DEVELOPMENT OF A FLIGHT DEMONSTRATION COARSE POINTING MECHANISM FOR GEO-GROUND OPTICAL COMMUNICATION TERMINAL.

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ABSTRACT

TELEO is a demonstrator of an optical laser communication terminal, launched towards geostationnary orbit in May 2023 as a hosted payload of a commercial telecom spacecraft. This flight laboratory will demonstrate new technologies (such as pointing mechanisms, optical amplifier, Infra-Red camera) and the associated concepts such as Pointing Acquisition and Tracking (PAT) strategy. The optical instrument is composed of a 26 cm diameter telescope held at launch and steered by a mechanism.

The Coarse Pointing Mechanism (CPM) is based on a three identical electrical actuators concept, developed in less than 2 years from TRL 3 to flight demonstration. This paper insists on the specific development approach, key success factors for on-time CPM delivery, major requirements and derived design features, optimized test sequence to the minimum needed, and finally lessons learnt.

1 Context

The laser communication market encompasses several major applications among which:

- Inter-Satellite Links (ISL), allowing low latency and high transfer rate,
- GEO-ground feeder links, answering to the growing need for short-term availability of huge data volumes.

To that extent, AIRBUS is developing multiple Coarse Pointing Mechanisms:

- The CPA70 70mm aperture mechanism is being developed for ISL with flight demonstration during the Compasso mission,
- the FOLC2/TELEO demonstration is the opportunity for AIRBUS, supported by CNES in the frame of the DYSCO project, to develop and test a new 260-mm aperture size laser communication Terminal ("TOP-M") featuring a CPM for GEO feeder links. Several components introduced in this new TOP-M terminal, including the CPM for GEO, come from early development carried out in the frame of the FOLC2 ESA ARTES activity.
- a GEO CPM version compatible with 500-mm class telescope is being developed in the frame of the CO-OP project (France Relance recovery plan, operated by CNES), based on the TOP-M CPM original design.

TELEO on-board terminal (OBT) is expected to be operated during 2 years, and its goal is to establish and maintain a bidirectional laser communication link with several optical ground stations (OGS).

More specifically, the TELEO demonstration goals for the space segment are to demonstrate the performance of the following key technologies:

- the telescope and pointing mechanisms, such as the CPM, based on 3 dedicated linear actuators, Fine Pointing and Fiber Injection Mechanisms (FPM/FIM) and the thermal regulation concept of an active terminal in geostationary orbit,
- PAT algorithms performance under real conditions.

This demonstrator has other objectives such as optical communication chain up to 10 Gbps validation, link budget computation and forecasting, atmospheric turbulences effect assessment, among others. Since they are non-mechanism related, they will not be presented in this paper, see [1] for more information.

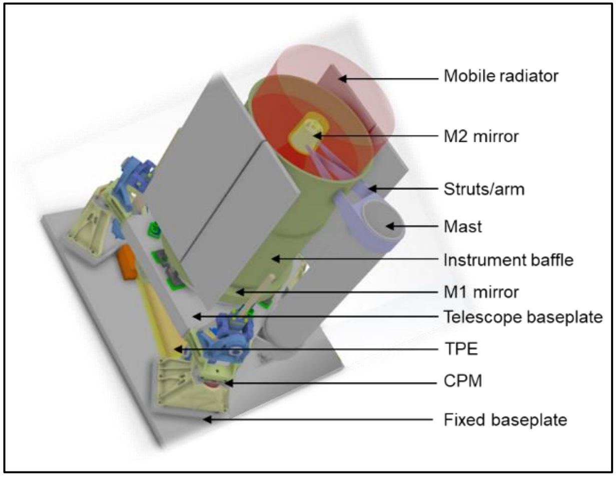


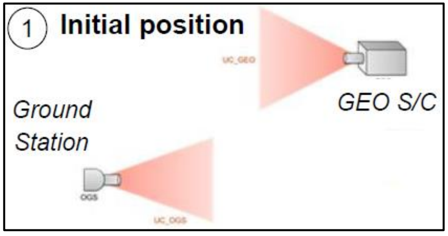
Figure 1. TELEO terminal overview. Coarse Pointing Mechanism (CPM) is actuating the telescope baseplate holding M1 & M2 mirrors. Terminal Proximity Electronics (TPE) is in yellow on the fixed part.

2 Pointing sequence and CPM Main requirements

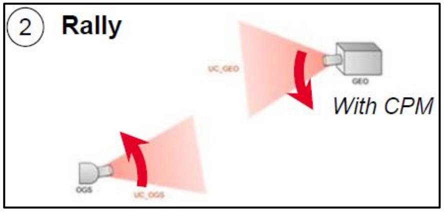
GEO/ground optical communication consists in taking light from a 10µm diameter optical fibre up to another 10µm optical fibre, separated by 36 000km. Therefore, pointing accuracy of the system is critical. The CPM is a contributor to the pointing, allowing large field covering. Fine pointing mechanisms are embedded in the mobile assembly and ensure the last hundreds of micro-radians pointing corrections at high frequency. Both mechanisms and associated algorithm ensure access to all earth disc and fine pointing of the system in closed loop.

The pointing, acquisition and tracking sequence is described in the following sequence:

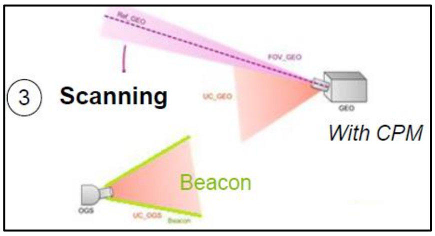
1- Initial: both TELEO and OGS (Optical Ground Station) are in any orientation.



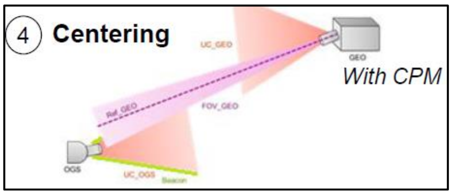
2- Rally: both TELEO and OGS orientate towards each other in open loop. It is requested to the CPM to have a speed of 0.375°/s for this phase.



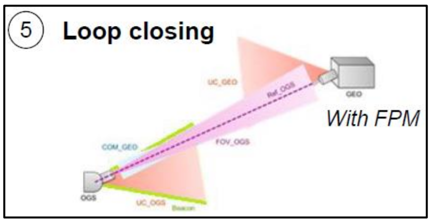
3- Scan: the OGS lights a beacon, and the CPM scans in a step and stares the uncertainty cone. It is requested of the CPM to minimize oscillations after each movement of 1mrad in 0.6s.



4- Centering: when the beacon is seen by the detector, the CPM is used to place it at its center.



5- Loop closing and data exchange: the Fine Pointing Mechanism enters in action to handle high frequency corrections. In this phase the CPM is used to de-saturate the FPM for low frequency, high amplitude disturbances e.g. thermoelastic distortions.



Therefore, the main requirements of the CPM are:

- Angular range : cone of +/-15°
- Speed of 0.375°/s,
- Pointing accuracy of a few hundred of µradians
- Stability after movements of a few dozens of µradians maximal amplitude.

Speed and accuracy are set to limit the time to establish the link and/or switch of ground station. The stability is required to ensure beacon detection during scan phase. All these requirements have to be fulfilled with a mobile mass of 30kg, and this mass shall be held by the CPM at launch.

3 Mechanism description

3.1 Architecture

The concept of this mechanism was initially developed and patented [2] for a low cost, low orbit, earth observation constellation, with an industrial approach in mind. Three identical linear actuators drive the payload on 3 axes, 2 rotations (tip/tilt) and 1 translation out-of-plane.

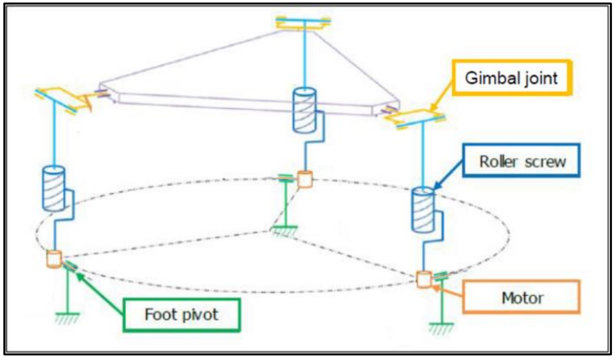


Figure 2: kinematic model of the CPM unclamped

At launch, the instrument is clamped by three HRMs (Hold and Release Mechanism), located near the actuators; after release the translation is used to place the actuators nut in a position where rotation of +/-15° is possible.

The mass of the CPM (3x 1-axis mechanisms) is less than 10kg.

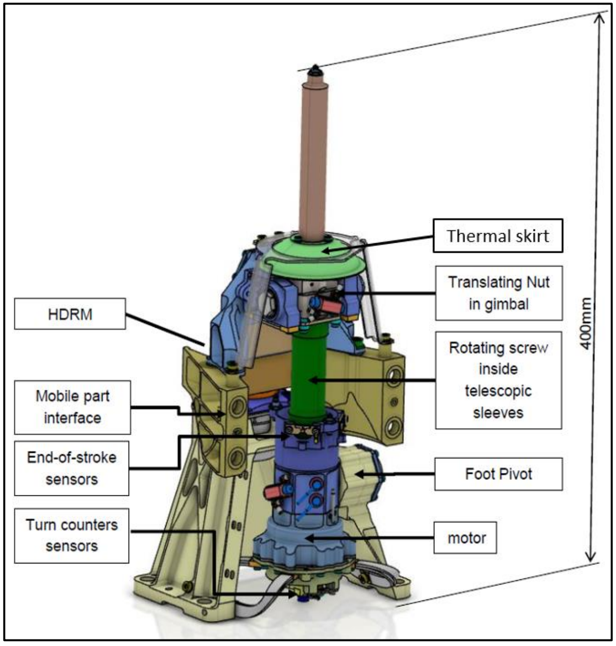


Figure 3: one axis mechanism description

3.2 Linear actuator

Each actuator uses a roller screw with 1mm pitch and a brushless motor. Fixed part and mobile part are linked using a foot pivot and a gimbal joint in order to be isostatic in operational conditions, i.e. when HRM are released. Orientation of the payload is possible within a 15° cone.

This architecture with a small screw pitch leads to a large kinematic ratio between motors angle and payload orientation (>2000). It allows to be commanded in open loop, avoiding expensive position sensors and keeping simple driving electronic. The brushless motors are driven in quasi-continuous micro-stepping mode, similarly to a stepper motor. Also, the small screw pitch gives a large irreversibility force, allowing to keep the mechanism steady without any holding voltage, lowering the mean thermal dissipation.

The motor is based on a usual 3-phases brushless design but has been developed specifically for this application. Even if driving electronic is not redounded, the motor includes redundancy coils, for potential future use in high reliability mission.

The architecture requires four pivots respectively for motor, foot pivot and gimbal. To reduce cost and lead-time, a solution with standard geometry ball bearings has been chosen. Only two references of bearing are used. One “big” for motor, foot pivot and gimbal central, one “small” for gimbal lateral. Nevertheless, bearings are custom-made for this application, mainly due to angular contact, material and required space grade lubrication.

3.3 Hold Down architecture

For launch, the mechanism shall be clamped. A simple plane/plane separation at each mechanism was selected. The main drawback is that it is hyperstatic and so requires shimming for assembly.

One main concern with HRM is emitted shocks. The HRM capsule is an off-the-self component widely used in many satellites (NEA9103 from EBAD), so the shock emitted by this part had to be sustained as is. However, another source of shock is the impact of the rod in the bolt catcher. These parts were designed internally, with the objective of minimizing the shock towards the mobile part supporting sensitive elements. First way is to minimize the energy stored in the extraction spring, then to soften the rod and bolt catcher by selection of plastic material for the bolt catcher and add of a damper made of soft material located at the top of the rod.

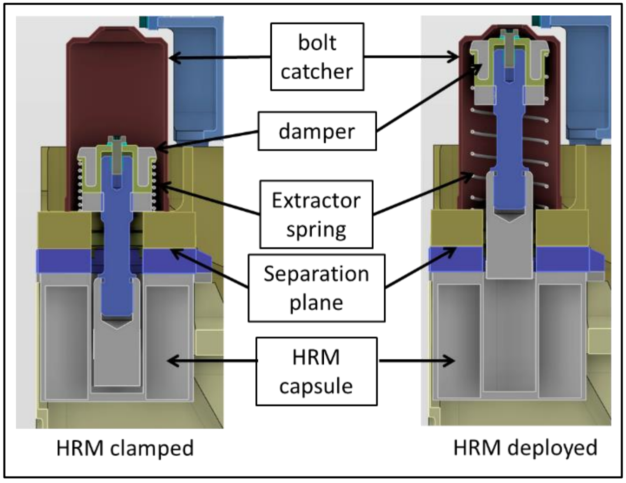


Figure 4: Cross sections of the HRM

To limit the transfer of launch loads from mobile part to the roller screws, a flexibility is added in the structure. Titanium blades are integrated in the gimbal joint structure (see Figure 2). Their stiffness has been designed to isolate the screw from the first mechanical modes of the telescope. This stiffness also helps to isolate from S/C microvibrations when unclamped.

3.4 Telemetry

As written above no fine telemetry is required. The objective of telemetry is for failure detection and end of stroke limitation.

The same component is used for both functions, i.e reed switches sensors. One pair (nominal and redundant) is placed at the bottom of the motor, with magnet onto the rotor. Their function is to monitor motor rotation by sending a signal at each turn.

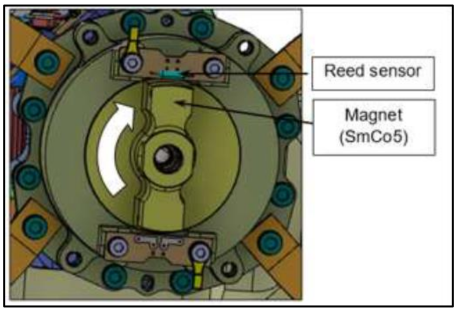


Figure 5:"Turn counters" sensors

The end of stroke function is ensured by the same reed switch module, one pair is placed above the motor, with the magnets placed on the upper telescopic sleeve, screwed on the nut, see Figure 3. This provides a detection of lower position to avoid risk of clash in case of wrong command.

The upper end of stroke is a mechanical end stop, without sensor.

3.5 Thermal control

Heaters ensure thermal control of the actuator to maintain lubricant viscosity in an acceptable range. Thermal straps add a conductive link between the motor and the fixed part to evacuate the heat.

MLI located around the fixed and mobile parts ensures passive thermal control against radiative space environment. Telescopic sleeves are placed around the rotating screw; they are in view of space so they are coated with low absorptivity coating in order to regulate the temperature of the screw. Their other function is to limit evaporation of fluid lubricants in orbit, and to avoid entry of particles in the roller screw or bearings during AIT phase.

A “thermal skirt” consisting in a spherical aluminium and thermal coated part is located above the nut. Its function is to avoid sun entry while allowing rotations between the mobile part and the nut. It avoids the use of a flexible MLI, often difficult to design and which requires mock-up to measure resistive forces and assess thermal leak.

4 Development approach

TELEO is a demonstrator, embarked as hosted payload of a commercial Telecom satellite. It means that the expected life duration is short (2 years) and there is no commercial customer. On the other hand, the schedule is very short with a strong deadline: if TELEO is not ready on time, the host S/C can be launched without it.

So the whole development was driven by schedule, and by the major “do not harm” the host S/C requirement. Technical and performance requirements have been challenged and updated all along the development thanks to the integrated team at system level and its demonstrator mind-set.

The core CPM team was composed by a development responsible, leading the industrial and institutional partners relationship; a functional responsible, defining the functional model and interfacing with system, electronic and PAT architects; and a design responsible, leading the CAD, mechanical and thermal analysts as well as manufacturing and test partners/suppliers.

Each member had several years of experience in space mechanism development and had the right mind-set, hardware oriented. In addition, all team members had an overlap of competences within the core team and with their interfaces. It led to a clear understanding of each other’s needs, a transparency on margins and trust between people resulting in fast decision-making, better and quicker risk anticipation and limited iterations.

In addition, the relationship with suppliers was as simplified and as smooth possible. First, suppliers have been selected based on schedule and proximity. As an example of simplification, the usual IRD/ICD exchange process was not systematically applied. For the customised roller screw for example, a more informal way was used, after 3D file exchanges and technical discussions/iterations, the manufacturing drawings parts where signed by both supplier and Airbus to allow manufacturing. It resulted in less design office work for both sides, smoother and quicker iterations and mutual confidence.

Even internally, the organisation was set to limit the interfaces. For instance, the CAD designer of the CPM was in the same office as the CAD designer of the terminal, facilitating detailed design discussions. Moreover the mechanical analyst of the CPM also performed the analysis at terminal level, leading to mechanical analyses performed directly coupled with the terminal, and no additional margins due to rigid interfaces.

Another consequence of development driven by schedule is the selection of separation materials for HRM; these materials shall have a high friction coefficient, and avoid any risk of cold welding. It was the first HRM assembly developed internally in Airbus Toulouse, friction tests had to be performed to characterise the friction coefficient. For schedule reasons, the choice of material for tests was limited to – literally – off-the-self available materials. It led to the selection of a titanium / aluminium + keronite® couple. Better couple and surface treatments exist in term of friction coefficient, but the selected one allowed to have test results in a few weeks and was sufficient for this application.

More generally, as there is no margin on schedule, it avoids taking any development risk, and so prevents usage of new/low TRL component (material, coating…).

Industrial opportunities were also taken as much as possible. For instance, the HRM order was added to a batch already ordered for AIRBUS. Furthermore, the reed switch module has been developed simultaneously for TELEO and another mechanism in development at this time. For schedule reasons, the models used for flight in TELEO were produced in the batch of Qualification Models, with automotive grade components (resistances). The lot acceptance tests of the reed switch component was on going during CPM AIT phase, so a risk has been taken.

The main partner in this development was COMAT, this company has been selected for Manufacturing, Assembly and Test of the CPM. Beside the long partnership existing between Airbus and COMAT for MAIT of mechanisms, the choice of selecting only one company for overall fabrication was also driven by schedule. Manufacturing and assembly are performed in the same facility. It allows managing priorities of machining according to the needs of assembly, and reorganising quickly in case of out of tolerance and/or need of a part rework.

Work with COMAT was organised as an “extended enterprise” based on trust on both sides. The geographic proximity between AIRBUS and COMAT allowed having many meetings at every steps of the MAIT phase, in order to shorten the loop of non-conformities management and test results validation.

Agencies (CNES and ESA) were also in the same mind-set of: “hardware to be on-time to be mounted on BADR-8 S/C host”. They accepted to optimize documentation for the main reviews w.r.t standard content, compensated by deeper and transparent technical discussions when needed.

5 Development plan & test sequence.

5.1 Development plan

At the kick-off of TELEO, the concept of the CPM already existed and a breadboard of CPM actuator had been manufactured and tested about a year before up to TRL 3-4. Functional tests of a 1-axis breadboard in laboratory environment had been performed. A beginning of 3-axes breadboard phase was initiated few months earlier in the frame of a GSTP ESA activity DOCS (Deep Orbit Communication System) for ESA. This DOCS development was stopped to allocate resources to FOLC2 and TELEO activities to design, manufacture and test a CPM flight model to be integrated within a demo-flight terminal rather than developing a new CPM breadboard.

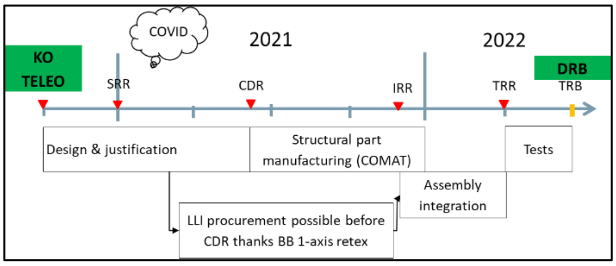


Figure 6: Development plan

The CPM development plan was comparable to a PFM one (Proto-Flight Model), but oriented on Hardware delivery and supported by regular risk & opportunity assessment. It led to:

- A limitation of reviews (no PDR for example) compensated by pragmatic risk management;
- A design phase minimized by re-using already fabricated & tested breadboard key components and functional architecture.
- Risk taken on long lead items procurement. Mostly based on COTS, they were purchased in advance of full justification, to cope with AIT schedule, being aware of the resulting design constraints.
- Complex functional tests and associated setup were anticipated very early in the design & justification phase, in co-engineering between design and AIT teams.
- Work share was cut as simply as possible, with clear interfaces and limited interdependences: design & justification by AIRBUS and M-AIT by COMAT.
- “Hardware oriented” way of working: Documentation was limited to the minimum required to reach the objective, with only PowerPoint slides. Sometime, documents were finalized after the milestone if needed to keep the hardware schedule, provided risks were fully assessed and managed. E.g. procurement launched before CDR, internal delivery before test reports writing…

This allowed a development from TRL 3-4 to flight demonstration in less than 2 years (Q4 2020 to Q2 2022) between kick-off and delivery for integration onto the TELEO terminal in a schedule compatible to be integrated on host S/C.

Only a “DM” (Demonstrator Model, similar as PFM – Proto Flight Model) was manufactured, without qualification model. This production of only one model was possible due to the fact that life test was not required for the demonstrator. Its leads to a significantly cost and lead time reduction of the AIT sequence of the demonstrator, but does not fully qualifies the mechanism on ground.

5.2 AIT sequence

The CPM test sequence was defined in order to be integrated with the overall test sequence of the terminal. With the objective of testing everything that was not possible to test at terminal level, and if possible avoid any redundant test.

The test sequence begins during mechanism integration, before tests performed at 1-axis level. Then the 3 actuators are assembled together with dummy mobile part and mechanism performance and environment test is performed. Finally, the test sequence is similar to a PFM one, with mechanical environment (Quasi-Static, Sine, and Random), HRM release test, TVAC, and performance tests between each environment test.

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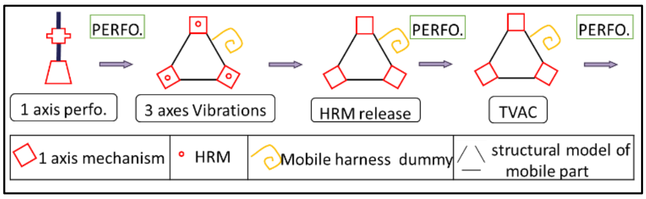

Figure 7: CPM Demonstrator Model test sequence

5.3 Components tests after manufacturing

Characterisations of the main components has been requested to their manufacturer with several objectives:

- Characterise performance to allow allocation of each specimens, and/or to compare this performance with measures after integration
- Detect any anomaly as early as possible.

Frictions of the ball bearings, irreversibility of the roller screw and performances of the motor (R, H, Kt) have been measured by their respective manufacturer.

This allowed allocation of the ball bearings, and in particular highlighted a good side effect of having the same ball bearing references. As their friction performances have different influence on the motorization margin based on their location, some bearings which would have been rejected for motor bearing were installed at foot pivot and gimbal locations.

5.4 Tests during integration – 1 axis

With the same idea of detecting any anomaly as early as possible, each component is tested just after its integration in the 1-axis actuator. Each bearing start-up torque is measured, even during its integration. This is a simple and indirect way to assess correct mounting with preload conditions..

The motor bearing and roller screws was subjected to a dry and viscous friction measurement, with a “free fall” test. An inertia and a ground encoder are mounted on the shaft launched by hand. Post processing of speed decreasing gives the dry and viscous frictions.

Motor performance has been measured with the same setup, with “free fall” tests with motor in open closed circuit. It measures motor dry friction and installed torque constant (thanks to back EMF), compared to the one measured by manufacturer.

At the end, all contributors to motorization margins are measured individually and the major ones were significantly better than expected.

Functional tests have been carried out in 1-axis configuration in a test setup inherited from breadboard, which allows performing functional tests in 0.g condition. The ground encoder used for free fall tests was used again in this configuration.

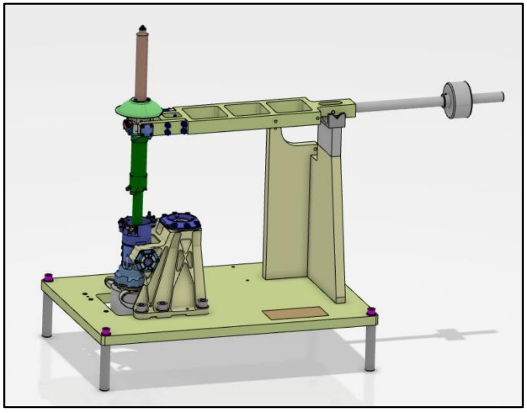

Figure 8: 1-axis 0g functional test setup

The tests performed on this set-up are electrical tests, grounding, sign test, motorization margin, end stop test, telemetry test (reed switches), repeatability.

One anomaly in this sequence is a slipping of the end stop detected on one specimen. After investigation, the root cause was the probable presence of grease lubricant of the screw under the end stop. After dismounting and cleaning off all actuators, one very slow slipping was detected on one specimen. It has been accepted as is, based on a worst-case assessment of the number of end stop contacts during the life of the demonstrator.

5.5 Performance tests – 3 axes

For 3 axes tests, a dummy mobile part of the terminal is integrated between the actuators.

Before and after each environment test, a sequence of functional tests was performed to monitor any drift.

These tests were defined focusing on the test set-up capability with regards to the functional requirement. No detailed test prediction has been produced and the number of test cases have been limited to the minimum needed for schedule reasons. For the same reason, minimal post-treatment was made to validate a test session and go to the next one. Usually, each test was validated directly after the measure by an AIRBUS responsible present in COMAT facilities during the tests. The detailed and complete post-treatment was made later on.

The first 3-axes test is threshold voltage, here used to monitor any drift of frictions. No significant evolution is noted.

Second main test is pointing accuracy. It consists in commanding the CPM in order to have the mobile part pointing towards an azimuth and elevation, measure the orientation using a laser tracker and compare the objective pointing vs the realized pointing. In order to be in quasi-0.g condition, the dummy mobile part was balanced in order to have its center of mass at the center of the 3 gimbals of the mechanism, so that gravity does not affect the orientation of mobile part.

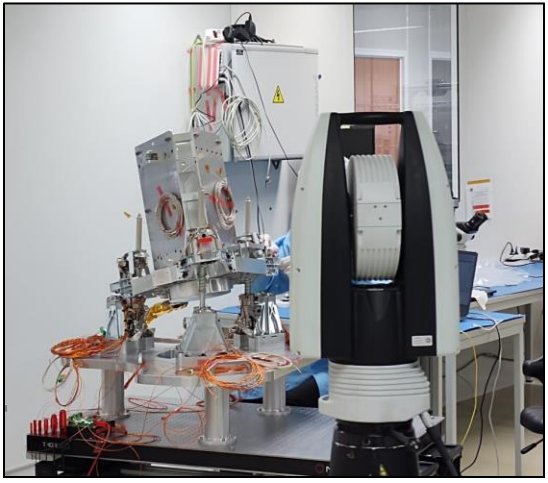

Figure 9: Pointing accuracy test setup

Raw results showed worse accuracy than expected but with most errors in azimuth, and in the same direction, by 14 mrad. FEM Analysis showed that the cantilever foot pivot under gravity gives a rotation of 12 mrad. By correcting the measures by this 12 mrad azimuth rotation, the pointing accuracy was <450 µrad worst case, after mechanical test.

Last measure is stability. The test consists in commanding a movement representative of scanning phase (1mrad in 0.6s) and measure the resulting rotations using a 3 beams interferometer.

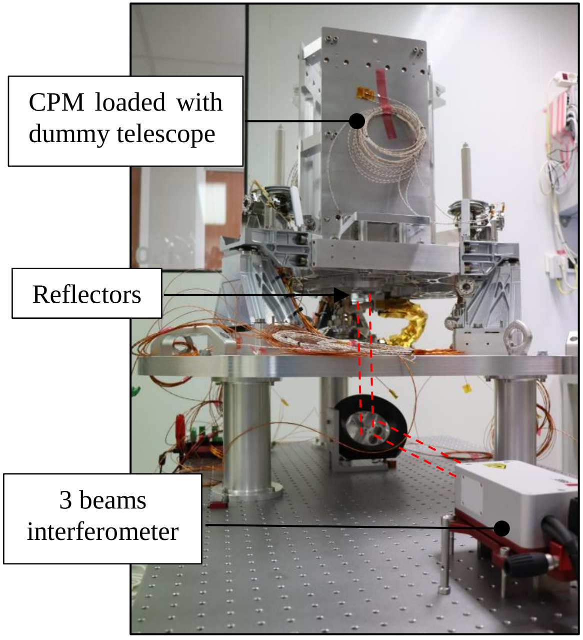

Figure 10: Stability test setup

The oscillations after movement are measured and post-treated in order to obtain the maximum amplitude, the frequencies and the damping.

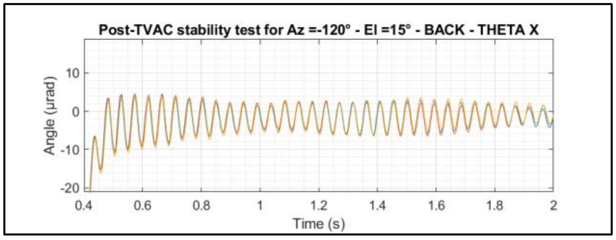

Figure 11: example of stability test result

These measures are used to build a dynamic model and adapt the parameters of PAT algorithm.

5.6 Mechanical environment test & HRM release

CPM loaded with a Mass, Centering and Inertia representative dummy has been submitted to Quasi-Static; Sine and Random environment.

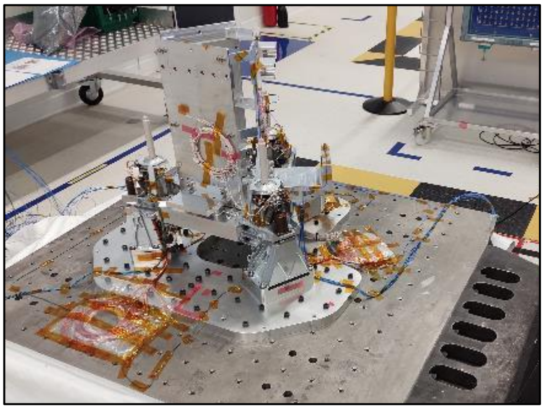

Figure 12: CPM loaded with dummy on shaker

The main issue in this test was a mechanical mode of each actuators occurring at a lower frequency than predicted by 12%. FEM has been refined and matched with the frequencies measured by a few percents. This new model has been then used for prediction of vibration test at terminal level.

After vibrations, the three HRMs have been released in order to measure shocks emitted towards the Fixed part (Satellite) and Mobile part (telescope, focal plane). This leads to lower shocks than expected, of 80.g maximum injected towards S/C and 540.g towards mobile part, at its interface.

5.7 Thermal Vacuum test

For TVAC, the CPM has been unloaded of the telescope dummy mass, for accommodation reasons inside the chamber, and to reduce temperature transition time.

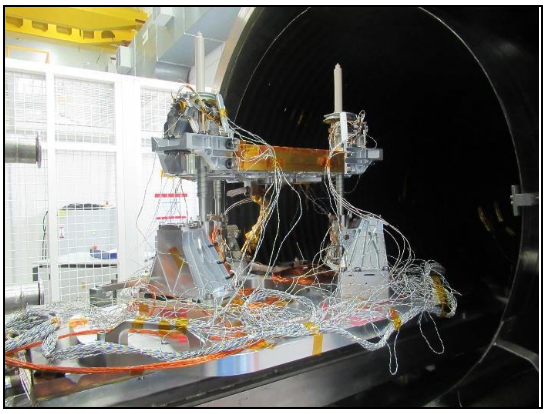

Figure 13: CPM in front of TVAC chamber

The number of thermal cycles has been limited at three, instead of the planned 8 cycles to reduce lead time. No thermal balance has been performed, but some test points have been set specifically to measure conductance of the thermal straps around the motor.
Motorization margin has been measured at hot and cold operational temperatures.
This test showed no major anomaly.
After TVAC, the thermal model was refined on the area of the motor and thermal strap to improve modelization of the thermal flux and cope with the observations. This modification was motivated by a better than expected conductance on the thermal strap and the late request of the system to increase the duty cycle of the motors, from 10% to 33% of the time (i.e. increase mean dissipated power). TVAC measurement and improved thermal model demonstrated the good thermal behaviour and therefore allowed to take into account this late evolution of need. This late evolution was related to the fast development of TELEO, not only for the mechanism but also for overall system and sub-systems.

6 Lessons learned

Development with less reviews, reduced documentation but with sufficient technical maturity is possible in the context of a demonstrator where equipment availability and lifetime are less critical than operational applications. However, it requires a climate of trust and transparency between all project stakeholders: Agencies, partners, suppliers and internal customers.
With COMAT, the MAIT partner, a strong cooperation was set all along the project. From design co-engineering session to Airbus presence in clean room during AIT phase: we worked in extended enterprise mode.

It also highlights the importance of internal R&D, without the Airbus-funded 1-axis breadboard, this development wouldn’t have been possible.

Technical lessons have been learned, either from positive surprises (low shock HDRM, friction of roller screw) and from bad surprises (FEM bearing modelization, end stop slipping, 1.g setup for pointing accuracy). All this return of experience is now applied in the development of the CPM for CO-OP and more generally other mechanisms in development within Airbus.

On May 27th 2023, a Falcon 9 launched BADR-8 satellite. A few hours after separation, the 3 HRMs of TELEO were successfully released and the CPM placed the mobile part in a safe position to avoid sun entry in the telescope during earth orbit raising phase. At the time these lines are written, TELEO is waiting to be in geostationary orbit to start its demonstration.

7 Conclusion

The development of this demonstrator was an enriching experience technically and on human level.
From COMAT and Airbus perspective, TELEO was an opportunity to develop a **versatile, scalable, lightweight and industrially friendly mechanism**. It is a big step to **start a new product line**, today in development with CO-OP and TeQuants for SatCom and Quantum applications.
This new space working approach deserves to be implemented and deployed on further projects.
The flight demonstrator approach is an enabler for **derisking and fast maturity increase** of a product and/or a sub-system.
It gives the possibility to consolidate design justification analysis and validation plan.
It offers quick flight performance return of experience for design optimization and improvement of the product line.
However, there are limitations; a flight demonstrator does not replace a complete qualification.

8 Acknowledgement

The CPM team would especially like to thank:
- **ESA** for the funding of FOLC2 ARTES and **CNES** for DYSCO contract and their continuous support.
- **Airbus UpNext** for the breadboard funding.
- All people; suppliers, partners, integrators, analysts, managers, experts, who provided support to ensure the success of this challenging development.

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