FULL APERTURE DIFFUSER ASSEMBLY, FULLY REDUNDANT AND HIGH RELIABLE OPTIC MECHANISM FOR ENMAP MISSION


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ABSTRACT

The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission whose aim is to monitor and characterize the Earth’s environment on a global scale. The FADA (Full Aperture Diffuser Assembly) has been developed, integrated and tested by HTS (in cooperation with RUAG Space Switzerland) according to specification of OHB, the responsible party for the complete EnMap-instrument. It is a two DOF (Degree of Freedom) mechanism positioned outside and at the main entrance of the ENMAP instrument. Due to its location on the instrument, the mechanism is subjected to the harsh orbit environment. As the mechanism is mission critical it has been designed based on a fully redundant approach. In particular the SDH (Sun Diffuser Hatch) hosts on its back side a spectralon diffuser, a LLM (Launch Lock Mechanism) and a FSM (Fail Safe Mechanism). In case of mechanism’s malfunction the system has been designed with a FSM that frees the main path of the light. The SDH with all its functionalities provides a very high reliability (0.999968648).

After successful completion of the design phases, the mechanism has been manufactured and assembled and is currently under qualification testing campaign. In particular the hardware has passed successfully all the functional and environmental tests (vibration and thermal vacuum). Next step is the life time test and the final inspection.

ENMAP MISSION OVERALL SCENARIO

The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission that aims at monitoring and characterising 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.

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 30km 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 1 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.

DESIGN MAIN DESCRIPTION

FADA key requirements

The most important requirements that affect the design of the mechanism are:
- Total mass of the FADA shall be less than 19 kg
- FAD assembly shall be qualified for a non-operating temperature range -65 °C to + 80 °C assuming MLI (multi layer insulation) on the FAD
- Maximum electrical peak power shall be lower than 10 W (max power variation due to environment less than 50%)
- The Design Life Time of the FADA shall be 8 years

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(5 years in-orbit lifetime and 3 years pre-launch activities. In addition the mechanism (QM) shall demonstrate compliance to a 800 cycles life test.

- At delivery the mechanism shall have no more than
  o 300 ppm (particulate contamination)
  o Molecular \(\rightarrow 1 \times 10^{-7} \text{ g/cm}^2\)

- In working position a normal to the diffuser front surface shall be coplanar with FADA X-Z plane with tolerance of \(\pm 5\text{arcmin}\) or better

- The repeatability of diffuser plate deployment in working position shall be within \(+/- 1\text{arc min}\) or better

- The mechanism (as also the FSM and the LLM) shall be fully redundant in all the components and functions (with exception of the structural parts)

- The FAD mechanism is mission critical and shall comply with the following reliability figures
  o a) 0.995 (EOL) SDH LLM does not open after launch
  o b) 0.998 (EOL) SDH stuck in closed or intermediated position and does not move anymore blocking the optical path for nadir looking

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**GENERAL Overview**

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 realised by employing a volume scattering diffuser that uniformly scatters solar flux in front of the telescope entrance pupil. The FAD assembly also provides protection of the diffuser surface from contamination and UV radiation, when diffuser is not in use, and keeps the telescope entrance closed during the launch.

The FAD assembly is located in front of the telescope and is mounted to the instrument cover structure (ICS), an aluminium honeycomb panel.

It is a 2 DOF mechanism and operation modes of the FAD assembly are controlled by the corresponding actuators which position SDH or DPH (Diffuser Protection Hatch) accordingly.

In case of malfunctioning of the SDH actuator the Fail Safe Mechanism takes the SDH out of the telescope field of view by spring preload means.

The FAD general design is shown in Figure 2 below. It consists of a Spectralon diffuser plate which is located in an aluminium hatch frame. The hatch is mounted on a titan pivot and can be moved by a brushless DC motor with a planetary gear head. In case of failure the special coupler and a preloaded spring allow removing of the hatch and the frame out of the light path.

A second hatch which is directly driven by an identical actuator protects the diffuser plate from sunlight in the stored position. This becomes necessary since the Spectralon is very sensitive to degradation under sunlight. Frangibolt release systems from TiNi Aerospace are used for locking of the hatches during launch and for the fail safe mechanism.

For reducing straylight illumination the back of diffuser hatch is equipped with a top baffle. During earth observation this baffle complements the inner diffuser baffle providing the required straylight reduction. An interface between the inner diffuser baffle and the telescope baffle forms a light tightened labyrinth without mechanical connection between two baffles.

The DPH also carries baffle vanes on its back. During sun calibration these vanes complement the sun port baffle of FADA.

The FADA is also equipped with rotational potentiometers, position and release sensors as well as emergency heaters and temperature sensors.

The overall dimensions of the mechanism are 690 x 495 x 474 mm.

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**Operational configuration**

The FADA is designed to presents three different configuration

- Launch
- Earth observation
- Sun calibration
Launch Configuration

During launch the DPH and the SDH are in closed positions (see Figure 4) which block the light paths in the earth and solar ports. This arrangement protects the telescope optics from possible contamination during launch and during first orbit manoeuvres. Launch lock mechanisms are employed to guarantee that the SDH and the DPH remain in these positions. Once on orbit and being opened by a special command these locking mechanisms are not used any more.

![Image of FADA in launch configuration]

Earth Observation

The SDH is in stored (open) position (see Figure 5) releasing the main light path for Earth observation. DPH remains closed to protect the diffuser from possible contamination and UV radiation.

![Image of FADA in Earth observation mode]

Sun Calibration

SDH is in working position (closed) and DPH is open (see Figure 6) allowing solar illumination of the diffuser front surface. The light path from Earth is closed.

![Image of FADA in calibration mode]

SDH detailed design

The most critical part in the FAD is the SDH. A malfunctioning in a closed position would lead to a total loss of the instrument and therefore the mission goals. Apart from mechanical structural parts all components of the SDH are implemented in a redundant version. The actuator has redundant windings and hall sensors. The FAD uses redundant plain bearings for the hatches. These can withstand high mechanical loads and work without lubrication which makes them more reliable than ball bearings.

The launch lock mechanism of the SDH is mechanically redundant and further built with redundant heaters. All sensors are also fully redundant.

Further an FSM (fail safe mechanism) is implemented which can overcome the nominal SDH operations under all configurations and positions. The FSM spring moves the hatch and the guiding arm of the SDH into stored conditions (see Figure 7)

![Image of FADA in launch configuration.

Figure 7. Section of the SDH in earth observation mode after FSM activation and release.

The front surface of the Spectralon plate is mounted on a metallic frame with eight standoffs which are tightened to the Spectralon main frame (see Figure 8). Sufficient large clearances between the frame, the Spectralon plate and the fixation standoffs can compensate different thermal expansions.

The standoff design (Figure 9) allows a defined torque for the fixation on the frame. On the bottom side an o-ring gasket is used to compensate thickness tolerances of the Spectralon and ensure a clamping force which does not vary significantly. In addition the clamping force is independent from the fixation torque of the corresponding bolts.

The described fixation points with the o-rings only press the Spectralon plate against the frame.

For stiffness reasons the Spectralon is additionally fixed in the centre region via slot thread parts to the SDH. All fixation elements are aligned such that their working lines meet in one point. This allows the Spectralon plate to expand star-like
Repeatability of end stop position

The SDH (as also the DPH) is driven against structural end stops. Assuming that these end positions are approached with a repeatability of maximum 0.01 mm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SDH</th>
<th>DPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of end stop position [mm]</td>
<td>±0.005</td>
<td>±0.005</td>
</tr>
<tr>
<td>Distance d to hatch rotation axis</td>
<td>378</td>
<td>236</td>
</tr>
<tr>
<td>Angular position error [°]</td>
<td>0.0015</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

Table 1. SDH (and DPH) end stop Repeatability

The repeatability of the SDH (as also the DPH) angular positions is well within the requirement of ±1 arcm = 0.017°.

The worst case out of plane deformation of Spectralon plate due to thermal loads is (see Table 2)

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Tolerance / deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical tolerances</td>
<td>Hot case [mm]</td>
</tr>
<tr>
<td>Thermal displacement</td>
<td>± 0.300</td>
</tr>
<tr>
<td>Displacement at centre of diffuser plate</td>
<td>+0.074</td>
</tr>
<tr>
<td></td>
<td>+0.374</td>
</tr>
</tbody>
</table>

Table 2. Displacement of the diffuser due to thermal loads.

Actuator unit

The actuator unit consists of a brushless DC motor with redundant windings and hall sensors in combination with a planetary gear head (see Figure 10).

The motor is designed and built by MACCON GmbH in Munich. It is a brushless DC motor with a compact design. The diameter of the stator is quite large in order to produce the necessary torque with low power consumption. The gear head is delivered from GYSIN with a special lubrication (Braycote 601EF). The housing of the motor is made of stainless steel. Table 3 shows the main parameters of the motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GPL-42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission ratio</td>
<td>450.63 : 1</td>
</tr>
<tr>
<td>Nominal torque [Nm]</td>
<td>12</td>
</tr>
<tr>
<td>Ø shaft [mm]</td>
<td>3</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>0.425</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>42</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>65</td>
</tr>
<tr>
<td>Efficiency under max. load</td>
<td>85 %</td>
</tr>
<tr>
<td>lubrication</td>
<td>Braycote 601EF</td>
</tr>
<tr>
<td>Backlash</td>
<td>&lt; 15 arcm</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-30°C to 90°C</td>
</tr>
</tbody>
</table>

Table 3. Actuator parameters.

Bearings

In order to reduce to the minimum the cleanliness contamination and also to give to the system more stability, plain bearings have been used into the design of the FADA. Glycodur plain bearings consist of a stainless steel casing with a sinter copper structure. PTFE is pressed into the sinter structure to achieve low friction forces. A small PTFE layer closes the bearing and works as gliding layer. The outside of the bearing is made of copper or stainless steel with a tin protection layer. Advantage of plain bearings is the avoidance of lubrication. They are able to withstand high mechanical loads. Further the simplicity, low weight and volume are strong characteristics.

For the FAD the Glycodur plain bearings have been chosen, since friction forces are not the key point in the motorisation analysis.

All bearings are redundant and separated by a metallic bush

Potentiometer

Angular position sensor is integrated in order to detect the actual position of the SDH (as also the DPH) with an accuracy of ±1 degree. A potentiometer from Betatronix is used with a maximum backlash of 0.2°. The Figure 12
shows the potentiometer.

*Figure 12. Betatronix Potentiometer.*

The potentiometer is electrically redundant. They are placed at the outside of the FAD housing. The housing throughput is realized by another plain bearing. The potentiometer axis is mounted on the SDH pivot (as also on DPH) and the housing is clamped to a bracket as shown in Figure 13. It is fixed to the rotation axes via flexible couplings which compensate small angular misalignments.

In line with the flexible coupling a rated break point is placed on the shaft for the case of the potentiometer getting blocked. Potential debris from the cracked shaft is collected in a cylindrical shaped container which is sealed towards the rotating shaft via PTFE o-rings.

*Figure 13. SDH positioning sensing.*

**Launch lock mechanism**

For all launch lock mechanisms (both SDH and DPH) Frangibolt release actuators from TiNi Aerospace are used.

They use a shape memory alloy to break a defined titanium fastener which holds together the separating parts. The actuator itself contains redundant heaters and redundant thermocouples. The fastener has a thread on one side and a nut head on the other side. A defined groove provides a specific breakpoint. The actuator part is covered by a housing including a small damping material on top and slits on the side for cable throughput.

Washers are used for equal force transmission. As release sensors micro switches will be triggered by a release bar which moves as a consequence from the breaking fastener. Figure 14 and Figure 15 respectively for SDH and DPH show a section of the LLM.

The SDH LLM applying two actuators in series (the DPH LLM is equipped with a single actuator). The Frangibolts are de-rated individually from the nominal break load of 4500N to cope with the requirement to reduced shock emission during release.

The interface between the FAD main structure and the released part is constructed as cup-cone interface. In this configuration shear forces at the fastener are avoided.

*Figure 14. SDH LLM section.*

For the detection of the LLM release a special release mechanism has been designed. It consists of two micro switches (main and redundant) which are held down by a release bar. The release bar is attached to a crash pad which is going to be compressed in case of the bolt having broken. The Figure 15 shows details of the concept applied to the SDH LLM.

The symmetric arrangement of the micro switches and the fixation of the release bar to the crash pad ensure the release bar to heave up straight triggering both release switches.

The crash pad has been designed in order to transform the kinetic energy of the loose part of the fastener into deformation energy. The head of the housing is enlarged to ensure clearance between the switch function components and the MLI which will be mounted above.

*Figure 15. SDH LLM detail.*

**Fail safe mechanisms**

The fail safe mechanism (FSM) is used to move the SDH and the drive-arm out of the instrument light path in case an error occurs (see Figure 16). Such an error could be a malfunctioning of the LLM actuator or any other part in the nominal drive chain (e.g. SDH actuator, bearings, potentiometer etc).

For the FSM a preloaded torsion spring is integrated between the drive arm and the SDH. In nominal operation the drive arm is connected to the SDH with a Frangibolt
of the same series used in the LLM. If the Frangibolt is released the spring moves the hatch into the stored position and the drive arm into the launch configuration. In this way all parts are out of the instrument light path.

![Figure 16. SDH FSM detail.](image)

The movement of the SDH and the drive arm is possible, because of the special coupler used within the drive chain. The coupler only works, while the drive arm and the SDH are connected by the Frangibolt. Further it allows the necessary angular movement of both parts. This becomes possible, because the total angular movement of the SDH is only 50 degrees. The Figure 17 shows the sequence of movements performed by both SDH and drive arm once the FSM Frangibolt is activated.

![Figure 17. SDH FSM activation sequence](image)

**MLI Detailed design**

The MLI design by HPS Gmbh München, ensures the proper functioning of the FAD mechanisms and provides access to all components that need to be accessible after MLI integration. As the FAD is directly exposed to the sun, the MLI consists of high-temperature resistant material. The FADA MLI is composed by 8 blankets (see Figure 20). Two main blankets cover most of the structure and are supplemented by smaller patches. The MLI will be fixed to the FAD, to the ICS and to the bus by glued stand offs. Further an electrical grounding connection exists via cables which are mounted with grounding lugs to the FAD structure.

![Figure 20. MLI Description.](image)

All edges of the blankets will be closed to mitigate particle contamination from the spacer. The baseline design to enclose the edges is an overlap from the outer layer which is attached at the inner layer with tape (see Figure 21).

![Figure 21. FADA with MLI.](image)

**Reliability calculation**

The Full Aperture Diffuser is working during the lifetime under the following mission scenario:

- **Lifetime:** 3 years under pre-launch conditions and 5 years under on-orbit conditions.
- **Move cycles:** 100 open-close cycles on ground and 100 open-close cycles on orbit.
- **Fail safe:** 50 cycles on ground (QM) and 1 cycle on orbit (if required). One open-close cycle is assumed to take 25 seconds. One fail safe cycle is assumed to take 26 seconds, with 24 seconds for heating the actuator at 32 V and two seconds for movement to operational position. The duration on ground and in orbit will not be distinguished. Thus 200 open-close cycles will be equivalent to an activity period of 1.39 hours. Additionally 51 fail safe cycles of 26 seconds activity will be equivalent to an activity period of 0.3683 hours (22.1 min).

The passive time period where the mechanism is not in...
use is calculated as the overall lifetime (70128 hours) minus the cycle duration (1.39 hours) = 70126.61 hours for actuation and 70127.63 for fail safe mechanism. Based on those assumptions the reliability figures have been calculated for each component and for each function:

SDH LLM = 0.999978944 (RL A)
SDH bearings = 0.999989704 (RL B)
SDH FSM = 0.997476993
DPH = 0.99996654

In the table here below (Table 4) the total reliability for the FADA has been summarised.

<table>
<thead>
<tr>
<th>Part</th>
<th>Formula</th>
<th>Total reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAD SDH</td>
<td>RL A * RL B</td>
<td>0.999968648</td>
</tr>
<tr>
<td>FSM for SDH</td>
<td>RL F * RL B</td>
<td>0.997466723</td>
</tr>
<tr>
<td>FAD DPH</td>
<td>RL D</td>
<td>0.999966540</td>
</tr>
</tbody>
</table>

Table 4. Total reliability calculation for FAD.

MODEL PHILOSOPHY AND TESTING ACTIVITIES

Model philosophy description

For the FADA mechanism a QM + FM model philosophy has been established. This was possible due to an important breadbording activity during design phase with the scope to consolidate the design of the most critical components/functions (e.g. crush pads to sense the open/close positions, trade-off between ball bearing and sliding bearing considering the harness friction etc.)

Particular attention has been put to the SDH diffuser plate: PFM, FS (flight spare) and two non-flight plates are present in the product tree. The two non-flight plate are identical to the two diffusers FM and FS (only optically degraded. The two non-flight plate are used for the FADA QM and FM respectively qualification and acceptance testing campaign. The FM diffuser will be installed into the mechanism just before flight. This is particularly important due to the loss of performance of the diffuser due to cleanliness.

Qualification testing campaign description &test results

The FADA was installed in a test rig allowing for testing under different configurations. Also easy access for inspection and refurbishment was given by this jig.

In order to measure the repeatability and the accurate alignment of the Spectralon Diffuser a metrology with an autocollimator was used (see Figure 25). With a 90° penta-prisma it was feasible to have simultaneous view on the mounting plane and a mirror attached to the Spectralon plane. So repeatability of hatch attached to the Spectralon plane. So repeatability of hatch attached to the Spectralon plane. So repeatability of hatch attached to the Spectralon plane. So repeatability of hatch positions could be referred directly to the FADA interface plane.
The functionality of the FSM has been duly tested confirming the good design. The FSM was able to be activated and free the optical path in all the possible positions of the SDH and in the worst environments. Environmental testing activities comprised sine/random vibration, shock susceptibility and thermal vacuum cycling. All tests were performed in clean lab environment, therefore the FADA was covered with a foil hood in order to minimise contamination. In principle the FAD showed a benign behaviour during vibration and shock testing. The high number of screwed connections resulted in damping figures from 2% to 5%.

Shock testing (see Figure 26), which was done on a ringing table, was rather demanding in terms of fixation and securing a one by one meter sized mechanism setup on the test bench. For safety reasons a mobile lab crane was attached.

Thermal Cycling test (see Figure 27) was carried out at the DLR in Bremen. Maximum and minimum test temperatures were +80°C / -65°C. Firing of Frangibolt launch locks and high and low operational temperature extremes (+70°C / -55°C) worked fine. Also a part of the directly connecting life test of the sun diffuser hatch (SDH) was done under thermal vacuum. Later inspection showed no indication of wear for the redundant plane bearings supporting the hatch.

**CONCLUSIONS**

The design of the FADA mechanism has been carried on following the standard project lifecycle (BB, PDR, CDR).

The QM has been manufactured and tested. In summary the test at QM level showed a robust mechanism design, no anomalies have been encountered. Also the accuracy and repeatability requirements have been demonstrated. All functions performed as expected; especially the number of redundancies which were proven during life tests gives confidence in the reliability of the FAD.

The FAD SDH reach a total reliability of $R = 0.9999$, which is compliant with the FAD requirement of $R \geq 0.995$ (The SDH launch lock mechanism does not open after launch). The FAD DPH reach a total reliability of $R = 0.9999$.

The fail safe mechanism for the SDH reach a total reliability of $R = 0.9975$, which is actual not compliant with the FAD requirement of $R \geq 0.998$.

The FADA FM is under integration at HTS premises and the acceptance testing campaign will be finished by the beginning of 2018.