S3/OLCI AND S4/UVN CALIBRATION MECHANISMS

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ABSTRACT

The Sentinel Satellites are the space components of the Copernicus programme for Earth observation. Among the first satellites, Sentinel 3 (S3) is observing the surface while Sentinel 4 (S4) is observing the atmosphere.

The S3 Ocean and Land Colour Instrument (OLCI) is an Earth observation instrument developed for the Sentinel 3 satellite. The S4 Ultraviolet Visible Near-infrared (UVN) spectrometer is an atmosphere observation instrument embarked on MTG-S in the frame of the Sentinel 4 mission. In both cases, the accuracy of the instruments relies on periodic in-orbit re-calibrations using a Calibration Mechanism Assembly.

The Calibration Assemblies of OLCI and UVN are composed of a multifunctional wheel holding reference diffusers and which is moved thanks to a stepper motor. The position control is performed with an encoder (OLCI) or a resolver (UVN). UVN also includes a reference White Light Source (WLS).

For these two instruments, CSL has been responsible for development of the Calibration Assemblies including the design, manufacturing, assembly and qualification of the mechanisms and the procurement, qualification and optical calibration of the reference diffusers.

This paper presents the design of these mechanisms and describes the qualification and lessons learnt for both mechanisms.

1. S3/OLCI CALIBRATION ASSEMBLY

Sentinel 3 OLCI Calibration Assembly is a mechanism developed, built, tested and calibrated by the Centre Spatial de Liège (CSL) in the framework of the ESA GMES Space Component Programme. In this program, the Sentinel 3 mission is focused on operational oceanography and global land application. The payload of the satellite is composed of a set of optical and microwave instruments. The mission requires the use of 2 concurrent satellites. To sustain operational services over a minimum period of twenty years two additional satellites are foreseen as replacement.

The Sentinel 3 satellites are composed of the following essential components:

- An advance Radar Altimeter concept;
- Appropriate system components for necessary atmospheric water vapour, aerosol and ionospheric corrections;
- Appropriate system components for accurate/precise orbit determination and on-orbit pointing knowledge;
- A second optical imager for Sea and Land Surface Temperature operational applications;
- A multi-spectral optical imager for Ocean and Land Colour operational applications.

The last instrument called OLCI (Ocean and Land Colour Imager) is the responsibility of Thales Alenia Space France (TAS-F). It is composed of five identical cameras which are pointed towards the Earth.

The performance of the OLCI instrument relies on in-orbit re-calibration of the cameras. This calibration is performed using the OLCI Calibration Assembly.

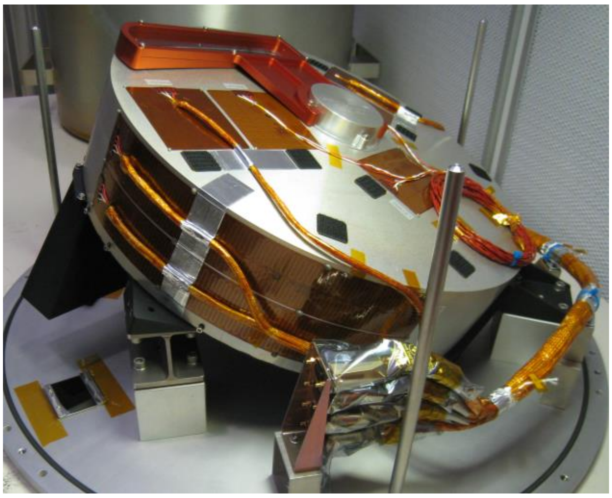

Figure 1. S3/OLCI CA

1.1. OLCI Calibration principle

The calibration of the cameras is performed in radiometry and in wavelength using reflective diffusers. Two sets of diffusers are placed in front of the cameras while being exposed to direct sunlight.

The first set is composed of two white quasi-lambertian diffusers. This set is used for radiometric calibration and is composed of a nominal diffuser and a spare one. The nominal diffuser is exposed at each calibration while the spare one is only exposed from time to time to verify the ageing of the nominal one.

The second set is composed a single doped diffuser. The doped diffuser is used to perform the wavelength calibration.

1.2. Mechanism design drivers and functionalities

The Calibration Assembly mechanism is located directly in the aperture of the cameras and, in addition to its calibration functions, it is also used as Earth aperture field stop and shutter. It is therefore definitively considered as a single point of failure as a failure could result in a loss of the mechanism functionalities or even the loss of the complete mission. A particular emphasis is then given to the mechanism reliability and robustness.
The diffusers positioning is another design driver of the mechanism as the in-orbit calibrations rely on the accurate transfer of the on-ground characterisation of the diffusers to the in-orbit measurements.
The mechanism is also designed to efficiently control the straylight as any unwanted light could corrupt the calibration measurements.
Lastly, the calibration hardware must be kept free of any contaminant, especially molecular as even invisible on-ground contamination could significantly impact the characteristics of the diffusers while in orbit. As a calibration reference, the stability of the diffuser optical performance along the mission is indeed an important requirement.

The mechanism has five positions which are:

- Earth observation which is the main observation mode;
- Shutter which blocks all aperture and allows protecting the instrument during launch as well as performing a dark calibration during operations;
- Diffuser 1 position that places the white reference in reflection between the sunlight and the cameras for in-orbit radiometric calibration;
- Diffuser 2 position which is a redundant diffuser to the first one;
- Wavelength diffuser which allows performing a wavelength calibration by placing a doped diffuser in reflection between the sunlight and the cameras.

1.3. Calibration Assembly design

The main component of the Calibration Assembly is a multi-functional wheel on which five symmetrical positions are defined as shown in Fig. 2.

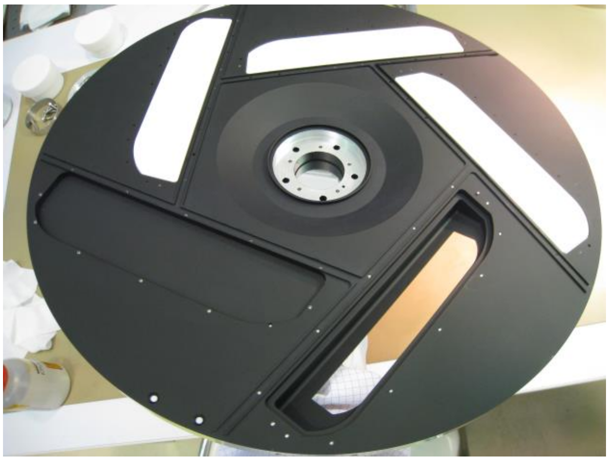

Figure 2. OLCI CA Multi-functional wheel

On each of these positions is mounted either a diffuser (white or doped), a shutter or an earth aperture stop. All the positions are spaced by 72°

This multi-functional wheel is attached to the Base Plate by the Driving Assembly.
The Base Plate is the main interface with the spacecraft. This part is tilted with respect to the light beam to illuminate the diffuser with the right angle.

The Driving Assembly, shown in Fig. 3, is the sub-part with all the motion functionalities and is composed of:

- Preloaded double precision Bearings with oil lubrication (Fomblin Z25);
- A stepper Motor;
- An absolute Encoder;
- All necessary interfaces and housing.

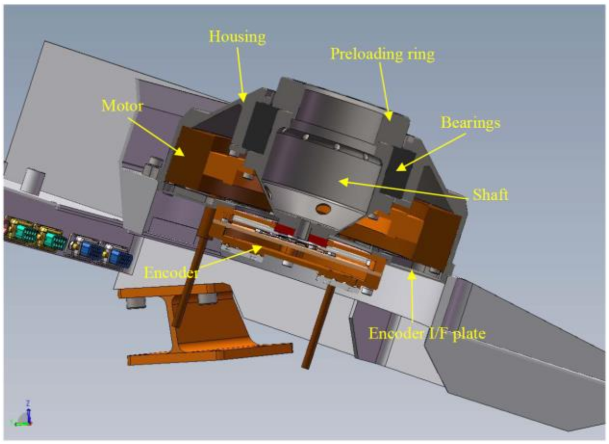

Figure 3. OLCI CA Driving Assembly

The Driving Assembly is designed to reduce contamination coming from the Motor and the Encoder, as well as from bearing oil evaporation, by venting towards the outside environment and not towards the optical cavities.

To withstand the vibrations during launch the mechanism is relying on the holding torque of the stepper motor. This is performed by maintaining the mechanism powered-on during the launch.

1.4. Test campaign

The Calibration Assembly was successfully subjected to a full test campaign. The test campaign is composed of:

- Performance test. This test checks that the instrument can operate within the specified performances and tolerances. It consists in moving to each position and measuring the actual position reached. This test is performed at CSL using the dedicated EGSE.
- Vibration tests. The vibration tests are composed of resonance search between 5 and 2000Hz, sine vibrations up to 100Hz and random vibration from 20 to 2000Hz. These tests are performed at CSL using the in-house shaker facility.
- Shock test. The qualification model was subjected to a shock test up to 1000g.
- Bake-out. Multiple bake-out are performed during the AIV to assure no contaminant is introduce at any time.
- Thermal vacuum test. The mechanism is subjected to a thermal cycling to verify that the assembly can withstand the full operational and non-operational temperature range.
- EMC test. The assembly withstood a full EMC campaign including susceptibility and emissivity.
- Lifetime test. During the thermal cycling, a lifetime test is performed to assess the performance during the full life of the mechanism under the operational conditions.

After sensitive tests such as vibration and thermal vacuum, a performance test is performed to verify the integrity of the mechanism.

1.5. Calibration campaign

One of the main parts of the AIV of the Calibration Assembly is the characterisation of the diffusers.
As the diffusers are used as optical reference for the in-orbit re-calibrations of the instrument they go through a lengthy calibration process composed of BRDF (Bidirectional Reflectance Distribution Function) measurements and Hemi-reflectance measurements.

In the frame of OLCI CA project, CSL developed a BRDF bench that is capable of measuring the diffusers while being mounted onto the multi-functional wheel.
This approach allows suppressing mounting repeatability issues by making the measurement only when the diffusers are in their final configuration.

The facility is capable of measuring relative BRDF as well as absolute BRDF and polarisation sensitivity.

For Hemi-reflectance measurements, CSL is equipped with spectrometers that were also used for measuring hemi-reflectance variations with respect to temperature.

1.6. Mechanism performance

The mechanism performance is the following:

- Diffuser positioning repeatability < 5'
- Encoder power < 0.6W
- Motor power < 6.7W
- Motor torque > 0.4Nm
- Rotation speed : 7.5°/s

1.7. Project status

Currently two S3/OLCI Calibration Assembly flight models (FMA and FMB) were built, assembled and qualified. The FMA was launched part of Sentinel 3A in 2016 while the FMB is planned to launch in 2017.
Two additional models (FMC and FMD) are under fabrication at CSL.

1.8. Lessons learnt

The development of the BRDF measurement facility was the most complex element of the activity performed for OLCI CA. Some optical parameters expected to be known very accurately revealed to be quite difficult to measure. It includes the attenuation filters transmission and the observation solid angle. These parameters finally required specific measurement procedure and correlation with calibrated references.
The design of the mechanism was re-using the design of the MERIS calibration mechanism developed by CSEM. It appeared that the improved mechanical analysis methods lead to larger than anticipated levels on the sub-systems. This required deeper analyses and understanding of the mechanical behaviour of these sub-systems.
The design was also based on a single duplex bearing holding the multifunctional wheel. This duplex bearing acted as a pivot point in the behaviour of the wheel. This led to large amplitudes of displacement at the edge of the multifunctional wheel, interfering with the cover. This had to be corrected during the QM campaign.

1.9. Acknowledgment

This activity has been performed in the frame of a contract between CSL and TAS-F for the design and development of the OLCI Calibration Assembly.
CSL wants also to thank CSEM for their support in the design of the OLCI mechanism.

2. S4/UVN CALIBRATION ASSEMBLY

The Sentinel 4 mission covers the needs for continuous monitoring of Earth atmospheric composition and air pollution using a high resolution Ultraviolet/Visible/Near-Infrared (UVN) sounder instrument to be deployed on two geostationary MTG-S satellites.
The radiometric accuracy of the UVN instrument relies on periodic in-orbit re-calibrations using the UVN Calibration Assembly (UVN CAA).

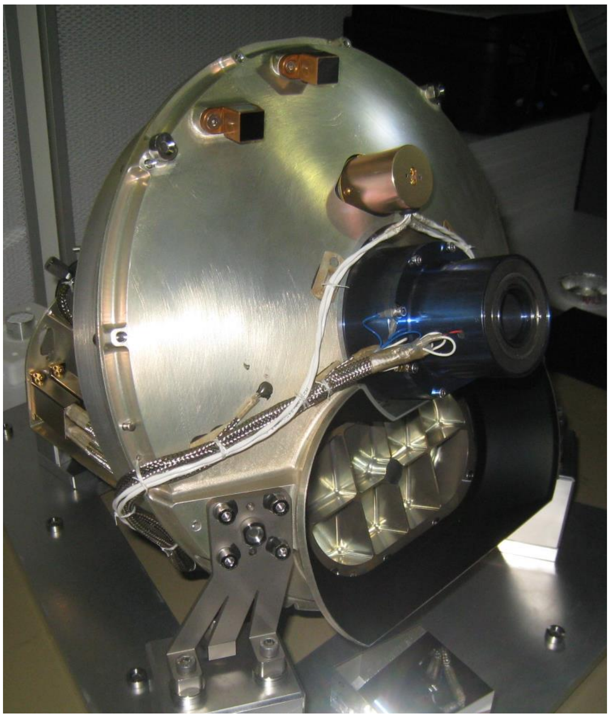

Figure 4. S4/UVN CAA

2.1. Calibration principle

The calibration of the camera is performed in two ways using the Calibration Assembly.
The first measurement is performed by placing a diffuser between the detector and the Sun. The camera is then calibrated using the Sun irradiance. To this purpose, two diffusers are placed on the multi-functional wheel in order to have one nominal and one redundant diffuser.
The second measurement is performed by switching on the White Light Source (WLS) which generates a collimated beam using a parabolic mirror, an integrating sphere and a slit. The parabolic mirror is mounted on the multifunctional wheel.

2.2. Mechanism design drivers and functionalities

The UVN Calibration Assembly has been designed under multiple constrains.
One of the main constrain is the allocated mass.
The second important constrain is the limitation of exported torques and micro-vibrations. The challenge is to determine the micro-vibration behaviour during the design phase before the availability of any micro-vibration measurement.
The next design driver is the lifetime of the different models. A long duration on-ground storage was defined and should be taken into account when defining e.g. the lubrication for bearings.
Given the optical configuration, the diffusers are now used in transmission (while OLCI CA used reflective diffusers). The use of QVD (a stack of ground glass plates) in transmission is also challenging in terms of BTDF and spectral features performance as well as for the mechanical mounting on the wheel.
For the UVN instrument, the Calibration Assembly is a single point of failure. Therefore a particular attention is given to reliability and robustness.
Another point is the straylight inside the diffuser cavity as any unwanted light could corrupt the in-orbit calibrations.
As for any optical hardware, all surfaces shall be kept free of contaminants, especially molecular.

The mechanism has three positions which are:

- Nominal Sun calibration which is the position where the nominal diffuser is placed between the Sun and the instrument aperture to perform an in-orbit calibration;
- Reference Sun calibration which is the position where the redundant diffuser is exposed instead of the nominal one;
- WLS mirror which is the position when the aperture is closed and a mirror is placed to see the WLS from the instrument.

2.3. Calibration Assembly design

The main component of the UVN Calibration Assembly is the multi-functional wheel on which three positions are defined as shown in Fig. 5.

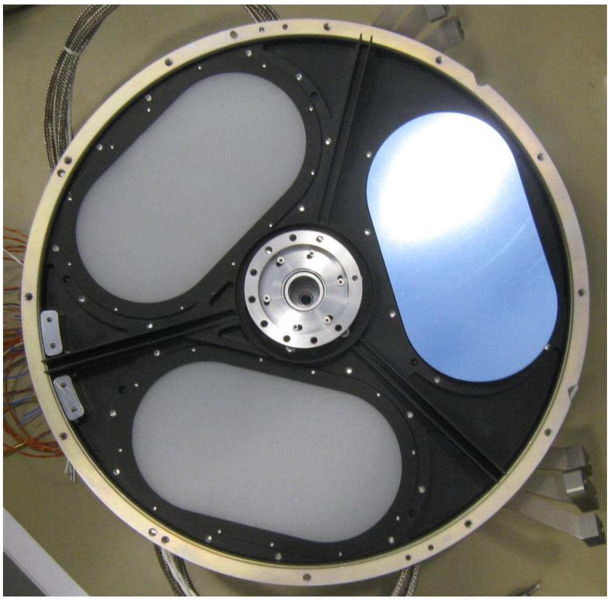

Figure 5. UVN CAA Multi-functional wheel

On this wheel are mounted two identical diffusers and a parabolic mirror.

The multi-functional wheel is mounted onto the Main Structure by its Driving Assembly.
The Main Structure is represented in Fig. 6 while the Driving Assembly is shown in Fig. 7.

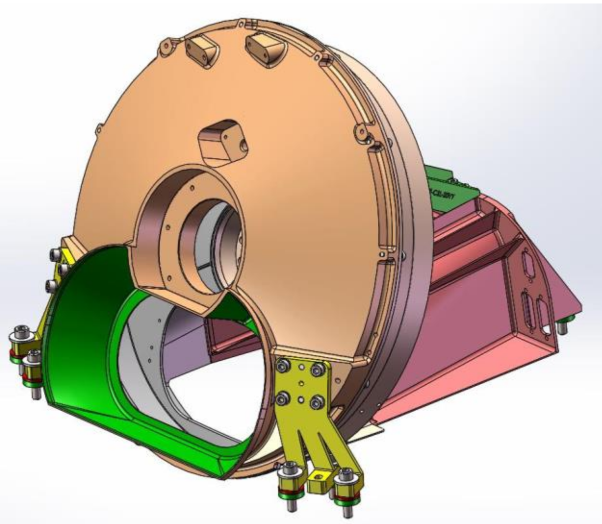

Figure 6. UVN CAA Main Structure

The Driving Assembly is composed of:

- A stepper Motor;
- A Resolver;
- Precision Bearings: one double Bearings in O configuration and one single Bearings with oil lubrication (Fomblin Z25);
- All necessary interfaces and housing.

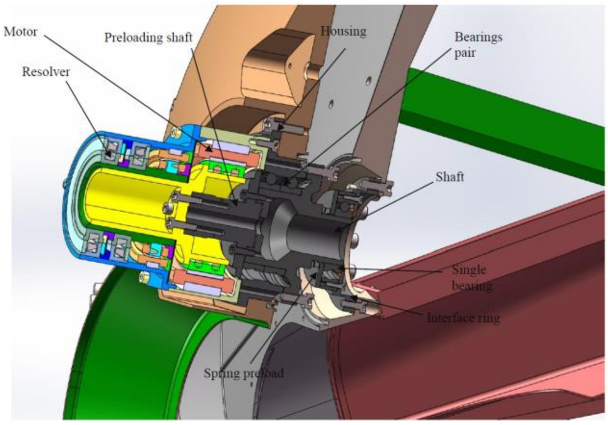

Figure 7. UVN CAA Driving Assembly

To withstand the vibrations during the launch a locking mechanism is incorporated in the design to prevent the wheel from turning. The Launch-Lock is a resettable SMA (Shape Memory Alloy) pin-puller as represented in Fig. 8.

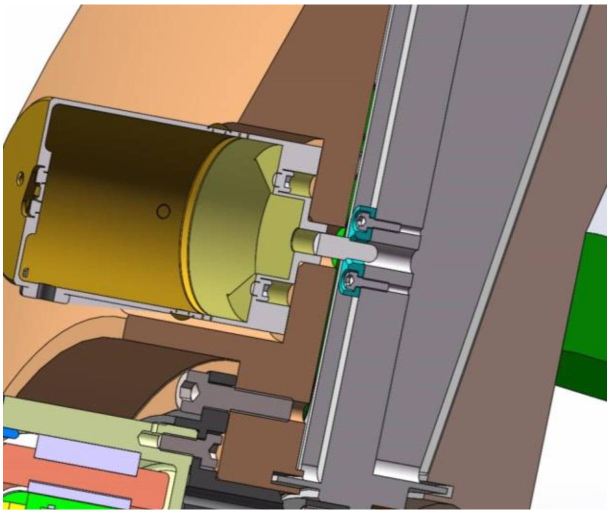

Figure 8. UVN CAA Launch-Lock

2.4. Micro-vibrations modelling and characterisation

MTG-S being an Earth observation satellite with accurate pointing requirements, the exported torques and micro-vibrations that are generated by sub-systems can degrade the performance of the MTG instruments. Therefore, the micro-vibrations emitted by the Calibration Assembly during the motion of the mechanism shall be reduced to the minimum achievable.
In this goal, the micro-vibrations and exported torques of the Calibration Assembly were estimated using a model and then characterised using a micro-vibrations table.

2.4.1. Micro-vibrations modelling

To evaluate the micro-vibration levels in the moving mechanism a Simulink model has been created in which were incorporated the elements that generate the vibrations as well as the main components that influence the transmission of vibrations in the mechanism.
The elements that generate the micro-vibrations are:

- The stepper motor
- The bearing
- The friction

The main elements that influence the transmission of the vibrations are

- The stepper motor controller
- The transfer function from the motor to the spacecraft interface;
- The lever effect from the spacecraft interface to the spacecraft CoG.

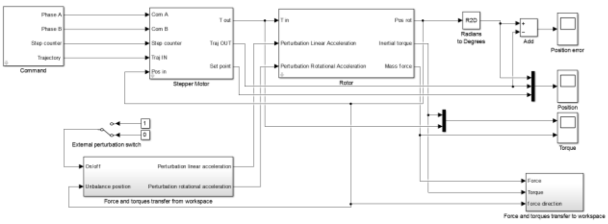

Figure 9. Micro-vibrations Simulink model

The stepper motor controller is a Simulink block that takes in input the motion that the motor should follow as well as the micro-stepping parameters and transforms it into the sine wave that will be the current input of the stepper motor.
The stepper motor is another Simulink block that takes in input the current of the two phases and that generates the output torque of the motor. The modelling also takes into account the detent torque of the stepper motor.
The next block of the simulation is the output shaft. This block simulates the behaviour of the driving shaft by modelling the resistive torque on the shaft. That includes the friction in the bearing and the rotation inertia of the multi-functional wheel. This block can also take into account some cyclic resistive torque generated by un-perfect balls or track.
The last block is the exportation of the results in the Matlab workspace.
The results of the Simulink computation are composed of the torques and forces generated by the assembly at the motor location.
After the simulation, a Matlab script is run in the workspace to take into account for the mechanical transfer function from the motor interface to the Calibration Assembly interface.
The input transfer function were previously recovered from the FEM analysis
Once the temporal results are obtained in Matlab, a frequency analysis is carried out to identify the exported torques and micro-vibrations in different frequency bands.
The final result of the analysis is a temporal response of the injected micro-vibrations at the spacecraft CoG.

2.4.2. Micro-vibrations optimisation

Using the produced model, an optimisation analysis was carried out to reduce the micro-vibrations exported to the spacecraft.
The driving of the stepper motor can be tuned by multiple parameters. The main parameters are the maximum current injected in the motor and the motion profile.
These parameters have been analysed to reduce the micro-vibrations to the minimum achievable.
The first optimisation performed was determining the impact of the input current as well as the sensitivity to the detent torque of the stepper motor. It was found that the micro-vibrations created by the stepper motor were primarily affected by the ratio between the holding torque (proportional to input current) and the detent torque. The higher the ratio, the lower the micro-vibrations level.
The second analysis performed was determining the impact of the driving profile on the generated micro-vibrations. Multiple profiles were tested including a constant velocity profile, a constant acceleration profile and a jerk profile.
It was found that the best profile to reduce the micro-vibrations is a jerk profile that tends to a constant velocity profile. Tuning the acceleration part of the jerk profile allowed reducing the micro-vibrations during the transient part of the curve.

2.4.3. Micro-vibrations characterisation

Once the sensitivity analysis and optimisation performed on the Simulink model, it was required to compare the results with physical measurements.
Therefore a test campaign has been performed using the in-house micro-vibrations measurement facility available at CSL. The test facility is a Kistler table on which the full mechanism is mounted as shown in Fig. 10.

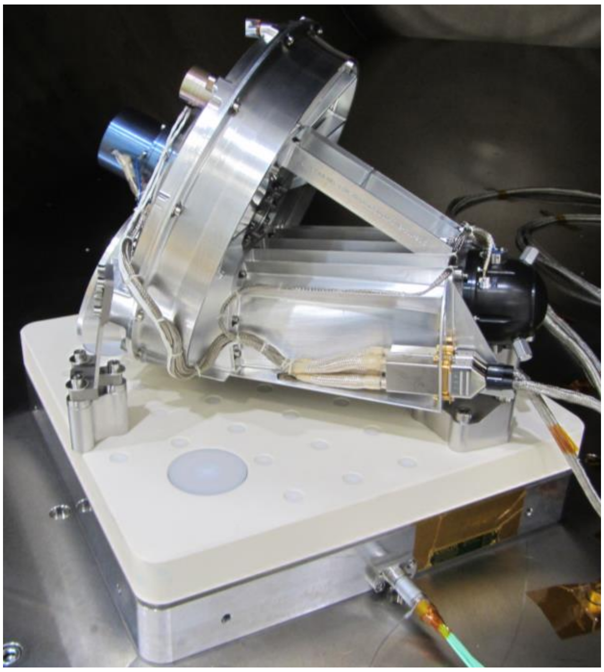

Figure 10. UVN CAA mounted on µVib table

The table is capable of recording the forces in three axes as well as the torques around the three axes with a high sensitivity.

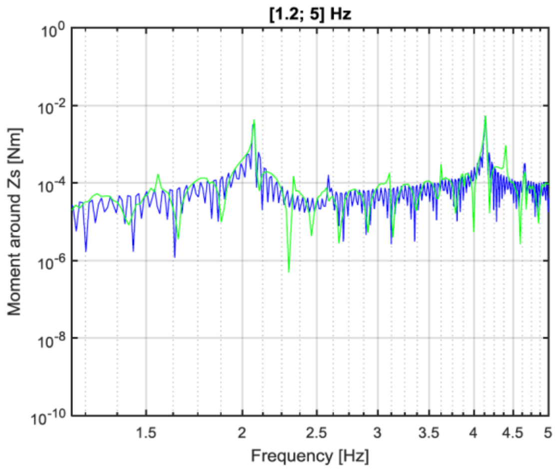

Figure 11. Simulated (blue) vs measured (green) µVib

The measurements appeared to be pretty well correlated with the simulation results. One example is given in Fig. 11. The simulation allows getting more accurate data at frequencies that cannot be measured, e.g. very low frequency range.

2.5. Test campaign

The UVN Calibration Assembly successfully withstood a full qualification campaign. The campaign consisted in:

- Mechanical performance tests. This test verifies that the performance of the mechanism is nominal. It compares the commanded motion to the read value from the resolver. The positioning accuracy and repeatability, the position stability are also measured. Another control performed is the motor power consumption and the torque margins of the mechanism.
- Vibration tests. As usual, the vibration tests are composed of reference low level sine sweep (resonance search) up to 2000Hz; sine vibrations up to 100Hz; random vibration from 20 to 2000Hz. These tests were performed using the shaker facility at CSL.
- Shock test. This test was performed with SRS up to 600g.
- Bake-out. For contamination purpose, the assembly is baked multiple times during the integration and after.
- Thermal vacuum test. The assembly was cycled through extreme operational and non-operational temperature.
- Lifetime test. During the thermal vacuum test, the life test of the mechanism was also performed.
- ESD susceptibility test.

2.6. Calibration campaign

The calibration campaign of the mechanism focuses on the characterisation of the diffusers.
The main characterisation is a BTDF measurement performed with the BRDF bench developed initially for S3/OLCI. The bench was adjusted to allow measurement in transmission instead of only reflection. Again, full advantage was taken of the facility by placing the whole mechanism inside the BTDF bench. The measurements acquired are taking into account not only the diffusers but also the surrounding environment of the mechanism. This methodology allows reducing to the minimum the mounting error of the diffusers because they are measured installed in the mechanism.
Compared to the OLCI reflective diffusers, the QVD diffusers used for UVN are more susceptible to generate spectral features, which can degrade the instrument measurement accuracy. The characterisation of the spectral features performance and the optimisation of the QVD characteristics (roughness, number of plates, coating) is therefore important. In the frame of the project, a dedicated spectral features measurement bench has been thus developed and used with success.

2.7. Mechanism performance

The mechanism performances are:

- Diffuser positioning repeatability < 1’

- WLS power < 4W
- Motor power < 5W
- Resolver power < 0.4W
- Motor torque margin > 7

2.8. Project status

A qualification model has been produced and was successfully qualified. Two flight models are under integration at CSL. The acceptance and calibration campaign will follow.

2.9. Lessons learnt

The lessons learnt of OLCI CA have been implemented in the UVN CAA design and development. Anyway, some new lessons could be extracted from our experience with UVN.

First of all, the computation of all screws revealed to be very pessimistic and forced the introduction in the design of several high resistance screws which was a quite costly solution. This could be avoided by maximising the size of the screws where room is available and by better designing interfaces with dissimilar materials.

This project allowed developing the tools for the micro-vibration simulations and investing in a high quality measurement table. It was then possible to have a good comparison between results of the analyses and the measurements. The measurements of the micro-vibrations were very challenging since it is sensitive to every external perturbation. This project allowed defining the best ways to perform this type of measurements. Some additional development are still planned to optimise the utilisation of the measurement table.

2.10. Acknowledgment

This activity has been performed in the frame of a contract between CSL and OHB-M for the design and development of the UVN calibration assembly.