SENTINEL-2 MULTI-SPECTRAL INSTRUMENT CALIBRATION AND SHUTTER MECHANISM

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ABSTRACT

SENTINEL-2 is the multi-spectral optical mission of the EU-ESA GMES program under development by Astrium GmbH in Friedrichshafen (Germany) for launch in 2013. SENER has developed and manufactured the Calibration and Shutter Mechanism (CSM) for the Multi Spectral Instrument (MSI) being lead by Astrium SAS (France).

The paper describes the solution reached for the CSM to comply, in only one simple mechanism, with the required functions of launch locking, shuttering and calibration.

1. INTRODUCTION

The Calibration and Shutter Mechanism (CSM) is located at the entrance of the Multi Spectral Instrument (MSI) instrument, a rectangular area of 800 mm x 300 mm approximately, mounted on the frame of the secondary structure.

Figure 1. Calibration and Shutter Mechanism.

2. REQUIREMENTS AND DESIGN DRIVERS

Operational requirements

During launch the CSM has to protect the instrument from sun illumination and contamination by covering the instrument entrance with a rectangular plate (named the door). This is the close position, which has to be maintained under the action of the launch loads.

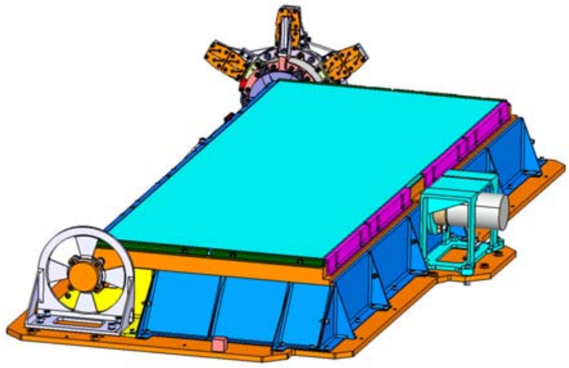

Figure 2. CSM in close position.

Once in orbit, the following functions are required from the CSM:

- In order to allow earth observation to the instrument the door needs to rotate from the close position 63° inwards the instrument and maintain it stable without power. This is the open position.

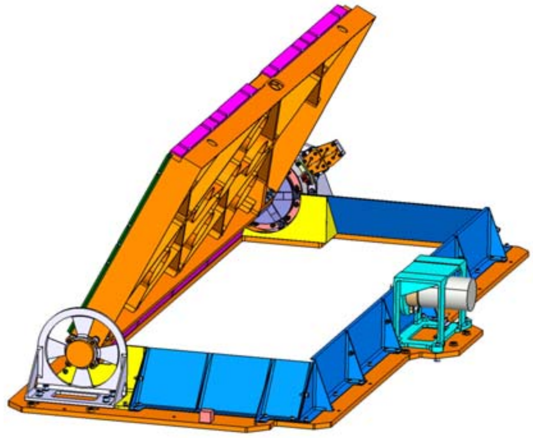

Figure 3. CSM in open position.

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- From time to time, in calibration mode of the instrument, the CSM inserts a sun diffuser in front of the primary mirror and the sun diffuser is illuminated by direct solar flux. This mode corresponds to a door position located 55° from the close position outward the instrument. This position must be also stable without any power supply.

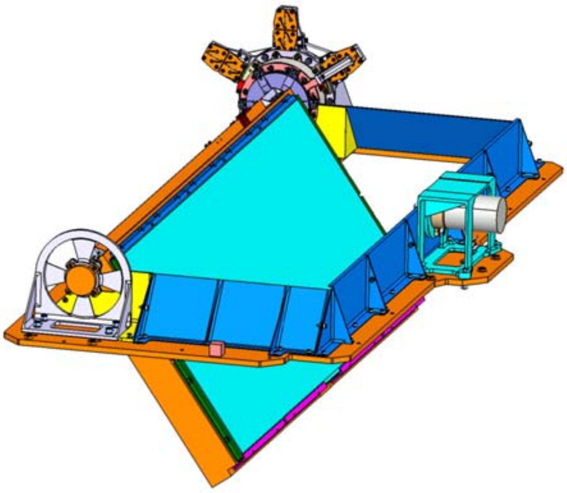

Figure 4. CSM in calibration position.

- From any position, in case of emergency, the CSM has to rotate the door to the close position to prevent the sun light to heat sensible components of the instrument. Similarly to the previous positions, the close position shall be stable without power supply.

In order to avoid direct sun light entering in the instrument in close position, maximum gaps of 2mm are required around the door by means of a dedicated baffle design. Moreover, in order to avoid reflecting sun light entering into the cavity some parts has to be black painted.

The lifetime consists of 700 operating cycles (composed of 500 in orbit, 100 on ground in vacuum conditions and 100 in air). One cycle is a complete movement from close to open, open to calibration and come back to close position.

<u>Performance requirements</u>

Motion between close and observation position must be completed in less than 30 seconds.

Open position accuracy +/- 1°.

Calibration position accuracy +/-0.1°.

Close position accuracy -2º/+3º.

Overall mass lower than 11.2 kg.

Stiffness in launch configuration higher than 150 Hz.

Power consumption during movement lower than 6 W.

<u>Environmental requirements</u>

Qualification temperature limits, -30°C to +60°C.

Quasi-static acceleration, 50 g.

Shock emissivity and susceptibility, 1000 g from 2000 Hz to 10000 Hz.

3. DESIGN DESCRIPTION

The following architecture of the CSM has been organized to comply with the previous requirements.

The rotation axis is defined in one of the longer sides of the door rectangle and the door is supported at both ends of this axis. In one of the ends, there is an electromechanical actuator which provides linear stiffness in axial and radial directions and also bending stiffness. In the other end, the door is supported by a hard preloaded duplex ball bearing in face to face configuration in order to minimize the bending stiffness. Besides the duplex ball bearing is mounted on a bracket with radial blades to give compliance in the axial direction.

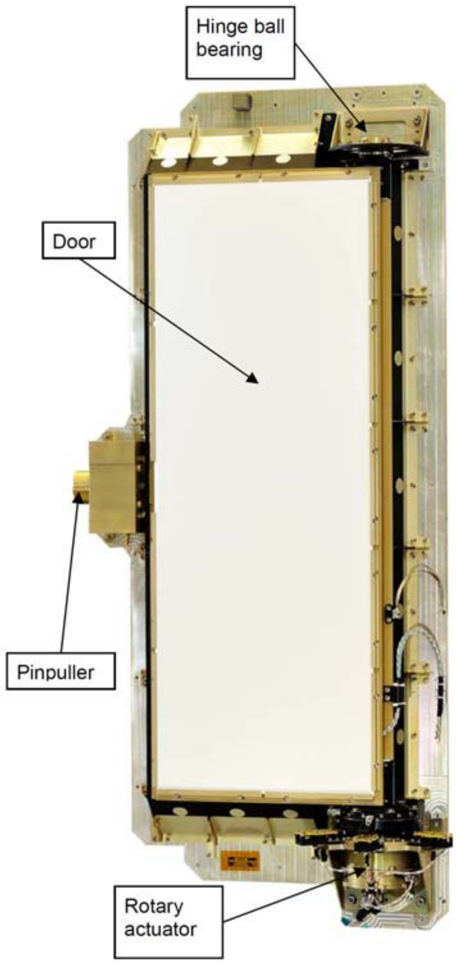

Figure 5. CSM mechanical configuration.

The door, apart from its own mass, has to support the sun diffuser mass (2.6 kg mass). During launch, the door shall not rotate and shall be maintained in the close position. Due to the mass unbalance of the mobile part, a launch locking device (LLD) is mandatory.

The way to lock the door is not obvious based on the fact that the door, after the release, has to be able to move outside the instrument to the calibration position and inside the instrument to the open position (observation mode).

A simple solution was found by using a pinpuller. In launch configuration, a pin is inserted in a bushing of the door maintaining it locked in the close position. The pinpuller is placed in the middle of the longer side of the door rectangle opposite to the rotation axis. It is supported in a bracket which provides flexibility in the direction of the pin. When the pinpuller is actuated, the pin is retracted and the door is released, therefore it is free to rotate in any of the two directions, inwards or outwards the instrument.

The rotation of the door is generated by powering the electromechanical actuator and commanding it in the desired sense of rotation. In unpowered mode, the detent torque of the actuator is enough to maintain the door stable under the action of the orbital accelerations and the harness elastic torque.

3.1. Door structure and sun diffuser

The door structure consists of a machined plate with stiffeners made of aluminium alloy. It is optimized for a high stiffness to weight ratio.

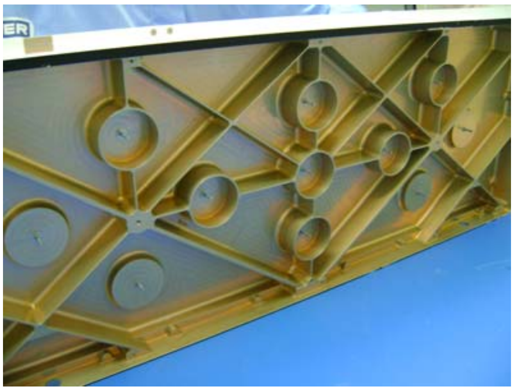

Figure 6. Door structure.

The sun diffuser is a rectangular plate (792 x 288 mm^2) made from a special Polytetrafluoroethylene (PTFE) which is used to calibrate the instrument. Its main feature is the very high diffuse reflection of the sun light. As a drawback the material shows a very low stiffness and strength and a much high coefficient of thermal expansion than the aluminium.

The door provides support for the sun diffuser. The interface between the sun diffuser and the door has been defined to comply with the following requirements,

- keep the stresses in the sun diffuser to lower than 1 MPa in order to avoid large permanent deformation.
- maintain the flatness stability of the sun diffuser optical surface avoiding permanent deformations.

when submitted to the mechanical environment (shock, sine and random vibrations) and the thermal environment (cycling between -10°C and +40°C).

The best results, to comply with the requirements, were obtained with the fixation of the sun diffuser to the door at eleven reinforced locations. A metallic insert is embedded in each of these locations. The bolt tightening torque has been defined to prevent sliding between the sun diffuser and the door.

No in-plane motion restriction was imposed at the edges of the sun diffuser for thermal free expansion or contraction. However, the out of plane motion was limited to 50 microns by adjustment of the gap between the sun diffuser and a frame, in order to prevent large deformation during the vibration tests.

3.2. Launch locking device

The device selected for the launch locking system is a pinpuller manufactured by TiNi Aerospace. The pinpuller, in the extended configuration, can withstand very high axial and radial forces. Pin retraction is achieved by coupling the recovery characteristics of Shape Memory Alloy (SMA) material with a special detent mechanism. Nitinol redundant wires are used to trigger the energy release stored in a loaded compression spring.

The pinpuller incorporates redundant power shut-off switches to prevent the SMA wire from overheating. Upon actuation and when the pin starts to retract the switch becomes open and the power supply does not reach the Nitinol wire.

The pinpuller can be reset manually with the help of a tool. For the application of the CSM, and in order to facilitate the on ground reset operations at instrument and satellite level, a specific tool has been designed to make the operation from the rear side of the pinpuller.

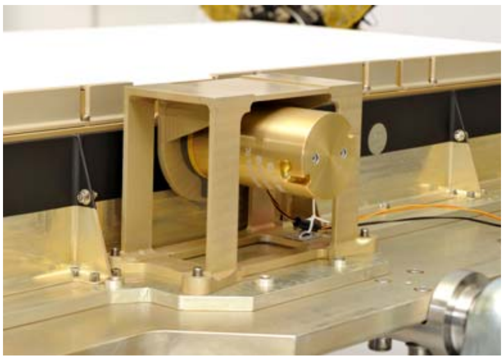

Figure 7. CSM Launch Locking Device.

To prevent fretting during the vibration loads and to reduce the extraction force of the pinpuller, a Vespel SP3 bushing is placed on a machined housing in the door structure. During launch the pin is inserted on the bushing.

The main data for the pinpuller functional performance are collected in the next table.

Non actuation shear load	2670 N
Pull force	445 N minimum
Mass	280 gr.
Operational Current	2.75 to 8.75 Amps
Actuator resistance	3.6±0.3 Ohms
Nominal power consumption	27 Watts @ 2.75 Amps
Shock susceptibility	8500 g @ 2-10 kHz
Release time At +70°C At Ambient At -65°C	 90 ms 160 ms 350 ms
Non-operating thermal range (pre-actuation)	-150°C ÷ +70°C
Operating thermal range	-60°C ÷ +70°C
Non-operating thermal range (post-actuation)	-150°C ÷ +150°C
Lifetime	> 100 operations

Table 1. Pinpuller performance characteristics.

3.3. Actuator

The actuator consists of the following main components:

- Integrated ball bearings system
- Harmonic Drive gear
- Hybrid stepper motor

Those components have been optimized in order to obtain a compact, small and light rotary actuator. One outstanding feature of the actuator is the ball bearings system, which integrates in the same block the ball bearings used for the rotation of the output flange and the ball bearings which allows rotation of the motor.

The ball bearings system has been designed and manufactured by ADR based on a detailed specification prepared by SENER. The main advantages of this concept are:

- To provide accommodation, within very tight dimensional and geometric tolerances, for the components of the Harmonic Drive gear, the output flange and the rotor of the motor.
- The resistive torque is reduced if compared to the classical pairs of ball bearings.
- There are no misalignments on the ball bearings induced during the assembly due to the geometry of other parts (housing, shaft..) and the system presents a better performance in terms of stiffness.
- Better alignment between the rotation axes of the input and the output elements which improves the accuracy of the rotary motion and the repeatability between several systems.
- Easier and more reliable assembly of the mechanism.

The output ball bearings have been dimensioned to provide a very high stiffness and output load capability. The system is completely manufactured in stainless steel AISI 440 C, therefore special attention was paid to the optimization of all the dimensions in order to reduce the mass of the item.

The ball bearings are hard preloaded in back to back configuration. The preload is applied and accurately measured by the manufacturer before delivery and is not affected by the assembly process of the rest of the actuator parts. With this configuration the ball bearings can be tested (stiffness, friction torque measurement…) independently of other operations.

The Harmonic Drive gear provides a high reduction ratio with very low mass and size, which is essential to obtain a compact and light design of the actuator.

Additionally this device allows operating with zero backlash obtaining a high positioning accuracy. The Harmonic Drive gear due to the multiple tooth engagement offers high torque capacity and relatively high torsion stiffness.

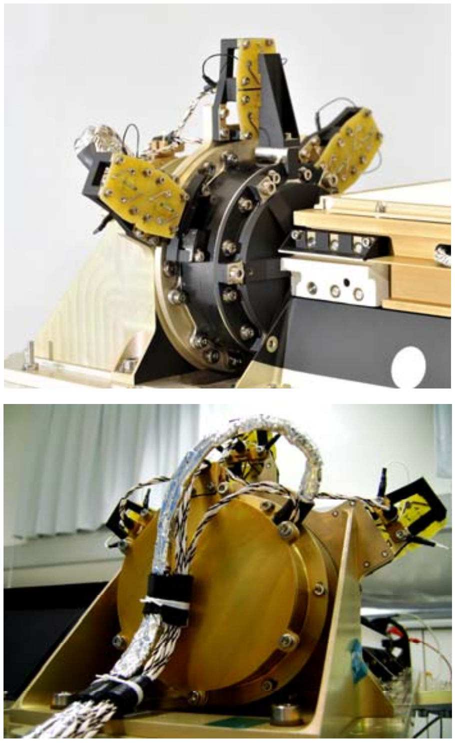

Figure 8. Rotary actuator.

The Harmonic Drive gear used in the actuator is based on the type HFUC size 20, with a wide flight heritage already demonstrated. However, the following modifications have been introduced to adapt the standard gear to the desired design:

- The wave generator, the flexspline and the circular spline have been manufactured in materials according to space standards.
- Conventional ball bearing retainer has been replaced by one made of phenolic resin.
- The Oldham coupling has been removed from the configuration. This option has been possible due to the very low run-out achievable between the output element (flexspline) guided by the output ball bearings and the wave generator, connected to the rotor bearing.

Special clamping ring has been designed to fix the flexspline to the output flange.

The assembly procedure of the gear elements was carefully studied together with the manufacturer. Finally, an easy and reliable integration within the actuator was achieved with the help of an assembly tooling.

The reduction ratio is 50 instead of the 160 previously used, in order to reduce the maximum speed in the stepper motor.

The gear has been manufactured by Harmonic Drive AG in Limburg (Germany).

The motor is a two phase hybrid stepper motor with redundant windings in the stator. The motor is from SAGEM size 35 PP with pancake design and delivered in frameless configuration, that is rotor and stator separately.

The stator is supplied mounted on a ring for easy assembly on the housing. Both elements, stator and rotor, are positive locked to the corresponding elements (stator housing and rotor shaft) in rotation and in axial direction.

Proper lubrication is essential to avoid problems in the operation of the movable parts. Desired characteristics of lubricants for space applications are very low vapour pressure, wide temperature service range and low viscosity for reduction of the resistive torque, especially at very low temperatures.

The ball bearings of the actuator have been lubricated with a combination of grease Braycote 601 applied in the balls and phenolic resin retainers impregnated in Fomblin Z25 oil under vacuum.

In the Harmonic Drive gear the same procedure has been followed for the ball bearing. Additionally, the same grease has been applied in other three areas: the teeth of the flexspline, the teeth of the circular spline and the interface between the ball bearing and the internal surface of the flexspline.

The sun diffuser is sensible to the grease contamination, its optical properties are degraded. To reduce the grease and oil evaporation losses from the actuator, the output ball bearing is provided with specially designed seal labyrinth.

Slightly out of the operational angular range, the CSM is provided with mechanical end stops in order to stop the door in a failure case and prevent from hitting neighbour elements. The design consists of a rotating part called the hammer (machined in the output flange of the actuator) and two fixed parts called end stops located in the limits of the operational angular range.

In order to minimize adhesion and prevent cold welding in case of contact, dissimilar materials have been used on the two contact parts. The hammer is machined in Ti6Al4V with treatment Solution Treated and Aged and the end stops are made of Stainless Steel 15-5 PH in condition H1025 with sputtered MoS2 coating.

During the CSM development, CSM performances were simulated by means of a detailed dynamic model of the actuator. In this stage, two natural frequencies of the rotating system were identified at 38 Hz and 117 Hz.

The minimum needed stepping frequency is 105Hz in order to reach the closed position in less than 30s. Nevertheless taking into account the resonance at 117Hz, the selected step rate for the CSM is 135Hz in order to ensure stability of the system.

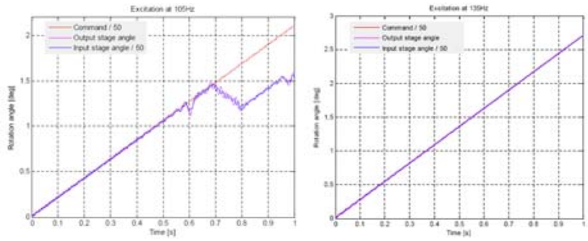

Figure 9. CSM instable and stable operation.

3.4. Hinge ball bearing

The hinge ball bearing is a super duplex thin section ball bearing in face to face configuration.

The raceways are lubricated with grease Braycote 601 EF and the retainer is impregnated under vacuum with oil Fomblin Z25. The ball bearing is shielded on one side and closed by means of a cover in the other side in order to reduce the evaporation rate of the fluid lubrication in vacuum.

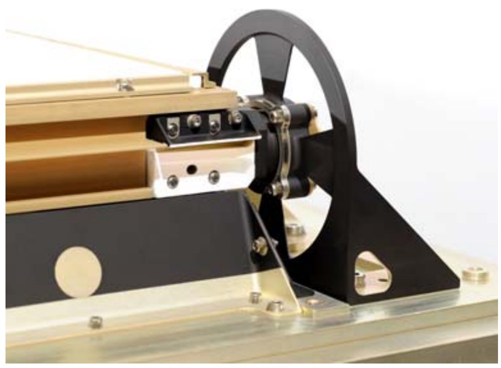

Figure 10. Hinge ball bearings.

The ball bearing is supported on a bracket which provides flexibility in axial direction thanks to its four radial blades.

3.5. Position switches

The CSM incorporates "external switches" linked to the door motion in the three operational positions (open, close and calibration). In each position there are two reed switches (nominal and redundant) with an in line arrangement. The reed switch is mounted on a PCB. The 6 PCB's are fixed to the actuator support. With the in line arrangement and the independent capability of adjustment for each PCB the accuracy of the reed switch signal is improved.

Two additional reed switches (nominal and redundant) are located at the input stage of the actuator, the trigger of this switch takes into account the reduction ratio of the gear (r=50) providing a more accurate signal. The two "internal switches" are mounted on the same PCB in a parallel arrangement due to space limitations within the actuator.

Two magnets are fixed to the underside of one arm, at a position which is 1 mm higher than the external reed switches. This magnet creates a magnetic field which activates each respective reed switch. In this way the positions are monitored. The magnet is bonded on one slot of the arm.

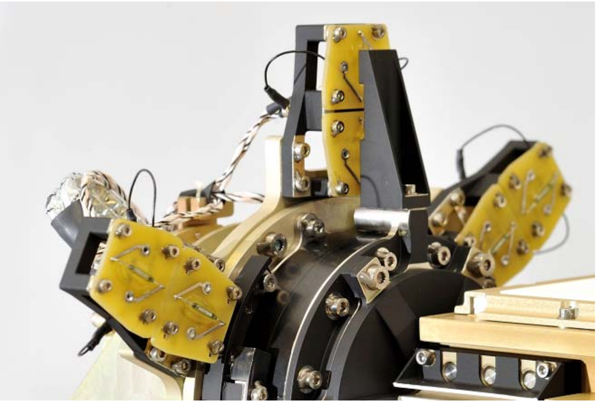

Figure 11. Position switches.

The reed switches provide the information required to define the three reference positions (closed, open and calibration) with the required accuracy.

The CSM actuator is to be operated in close loop using the signals of all the switches in order to reach the three stable positions of the mechanism when is required by the satellite.

3.6. Protection baffles

The gap between the door and the base-plate of the CSM is protected by means of several baffles in order to avoid sun-light entering inside the cavity of the MSI. Light reflection is avoided by means of black painting.

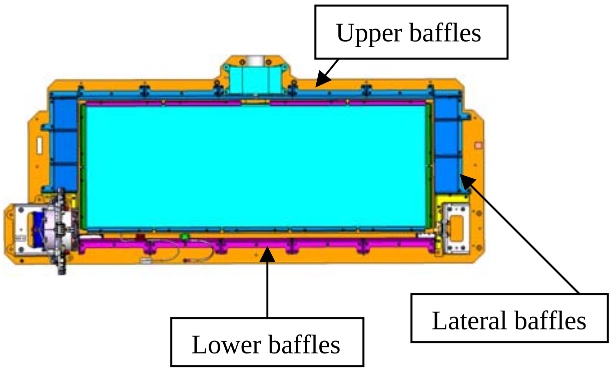

Figure 12. CSM baffles disposition.

The upper baffle has two edges, one of them overlaps respect to the door and the other one is 2mm offset from the door avoiding sunlight entering the cavity in close position without having interference during the door movement.

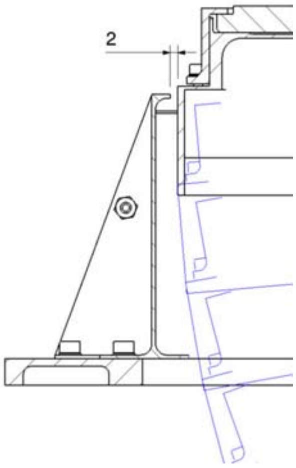

Figure 13. Upper baffle design.

Lateral baffles are 2mm offset from the door in close position, close enough to avoid sun illumination to sensitive MSI components.

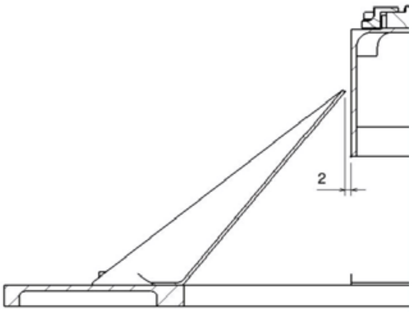

Figure 14. Lateral baffle design.

In the same way, the lower baffle protects the MSI with a maximum gap of 2mm in close position. In addition to that, in open position the baffle avoids light entering in the side of the rotation axis by means of an overlap of the baffle.

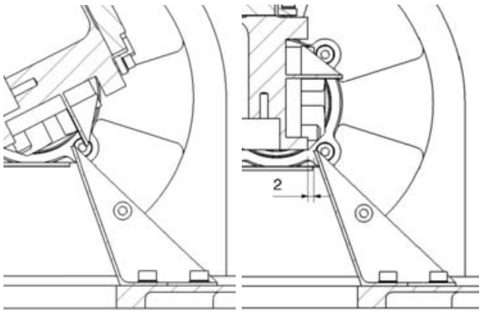

Figure 15. Lower baffle design (open and close pos.).

4. PERFORMANCES

The final performances of the CSM are summarized in the next table.

General dimensions **Door dimensions**	1102 x 445 x 177 mm3 815 x 320 x 47 mm3
Mass	CSM mass: 12.4 kg Rotating mass: 5.6 kg
Stiffness in launch configuration	91 Hz
Step angle (resolution)	0.02°
Step rate	135 Hz
Nominal angular range	118º
Actuator power consumption	4.3 W
LLD release power consumption	27 Watts @ 2.75 Amps < 300 ms
Thermal range	-30°C ÷ +60°C
Lifetime	1859 output revolutions (92950 rev. at motor level)

Table 2. CSM performance characteristics.

5. QUALIFICATION TEST PLAN

The CSM QM was submitted to an exhaustive qualification test campaign. The following paragraphs describe the most outstanding test carried out.

5.1. Functional/performance tests

The purpose of the functional/performance test is to demonstrate the capability of the CSM to meet the specific functional requirements. The test includes the following operations:

– Pin-puller release operation.

– Characterization of the angular ranges of the 8 position reed-switches.

– CSM Nominal operation. Verification of reed-switches and actuator performance and stability. This is verified in the CSM four door moving nominal operations: Closed position to observation position, observation position to closed position, closed position to calibration position and calibration position to closed position.

– Motorization margin: calculation of the motorization margin for the mechanism actuator. This is verified in the CSM four door moving nominal operations: Closed position to observation position, observation position to closed position, closed position to calibration position and calibration position to closed position.

– End stops impact test. The end-stop is impacted at door nominal speed assuming maximum supplied voltage.

– End stops angular positions verification.

– Failure case simulation (one actuator non-operating winding in short circuit). Motorization margin calculation.

In order to detect if any degradation in the CSM functional performance occurs during the test campaign and to be able to determine the cause of this degradation, several functional checks have been established at different stages of the test campaign:

– Initial functional test
– Reduced functional test after vibrations test
– Reduced functional test after on-ground ambient conditions life test
– Reduced functional test after shock test
– Reduced functional test in vacuum conditions at cold temperature
– Reduced functional test in vacuum conditions at hot temperature
– Reduced functional test after in vacuum life test
– Final functional test

5.2. Vibration tests

The vibration testing included sine and random excitation apart from the resonance survey for eigen-frequencies determination.

Although the requirement was to test the CSM at 50 g, the vibration facility limited the capability to 25 g. Moreover, notched inputs were defined for random and sine vibration tests due to sun diffuser low strength, being stress on the sun diffuser the limiting parameter of the CSM test inputs.

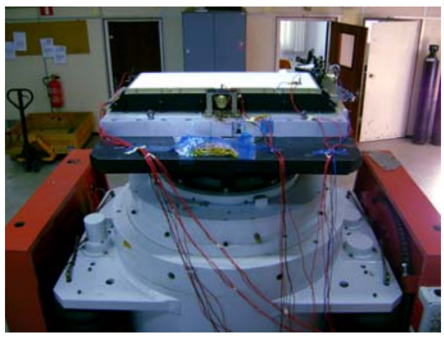

Figure 16. Vibrations test.

With the data gathered during vibration tests, the Finite Element Model (FEM) used for the CSM design was correlated in order to understand better the mechanism behaviour and extrapolate the test results (sun diffuser stress, forces…).

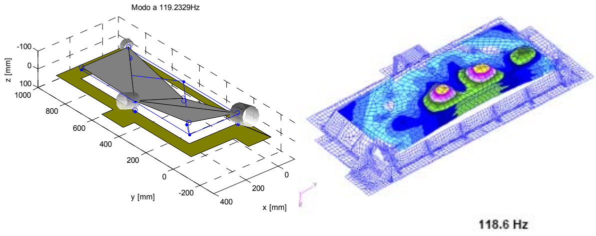

Figure 17. CSM FEM correlation.

5.3. Shock test

The CSM was tested with pyroshock loads to reproduce the specified SRS. Just with one shot of the “powder actuated nail gun” it was possible to obtain the required SRS in the three accelerometers input locations of the CSM and simultaneously in the three axes.

Figure 18. Shock test.

5.4. Lifetime test

The lifetime specified for the CSM consists of 700 operating cycles (composed of 500 in orbit, 100 on ground in vacuum conditions and 100 in air). One cycle is a complete movement from open to calibration and come back to open. To demonstrate the lifetime requirement the following tests have been performed (life factors included):

- On-ground lifetime test (ambient conditions), 400 cycles.
- In-orbit lifetime test, 2460 cycles (one third at +60°C, one third at ambient temperature and one third at -30°C) in vacuum conditions.

5.5. Thermal vacuum test

The CSM is installed in a thermal vacuum chamber and submitted to 8 thermal cycles between -30°C and +60°C.

In the last cycle, at cold and hot temperatures, a functional/performance test is carried out to check compliance to the requirements in these conditions.

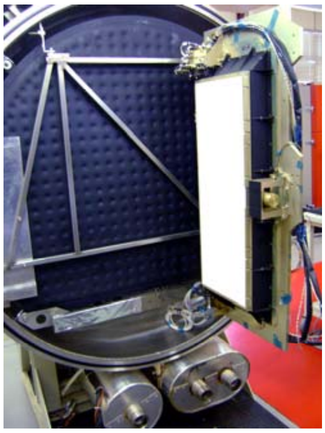

Figure 19. TV test.

6. CONCLUSION

Usually calibration and shutter mechanisms are performed separately. In the SENTINEL-2 MSI Calibration and Shutter Mechanism these two functions are gathered in one single mechanism in order to reduce mass, cost and quantity of mechanisms of the satellite, increasing its reliability at the same time.

A face to face ball bearing as rotation axis hinge in the opposite side of the actuator is used supported by means of an axially flexible support. Apart from that the pinpuller mounted on a flexible support, holds the door during launch by means of a cylindrical contact with respect to the door bushing. This design is the result of the optimization made in order to reach a stiff and robust but light and hyper-statically low constrained mechanism to make it compatible under possible thermal environments.

The pinpuller provides a reliable launch locking device and allows after pin retraction the mechanism to rotate both senses.

The use of the combination between motor shaft and external shaft reed-switches signals allows reaching high precision performance of the CSM with contactless switches (± 0.1º positioning in calibration position). Apart from that, the use of the developed robust and high resolution stepper actuator is essential to fulfil the operational precision and the motorization margin at the same time.

The CSM has been submitted to an exhaustive qualification campaign that has confirmed the validity of the design to fulfil the mission requirements.