
</tr>
<tr>
<td>Second part life test</td>
<td>100%</td>
</tr>
</tbody>
</table>

Position accuracy and repeatability was verified on QM and FM during functional testing and repeated after
environmental testing in the frame of the final inspections. In Table 3 the test results from SCMA FM are listed. The measurements of angular difference between SCMA mirror and reference mirror were done with motor unpowered.

Table 3: SCM FM test results on position accuracy and repeatability.

<table>
<thead>
<tr>
<th></th>
<th>Nominal side [arcmin]</th>
<th>Red. side [arcmin]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position accuracy [&lt; 5 arcmin]</td>
<td>&lt; 2.4</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>Repeatability [&lt; 1 arcmin]</td>
<td>&lt; 0.36</td>
<td>&lt; 0.18</td>
</tr>
</tbody>
</table>

The FM test campaign verified successfully that the positioning accuracy of the SCMA is better than the required ±5 arcmin. Also, the position repeatability was verified to be much better than the required ±1 arcmin. The fail-safe mechanism (FSM) inside SCMA was also tested on QM. In total 50 actuations were tested successfully. Cleanliness of the mechanism was also verified to be within the specified limits.

SSMA
For functional tests and during life test, the SSM was mounted on a dedicated GSE (see Figure 12). The frame allows orienting the SSM w.r.t. the gravity vector for tests on the SSM actuator and for Frangibolt® refurbishment. For position measurements, a laser displacement sensor was mounted on a supporting structure (blue parts in Figure 12), which allows tilting the laser sensor by 45° and having precise end stops defining the sensor’s position.

With this setup the absolute position accuracy was measured in the QM functional test to be 7.5 arcmin (FM +0.38 arcmin) and after environmental testing to be 8.4 arcmin (FM +0.44 arcmin). All results are well within the specified +/-10 arcmin requirement.

The position repeatability of the end stop position was measured with a laser distance sensor. The sensor remains in its position while the mirror was moved 10 times by more than 20° out of its end position. After returning to the end position, the mirror position was measured. The position repeatability measured was max 1 µm (0.14 arcmin) on QM and FM.

The life test on the QM includes 50 releases of the Switch Mirror in total whereby 4 releases are done by the Frangibolt® and the remaining ones are manual release. After the manual releases, two further releases by Frangibolt® were done. The actuator released in all tests without failure. Cleanliness of the mechanism was also verified to be within the specified limits.

FADA
For the FADA mechanism a QM + FM model philosophy was established. The FAD qualification program comprises physical properties test, functional testing, environmental testing and life test. Vibration was completed successful and without any anomalies. Comparison of main resonance frequencies showed no frequency shifts of 5% or more. The lowest measured response frequency is 167 Hz.

In Table 4 the angular measurements of the autocollimator after each movement and repositioning of the SDH are summarized for QM and FM.

Table 4: QM and FM SDH positioning and repeatability measurement

<table>
<thead>
<tr>
<th>Measurement</th>
<th>QM Angle Deviation [arcmin]</th>
<th>FM Angle Deviation [arcmin]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>-3.19</td>
<td>3.06</td>
</tr>
<tr>
<td>1st</td>
<td>-3.16</td>
<td>4.48</td>
</tr>
<tr>
<td>2nd</td>
<td>-3.20</td>
<td>4.50</td>
</tr>
<tr>
<td>3rd</td>
<td>-3.19</td>
<td>4.48</td>
</tr>
<tr>
<td>4th</td>
<td>-3.19</td>
<td>4.36</td>
</tr>
<tr>
<td>5th</td>
<td>-3.19</td>
<td>4.38</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.04</td>
<td>0.13</td>
</tr>
</tbody>
</table>
The accuracy check of diffuser plate inside SDH was performed to verify the position of the Spectralon plate after environmental testing. An optical setup was built up and the Spectralon alignment tool installed within the FADA.

The base plate (mounting plate) normal is referenced with a pentaprism. Initial alignment of the closed position of the Spectralon is determined to $a_0 = -0.5$ arcsec. After opening and again closing the SDH, the following measurement results were obtained for repeatability:

- After 1st open close: $a_1 = 0.3$ arcsec
- After 2nd open close: $a_2 = 0.0$ arcsec
- After 3rd open close: $a_3 = 0.2$ arcsec

The position repeatability of the diffuser plate was measured to be in the range of $[-0.5, +0.3]$ arcsec, which is well within the required tolerance of $+/\pm 0.1$ arcmin.

The main activity in life testing was the open/close movement of the SDH nominal electrical side in vacuum. 800 cycles were performed, 400 at room temperature and 400 cycles at -45°C. Each 25th cycle a current measurement of the actuator was performed to detect potential degradation. Telemetry of switches and potentiometers was checked as well. The measurement results are shown in Figure 14 and Figure 15. The measured values are quite constant within each section of the test and don’t indicate any degradation.

Cleanliness of the mechanism was also verified to be within the specified limits. Overall the qualification of the FAD mechanism at subsystem level was fully successful.

**PERFORMANCE AND VERIFICATION IMPACT ON INSTRUMENT**

The test results from successful characterization of mechanisms at subsystem level has been used as input for instrument STM (Structural and Thermal Model) testing. During this STM test campaign a high shock was measured in the optical bench due to the release of the Frangibolts® (instrument internal shock source). Here especially the high frequency part is of interest. Figure 16 shows the shock spectrum measured close to the Frangibolt® fixation to the optical bench.

![Figure 16: Shock spectrum before redesign: Peak of about 8000g at 12kHz (Sensor 8nX+).](image)

This high shock introduced into the system has been concluded to be critical for the most sensitive optical elements. The criticality assessment has been supported by complementing shock tests on unit level. These test results obliged the system to have a major redesign at mechanism level after successful QR. This has been achieved via a redesign of the launch lock bolts in terms of breaking force and surface treatment. In addition the Frangibolt capture housing design was modified to reduce shock transmission. After redesign a new instrument STM shock testing campaign as well as a delta qualification at mechanism level was conducted. Goal was to prove the effectiveness of the redesign in reducing the shock introduced close to the optical elements. Figure 17 shows the test results at instrument STM level after the redesign.

![Figure 17: Shock spectrum after redesign: Peak of about 1600g at 9kHz (Sensor 7nX).](image)
The results show an overall reduction in release energy after incorporation of the redesign. The effectiveness of shock load reduction has been proven by successful shock qualification of all relevant optical subunits.

A second major impact for the system is that the Frangibolt technology is by definition not resettable without physical substitution of the bolt. This obliged the system to adapt the AIT flow, in order to avoid the usage of the mechanisms after a certain stage of instrument integration. In addition, the primary goal for the instrument on-ground activities is to avoid any unnecessary shock events for the flight hardware.

**CONCLUSION AND LESSONS LEARNT**

The use of the Frangibolt technology, present on all the three mechanisms for release of the LLDs, has two major impacts at system level:
- Shock in the optical bench
- AIT flow

A lesson learnt from the project is that despite having successful test results at subsystem level, tests of mechanisms inside an instrument in representative configuration is vital for a successful mission.

**ACKNOWLEDGEMENTS**

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