ABSTRACT

The Corner Cube Mechanism (CCM) of the Infra-Red Sounder (IRS) for the Meteosat Third Generation (MTG) satellites completed an extensive qualification test campaign demonstrating the high-precision mechanism met stringent requirements for operation in the harsh environment of space at geostationary orbit. The Qualification Test Program was performed both at component/sub-system level and at mechanism level.

The FM (Flight Model) Acceptance test campaign was hindered by two major setbacks. The first was encountered just prior to the random vibration tests on the PFM (Proto-Flight Model), where it was discovered that a number of critical bolts had loosened despite the fact that they were locked by adhesive. The second with the discovery of the FM2 Optical Switch (OS) ruler broken inside the mechanism while the final sequence of the bolt replacement procedure.

The PFM and FM2 performance tests confirmed the previous EQM (Engineering Qualification Model) test results. The maximum lateral deviation for a stroke of 10mm was measured <0.4µm compared to the 2µm specification.

1 INTRODUCTION

Results on the subsequent qualification and acceptance test campaign at mechanism level are reported here which were performed on the EQM and the PFM. The results of the component and sub-system level qualifications were published during the 16th ESMATS in Sept. 2015 [R1].

The main performance requirements for the CCM are:

- A linear trajectory generation along the delay line translation axis over a functional stroke of ±5 mm (±9 mm calibration on ground)
- Maximum lateral deviation of the corner-cube apex of less than 1 µm from a true straight line
- Constant linear motion of 1 mm/s and speed stability requirements during dwell time (instantaneous speed error <0.25mm/s and RMS speed value <0.06mm/s)
- Highly limited dynamic exported forces from the mechanism to the optical bench in a micro-vibration environment

The critical qualification tests performed on the EQM were the environmental random vibration and shock tests followed by the crucial micro-vibration tests. The remaining qualifications tests for thermal balance and thermal cycling were performed on the PFM.

Both the EQM and PFM survived the vibration and shock tests but these events were not the only technical and programmatic challenges that were faced and resolved. With the hurdle of the qualification tests behind the team, the acceptance level tests of the FMs were considered as a repetition and less critical.

The acceptance test campaign of the two flight model CCMs started in mid-2017 following the successful qualification test campaign on the EQM. The FM acceptance test campaign was comprised of a series of critical tests: performance tests, random vibration tests, thermal vacuum cycling (TVC), performance tests after environmental tests and micro-vibration tests. The test campaign was covered by successes and setbacks but, at the end, solutions were found and implemented.

The TVC part of the Proto-Flight Model (PFM) tests completed the qualification of the CCM since these tests were not performed on the EQM. A delta-QR (Qualification Review) was held successfully validating the overall test program for final delivery of the PFM to Thales Alenia Space (TAS-F) for integration of the CCM at interferometer level.

2 VOICE-COIL MAGNETS

At component level, the voice-coil actuator NdFeB magnets (VACODYM633AP) went through a qualification programme with their Aluminum IVD coating as reported in [R1] to address a major issue of Nickel coating delamination. However, this new
combination was not selected by the MTG team following long duration thermal humidity tests where some samples showed divergent results with respect to coating thickness discontinuities and cracks. EDX (Energy Dispersive X-Ray) analysis revealed the presence of oxygen on the top surface of one magnet and underneath the IVD Aluminium coating which could lead to oxidation or corrosion conditions of the magnet. In view of the results, it was concluded that the IVD magnet coating process needed further improvement and could not be considered as fully qualified [R1].

A new qualification campaign ensued with the change to Sm2Co17 magnets (Recoma32S from Arnold Magnetic) without a coating. Thanks to the recent SmCo alloy performance improvements, the impact to the CCM was negligible and the motorisation margins were maintained.

The objective of the test campaign was to validate the design, the manufacturing and assembly processes of a mechanism that is as representative as possible to the final flight version.

The critical performance parameters measured during these tests were the mobile mirror lateral shifts and the speed stability.

The maximum short term (15 min.) lateral deviation parabolic shift for the on-ground calibration stroke of 18mm (±9mm) was extremely low and measured at ±2nm in Z and ±4nm in Y directions compared to the ±0.5µm specification for a functional stroke of ±5mm.

3.2 Mechanical vibration tests

Mechanical vibration tests simulate the extreme noise and vibration environment generated during the launch phase. The delicate mechanism is in a launch locked configuration in order to ensure that it will survive the vibration loads. The EQM survived the random profile vibration tests and shock tests in all three directions. Following the environmental tests, the performance tests were repeated and a close inspection of the launch locking device critical surfaces were made.
3.4 LLD contact pads

One of the inspection areas following the vibration tests was to verify the state of the LLD contact pads. The contact surfaces between the WC (Tungsten carbide) coated Titanium pads and the stiffening columns maintain the mobile stage in its neutral position without sliding.

Observing the clamping surfaces of both WC pads and stiffening columns, it can be deduced that no mobile stage sliding was induced by the shocks or vibrations tests. Considering the mating materials, the pitting appearing after environmental tests is as expected and results from the double flight locking of the LLD.

3.4 EQM Micro-vibration tests

The EQM micro-vibration tests were performed on a dedicated micro-vibration test bench developed by TAS-F to measure the exported forces of the CCM while in operation and to inject a simulated spacecraft disturbance noise profile. The results with the EQM showed non-conformances to the specifications which required significant exchanges and clarifications between CSEM-TAS-OHB-ESA to correctly understand and interpret the impact in performance.

While the mechanism is displacing the corner cube at a speed of 1mm/sec, the exported forces to the instrument during the reversal stroke were measured at 7.2mN.

Some of the major results discovered were high amplification of CCM resonance modes from induced perturbations from the CCS (cryo-cooler system) harmonics. With the injected micro-vibration disturbance profile, two speed stability parameters were measured:

- Absolute speed error during dwell time measured at 0.73mm/sec (spec: 0.25mm/sec)
- Standard deviation of speed error during dwell time measured at 0.29mm/sec (spec: 0.06mm/sec)

Even though these values were out of specification, the results were expected since they are directly proportional to the injected disturbance levels. The injected disturbance is a sum of various satellite sub-system contributions mainly cryo-coolers and reaction wheels which at the time of the tests were being reviewed at satellite level to determine budgets and margins.

The most critical frequencies affecting the CCM performance were 173Hz (Y-direction, lateral shift impact) excited by the 3rd CCS harmonic, 230Hz (X-direction, lateral shift impact) excited by the 4th CCS harmonic and 330 Hz (X-direction Intermediate Stage, speed stability impact). The solution investigated to minimise the impact of the CCM resonance modes on performance was the implementation of mobile mass tuning to shift critical frequencies outside the disturbance bands. Analyses were performed to determine the impact of the additional masses based on EQM measurements and verified on the PFM.

A compromise had to be found to avoid excessive mass on the mobile stage which would have an effect of additional stresses during vibration tests and a sufficient frequency shift away from the CCS harmonics. The optimum configuration that was tested on the PFM was an intermediate stage mass of +10g and a mobile mass of +50g. The addition of 10g on the intermediate stage reduced the 320Hz mode to 313Hz shifting it away from the CCS disturbance zone identified at 330Hz.
The FM test campaign was hindered from a number of critical anomalies both at sub-system and mechanism level. A major setback was encountered just prior to the start of the random vibration tests on the PFM. A planned inspection of the CCM was carried out on the shaker table and it was discovered that a number of critical bolts had loosened despite the fact that they were locked by adhesive. For the PFM on the CSL vibration shaker, 9 bolts were identified and on the FM2 still at CSEM, 10 bolts were found loosened.

Since some of the identified bolts were previously removed to install the additional mobile masses for frequency tuning, it was believed that heating the bolt heads to soften the EC2216 for removal was the culprit. A full inspection found that the majority of the loosened bolts had been exposed directly or in proximity to temperatures around 80 to 100°C by the hot air gun.
A short list of possible root causes and contributors (out of 23 identified) are listed below:

- Lack of adhesion of glue on screw heads
- Glue deterioration induced by local heating during glue removal
- Thermal expansion coefficient mismatching
- Wrong tightening torque
- Screws touching the bottom of the tapped holes
- APS Nuflon-N friction coefficient too low
- APS Nuflon-N coating w.r.t screws reversibility influenced by temperature

An investigation was carried out to determine the source of this major non-conformity. Submitting test samples (Fig. 15 & 16) to 80°C heating in a climatic chamber produced “spontaneous” screw untightening with screw head rotation (see Fig. 17) of 40-50°. The untightening torque was verified and found to be 0Nm to 40% of the initial tightening torque. The EC2216 epoxy had little to no effect in blocking the bolts.

The six-month investigation concluded that the APS Nuflon-N antifriction coating (varnish charged with PTFE) applied on the bolt threads (and under the head) is affected by a temperature rise (local heating or thermal cycling). The coating thickness was between 4-8 µm providing a tested coefficient of friction of 0.05 to 0.09. The friction coefficient of the Nuflon-N coating dropped below 0.04 due to a temperature increase (during bolt exchange procedure) creating a reversibility condition which allowed the bolt to loosen.

The implementation of a corrective action consisted of the replacement of all mechanism bolts using the IASI heritage coating and without disassembly of the CCM. All the R-SAT screws had their Nuflon coating removed as part of the process and recoated with the IASI sprayed PTFE coating. The TEFLISS-2 PTFE spray coating (Fig. 18) was tested to determine optimum parameters for coating thickness and tightening torque.

The final friction coefficient range for the coating was $\mu = 0.17$ to 0.24. The tightening torque for a M5 screw was set to 9.6Nm to provide a value of 70% of yield during tightening.

Various tests were performed to validate the process and measure the screw untightening torque. Samples were tested at room temperature (RT) for comparison with subsequent tests. Samples were heated to 80°C with and without the EC2216 epoxy. Results showed that the heating of samples increased the untightening torque from 5 to 20% when compared to the RT data.

The samples were finally tested in a thermal chamber with a cycling profile (-15 to +45°C) similar to the TVC tests and again followed by measurements of the screw untightening torque (Fig. 19).

All the bolts (110 per CCM) were replaced sequentially without compromising the alignment and assembly tolerance of the mechanism (Fig. 20). Thanks to the design (and by chance), all bolts were accessible without the need of disassembling critical components.
5 FM2 OS ruler broken inside the mechanism

Another setback was encountered during the acceptance test campaign with the discovery of the FM2 Optical Switch (OS) ruler broken inside the mechanism while the final sequence of the bolt replacement procedure was being carried out.

Observations were provided by Schott following their expertise of the broken ruler indicating that a material flaw was present. Lots of small chipping were observed along the length of the glass edges. Flaws such as these on the glass surface most often originate during the grinding process to remove the sharp edges. The pit marks along the chamfer are typical damages and problematic since they are potential fracture origins.

The Schott interpretation of the failure was:

- The breakage was caused by the combination of a flaw and an applied tensile stress
- The flaw is located on the edge of the ground glass surface facing the metal frame
- It is highly probable that the flaw comes from the grinding process itself and is not introduced by additional mechanical contact after grinding
- A flaw on the surface of a brittle material represents a weak spot & diminishes its strength and facilitates breakage
- The shape of the broken glass part indicates an introduced tensile stress by bending
- The course of failure is therefore: The glass part was bent away from the metal frame, thus introducing a tensile stress into the grinded glass edge which leads in combination with the present flaws to the fracture of the specimen

The general conclusion and most plausible failure scenario considered was a combination of individual parameters that led to the optical switch glass ruler to break. If a surface defect existed from the start (following the grinding process), the Codechamp component level vibration tests (two vibration tests) could have propagated a fracture along the glued surface. This fracture would not have been visible either due to the glue or small crack size. Subsequent inspections by CSEM with an endoscope through the inspection window could have made contact with the ruler and further propagated the crack. The various manipulations during the bolt exchange procedure could have led to total failure on a ruler that was already fragile.

Following the investigation, Codechamp’s supplier implemented corrective actions by polishing instead of grinding the glass edges. The glass ruler was replaced and the OS hardware retested (vibration and TVC) at component level before being re-integrated in the CCM. Additional inspections were made on the PFM to verify that its ruler was intact and in good condition.

6 FM PERFORMANCE TESTS

Following the various corrective actions, the PFM and FM2 acceptance tests were performed during the first half of 2018. The PFM and FM2 performance tests confirmed the previous EQM test results. The maximum
lateral deviations for both long term (e.g. LLD release) and short term for a functional stroke of 10mm (±5mm) was measured after the environmental vibration tests and given in the table below.

<table>
<thead>
<tr>
<th>Lateral deviations (PFM)</th>
<th>Spec</th>
<th>Y-dir</th>
<th>Z-dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant shift (Long term)</td>
<td>±20µm</td>
<td>0.6µm</td>
<td>8µm</td>
</tr>
<tr>
<td>Linear shift (Long term)</td>
<td>±2µm</td>
<td>0.1µm</td>
<td>0.4µm</td>
</tr>
<tr>
<td>Parabolic shift (Short term)</td>
<td>±0.5µm</td>
<td>3nm</td>
<td>2nm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lateral deviations (FM2)</th>
<th>Spec</th>
<th>Y-dir</th>
<th>Z-dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant shift (Long term)</td>
<td>±20µm</td>
<td>1.3µm</td>
<td>9µm</td>
</tr>
<tr>
<td>Linear shift (Long term)</td>
<td>±2µm</td>
<td>0µm</td>
<td>0.4µm</td>
</tr>
<tr>
<td>Parabolic shift (Short term)</td>
<td>±0.5µm</td>
<td>3nm</td>
<td>4nm</td>
</tr>
</tbody>
</table>

Following the EQM micro-vibration tests, improvements were identified to shift mechanism frequencies away from the input disturbances generated by the cryo-coolers which affected speed stability and lateral shift. Local mass tuning implemented on the mobile stages of the CCM improved performance in these areas.

The test setup at TAS-F, Cannes premises was slightly improved with respect to the EQM tests by placing the Z-shaker directly underneath the platform and taking into account the accelerometer mass in the balancing mass used for the mobile stage.

Figure 25. PFM during micro-vibration tests at TAS-F

With the injected micro-vibration disturbance profile, the two main speed stability parameters were measured:

- The absolute value of speed error during dwell measured at 0.54mm/sec (EQM 0.73 mm/sec) (spec: 0.25mm/sec)
- The standard deviation of speed error during dwell measured at 0.12mm/sec (EQM 0.29 mm/sec) (spec: 0.06mm/sec)

Both models were delivered to TAS-F, Cannes at the end of 2018 for integration in the Interferometer Assembly and further testing.

7 LESSONS LEARNED

Some of the main lessons learned over the course of this project are provided below from the project manager’s point of view:

- The collaboration and commitment of the suppliers to the CCM project allowed for fruitful discussions and identification of solutions when problems arose (both minor and major).
- Having two people following a subcontractor is important for redundancy.
- Do not underestimate a recurring development if manufacturers and materials need to be changed.
- The support from company management to organize resources attributed to the project during critical phases was crucial.
- The support from the client to propose and back solutions without finger pointing keeps a positive spirit during the investigation process when unplanned events arise.
- Just because items have been identified in a risk register or a FMECA (Failure Modes, Effects and Criticality Analysis) table does not mean all potential problems have been identified. The loose bolts or broken ruler could never have been envisioned in any stage of the project.
- The flight spare kit that was manufactured in parallel to the FM hardware was important when the bolt replacement process started. All critical hardware was available in case anything was damaged during the refurbishment.
- Progress Meetings with the client and participation from suppliers and sub-contractors keeps everyone in the loop and identifies responsibilities.

8 CONCLUSION

The CCM project started with the design and qualification of new magnets and coatings for the voice-coil motor following the discovery of Nickel delamination on the IASI (Infrared Atmospheric Sounding Interferometer) CCM due to NdFeB magnet corrosion. An extensive development and test campaign was carried out to finally implement a solution using Sm2Co17 magnets with no coating.

Following the EQM test campaign, the CCM development was on track and with significant margin for delivery of the flight hardware. A major setback was encountered with the FMs which consisted of critical bolts found untightened prior to the start of vibration tests. The investigation concluded with the implementation of a heritage PTFE sprayed coating used on the IASI CCMs. The various problems encountered were successfully resolved with the open discussions during the non-conformance review boards among participants from CSEM, TAS-F, OHB and
ESA. Frequent discussions with the customer and subcontractors at technical level was maintained throughout the duration of the project.

The PFM and FM2 performance tests confirmed the previous EQM test results. The maximum lateral deviation for a stroke of 10mm was measured <0.4µm compared to the 2µm specification. Both flight models have been delivered to TAS and are one of first flight hardware items delivered in the frame of the MTG IRS programme.

![Figure 26. CCM FM2](image)

**ACKNOWLEDGMENTS**

The authors would like to thank:

- Thales Alenia Space (Cannes, F) for their continued support and co-operation over the course of this project (G. Luciano and his colleagues).
- Subcontractors and partners for their contribution & involvement throughout the development effort:
  - Cedrat Technologies SA for the development of the voice coil motor (A. Guignabert)
  - Ruag Space System Nyon (CH) for manufacture & assembly of mechanisms (S. Liberatoscioli)
  - CODECHAMP for the optical switches (P. Vuillemard and her colleagues)
  - ARCOFIL SA (St-Imier, CH) for their manufacturing (WEDM) capabilities on the critical flexure components notably the driving lever and membranes
  - Almatech (CH) for the FEM simulations
- The European Space Agency (ESTEC).

CSEM thanks them for their support.

**REFERENCES**


**Key words:** Mechanism, linear scan, high-precision, flexures, interferometer, earth observation,