TESTING OF BEPICOLOMBO ANTENA POINTING MECHANISM

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ABSTRACT

BepiColombo is an ESA mission to Mercury, its planetary orbiter (MPO) has two antenna pointing mechanism, High gain antenna (HGA) pointing mechanism steers and points a large reflector which is integrated at system level by TAS-I Rome. Medium gain antenna (MGA) APM points a 1.5 m boom with a horn antenna. Both radiating elements are exposed to sun fluxes as high as 10 solar constants without protections.

A previous paper [1] described the design and development process to solve the challenges of performing in harsh environment.. Current paper is focused on the testing process of the qualification units. Testing performance of antenna pointing mechanism in its specific environmental conditions has required special set-up and techniques. The process has provided valuable feedback on the design and the testing methods which have been included in the PFM design and tests.

Some of the technologies and components were developed on dedicated items priort to EQM, but once integrated, test behaviour had relevant differences.

Some of the major concerns for the APM testing are:

- Create during the thermal vacuum testing the qualification temperature map with gradients along the APM. From of 200ºC to 70ºC.
- Test in that conditions the radio frequency and pointing performances adding also high RF power to check the power handling and self-heating of the rotary joint.
- Test in life up to 12000 equivalent APM revolutions, that is 14.3 million motor revolutions in different thermal conditions.
- Measure low thermal distortion of the mechanical chain, being at the same time insulated from external environment and interfaces (55 arcsec pointing error)
- Perform deployment of large items guaranteeing during the process low humidity, below 5% to protect dry lubrication
- Verify stability with representative inertia of large boom or reflector ~20 Kgm^2.

1. DESIGN DESCRIPTION

The HGA-APM is an elevation over azimuth mechanism with hollow actuators which house dual rotary joints for X and Ka band. Dry lubricated CDA gearhead motors motors with a 120:1 ratio drive the mechanism.

The motors are meshed through a preloaded antibacklash pinion to a main wheel also dry lubricated. Beryllium substrate Inductosyn transducers provide the position feedback.

Figure 1 HGA EQM APM without shield

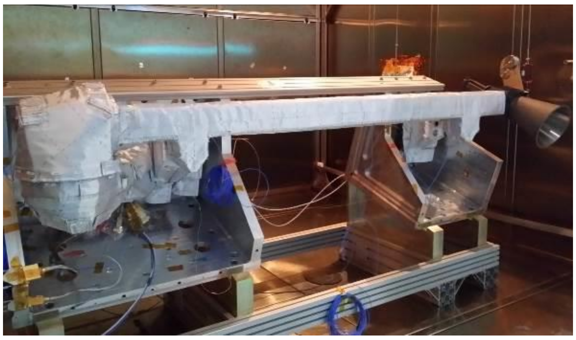

Figure 2 MGAMA: APM, boom and horn

The azimuth twist capsule connects the elevation stage elements to the Spacecraft recovering the azimuth rotation of 360º. The elevation twist capsule rotates the excitation cable of elevation inductosyn rotor.

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The APM is surrounded with a protective shield that homogenizes temperature internally by radiation and holds the high temperature MLI to protect the APM from the external environment. The external aluminium protection is connected by radiation to the interface of the spacecraft heat pipes creating a link that may transfer up to 50W without contact.

The hot temperature MLI was developed by RUAG Space Austria, based on a thermal shield of Nextel® fabric with titanium and aluminium internal layers, in some cases or areas with VDA Polyimide internal layers. The thermal insulation is attached to the mechanism with titanium stand offs and with Inconel wires at the countour labyrinths.

Both HGA and MGA APM qualification models have been tested, and for the MGA also at main assembly level (called MGAMA) with the horn, boom and hold-downs.

2. THERMAL VACUUM TESTING

Both HGA and MGA APM have a gradient between their exposed shield and antenna interface and their thermal connection to the spacecraft thermal control heat pipes.

In the output to MGA boom or HGA reflector the temperatures are above 200ºC, in the protective shield they reach 200ºC while the heat pipe interface are cold, thus the mechanism works with a heavy gradient along it which needs to be tested.

The radiofrequency rotary joints have an internal dissipation that is relevant provided that they are made of Titanium with low thermal conductivity, that means that in operation heat spots appear while especially for Ka band the RF performance is sensitive for internal shape changes. That hot case performance may only be tested with the Radiofrequency power applied though it.

The challenge was to go beyond TV chamber temperatures and to obtain this temperature map of the APM with high gradients. A thermal control system controlled this during the thermal vacuum and thermal balance test. In the EQM model, plates with heaters are attached in areas to simulate solar heat flux. The heaters are activated though a control system that provides pulse width modulation of the heat with control loops based on thermistors reading.

The PI control loops provide optimized and controlled power supply to achieve the required temperature in each area in reduced time at a known rate without overshoot. The power input in each area is known in time domain with the characterization of the heaters in temperature. This is very helpful for the thermal model correlation. The heater plates are attached bellow the MLI in order to have the correct power balance and reproduce the thermal behaviour during cooling down. For PFM the MLI cannot be reassembled because it is very sensitive. The temperature map is achieved with IR lamps around the shield compatible with the motion and without MLI.

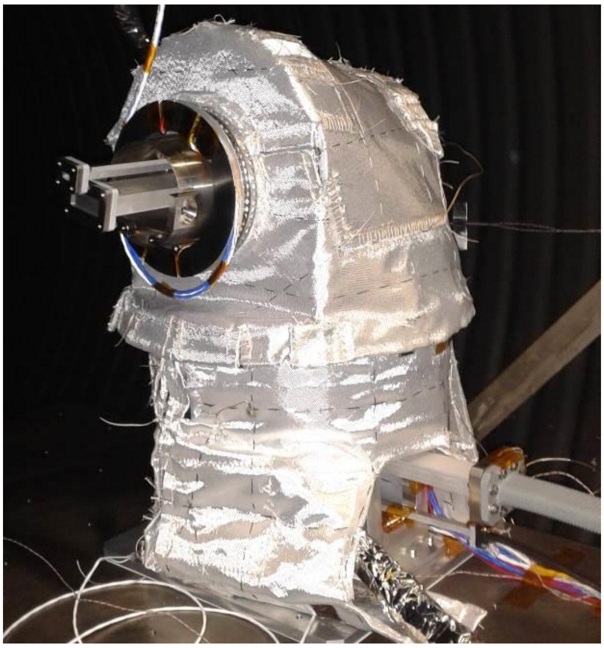

Figure 3 HGA EQM APM in TV test configuration with MLI and RF loads and input Waveguides

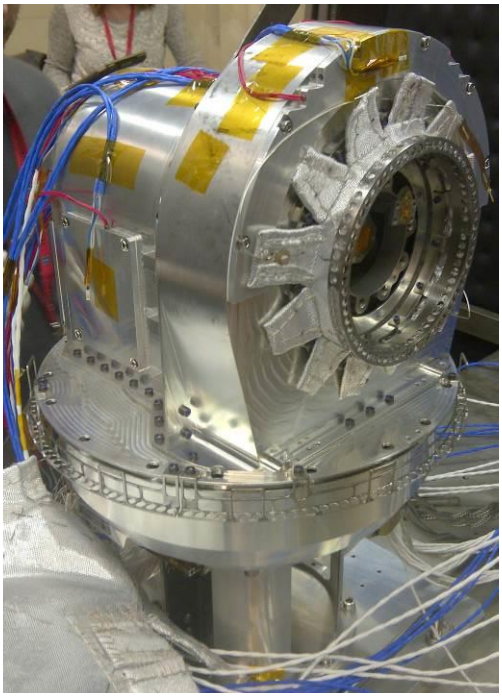

Figure 4 HGA APM instrumented with heater plates and thermistors outside the shield

The spacecraft heat pipes are simulated with aluminium elements attached with thermal filler to both the APM and the chamber regulated plate. Those interfaces are also controlled by heaters of the test thermal control system.

A reflector simulator provides the boundary temperature to the elevation output shaft with heaters. It requires a movable heater and thermistor connection in the elevation stage compatible with the degree of freedom. There is a bundle in the front of the mechanism for that purpose. The elevation simulator is black anodized to follow the temperatures of the chamber shroud when not heated to simulate the cold cases in which the antenna interfaces are colder than the APM.

2.1 Radio frequency measurement in temperature

RF tests in thermal vacuum conditions are, in general, quite complex, due to the difficulties to perform proper calibration of the set up. However, it is much more complex in this case, because the APM RJA has 2 bands (X and Ka) and the unit is rotating while measuring, making not feasible to route the RF output of the APM to go out of the chamber. Hence, only one port measurements can be accomplished and that provides only return loss measurements, what allows testing both bands ant the same time using one Vector Network Analyzer (VNA) port for each band.

The chamber is equipped with dual band feed-through for X and Ka band, and flexible waveguide routing along the chamber which ends in straight waveguides before interfacing the rotary joint inlet.

Calibration of the set up (VNA + cables) is mandatory. So, previously to start the test three cycles must be performed to allow characterization of the three standards needed for the process: A matched load, a short circuit and a quarter of wave+short. Once the set up was calibrated for both bands, the APM is ended with a RF matched load based on SiC absorvers at each of the output flanges.

In this scenario, the APM is cycled and moved and the Return Loss is not only continuously monitored to observe any variation, but specially tested at 10 specific RF critical azimuth & elevation combinations previously identified during the functional tests. In this way, it is fully ensure no degradation occurs during the thermal vacuum cycling.

However, insertion loss variation in temperature is has to be measured . To do so, for the last cycles of the cycling the APM was ended with an RF short plate at each one of the RJA RF elevation flanges (one per band). Since in these conditions all the energy is reflected, it can be possible to derive the Insertion Loss form the Return Loss obtained results, applying time gating post processing and dividing by two.

Finally, it is worth to mention the importance of keeping the set-up completely fixed during the all the RF test sequence, because any minimum variation will affect to the accuracy (much specially at Ka band).

To verify the effects of power in the rotary joint from thermal dissipation point of view power amplifiers were used for X and Ka band isolated from the measuring system through RF switches. During one of the thermal vacuum cycles performed with the short circuit attached to the output test a power slightly higher than one half was introduced in the APM in order to create the internal thermal dissipation of the rotary joint with the forth and reflected waveguides. After one hour of power the RF performance was measured again showing no sensitivity to self heating.

This was also performed with short duration with the nominal current and the RF load in order to check sensitivity but without overheating the load.

In general RF results were very representative in X band but showed higher uncertainty in Ka band, which is more sensitive to set-up variation during the test. As a lesson learnt in the PFM the testing on Ka band was performed with rigid waveguide routing with one of the waveguide in copper to be adapted to the final position and guarantee low CTE load.

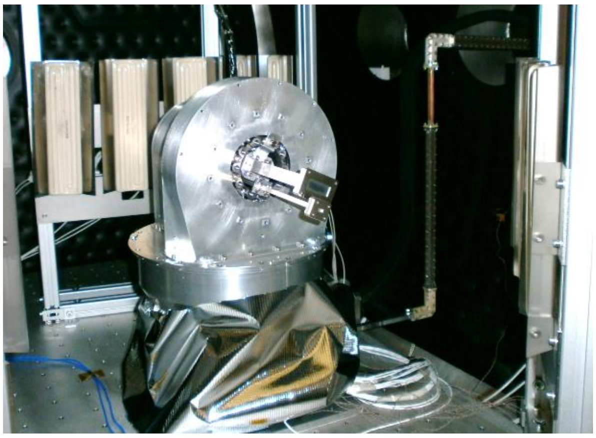

Figure 5 HGA PFM in TV test with IR lamps and fixed Ka waveguides

2.2 Thermal pointing stability

Thermal pointing stability was performed twice. First, during EQM campaign thermal vacuum test. Behind the chamber a theodolite followed through and optical grade window the reference cubes in the output of the APM during thermal excursions and during some ranges of pointing.

Figure 6 Theodolite, window and alignment mirror

The theodolite was able to see the mirror in several positions in that way the complete angular behaviour, that is azimuth and elevation in front and lateral view was tested during different thermal cycles.

As the equipment was linked with stiff supports for the heatpipe simulation, the expansion of those elements disturbed APM behaviour. Even if the thermal interface of the APM is has certain flexibility with respect to the main structure of the APM, it introduced a significant force. Additionally this cube was placed close to a heater that may have distorted the local thermoelastic expansion.

For the PFM those distortion were solved in a specific test with an isostatic support of the equipment. The temperatures were achieved with IR lamps instead of heaters. The gradient in the equipment is created thanks to the joint with copper flexible braids between the heat pipes IF and the chamber base plate

Figure 7 Isostatic support, thermal braids and IR lamps

Another reference cube was attached in a way that the theodolite may point both without re-configuration. In this way the theodolite could follow the displacement of both APM and the chamber support plate in the same time and get the differential value as thermal distortion of the APM only.

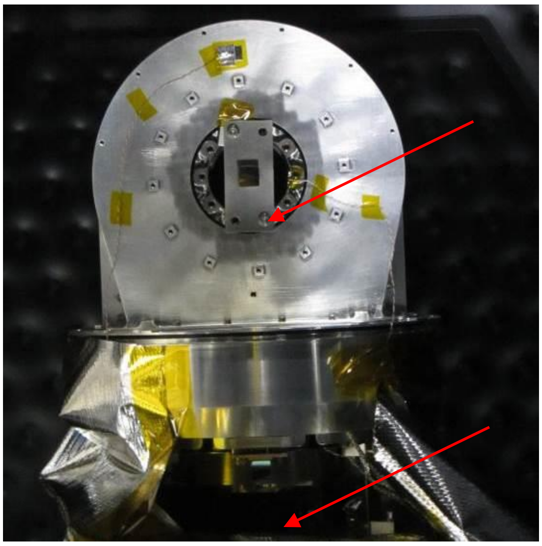

Figure 8 Optical cubes as seen from the measurement window

As a result the APM shows very small thermal distortion with the heavy gradients along it.

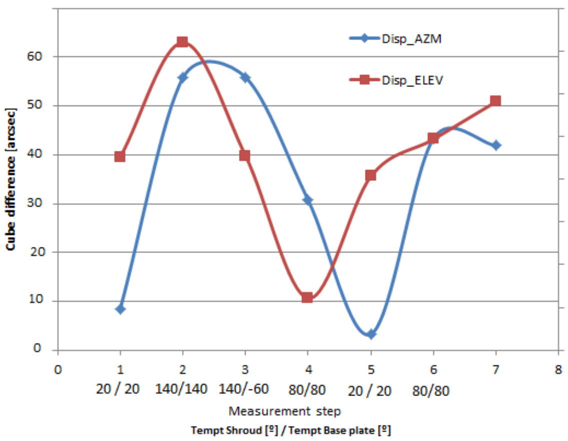

Figure 9 APM Thermal distortion between different measurement temperatures

2.3 Reed switches drift with temperature

Each inductosyn transducer has two sensors, that is, two sine and cosine systems per transducer. The N and N-1 cycles per revolution patterns may be used in “nonius” configuration to obtain fine and coarse information and have absolute angular position. In the BepiColmbo APM they are used as main and redundant connected to main and redundant electronics without cross-strapping, thus there is just reduced absolute information repeated N times, that is, N cycles of 360º/N degrees.

During initialisation, spacecraft on board computer re-boots or re-configuration an external reference indicates which of the N cycles within the 360º is the current one.

High temperature reed switches provide that external reference without contact. Through their operation in temperature is ensured during the thermal excursions they showed a significant drift of the switching on position. The shift was enough to risk the reference search strategy. That triggered a new need of screening the switches by their sensitivity to temperature prior to their selection and assembly in their supports, and a characterization in temperature campaign to validate them.

2.4 MGA elevation twist capsule

During the MGA-APM Thermal vacuum testing the elevation stage got blocked almost at the end of the test. After inspection it showed that the foil supporting the cables had contacted the support of the switches and got bent over it.

The twist capsule had some gapping during its function and as soon as it was enough to contact the elevation switch support it lost its configuration. The foil and cables was too sensitive to loss of configuration.

A redesign was included to route the inductosyn rotor cable through the hollow shaft around the elevation waveguide of the rotary joint. That concept was validated in a dedicated model which was subjected to vibration and shock test and then life cycled in climatic chamber in temperature above the required number of cycles and showed a robust configuration. A parallel testing and samples inspection of the inductosyn mu-metal braid showed that there was no risk of cold welding for the braid strands for the level of contact stress of this application. Also the concept was applied successfully in HGA and MGA and tested in TV tests.

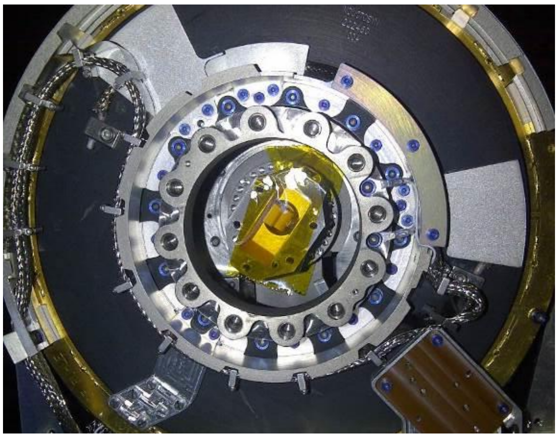

Figure 10 MGA Twist capsule after contact with switch assembly

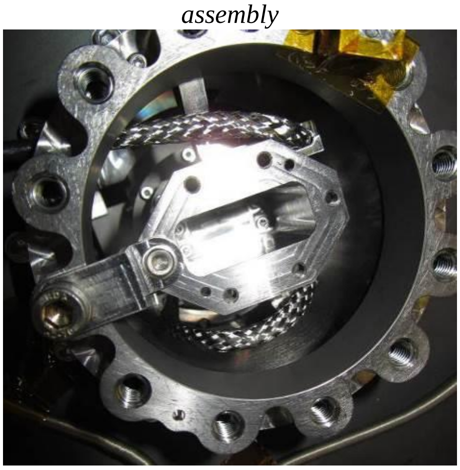

Figure 11 Hollow shaft elevation twist capsule

3. VIBRATION AND SHOCK TESTS

During the HGA-EQM vibration test the position sensor was monitored in order to check the behaviour of the actuator and know if steps are lost in the gearhead motor. The sensor demonstrated that there are no steps lost during vibration.

During the last part of the vibration testing the MLI got damaged in the contour of the APM. The MLI was retained to the contour by Inconel wires those wires were able to tear the holes in the ceramic and metallic layers creating lot of debris during the test. The performance after the vibration were correct but a slight frequency shift was observed due to the decoupling of the MLI layer which has a relevant mass for first frequency which is the oscilation to the shield that holds it.

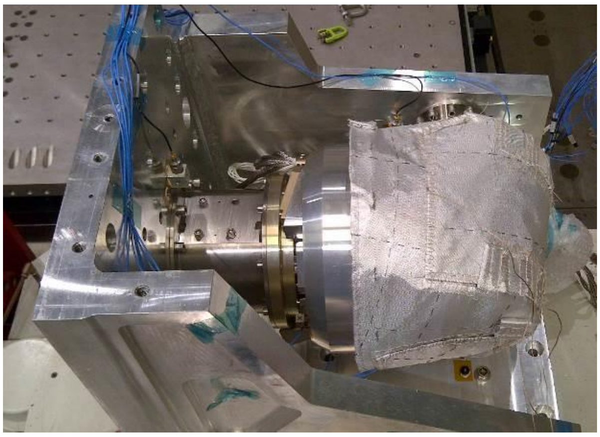

Figure 12 HGA APM vibration test

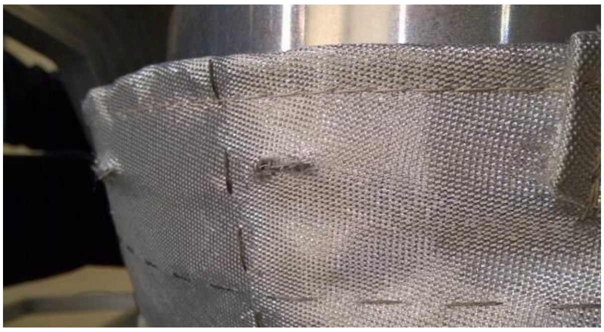

Figure 13 Damaged area of MLI in the contour

In order to reduce the stress in the holes load spreaders were used, The load spreaders are thin titanium plates with Nanovation ceramic coating which distribute the load of retention of the wires.

Figure 14 . Coated loadspreaders

Dedicated comparative test were performed on a sample of MLI retained with and without load spreaders. The sample was exposed to several runs of sine and random increasing the input levels. It was not possible to break the attachment area with the load spreaders. Afterwards the sample was inspected layer by layer to check which layers were affected and the status. There was no relevant damage in any layer with the new solution. That was later also confirmed with the vibration of MGAMA which had this solution implemented.

In the shock test the motors are powered as during the flight the most relevant shock are produced by separation events that take place after the antenna release. However the sensor was not monitored during the test and there is no data available to know if steps are lost during the test of.

4. HGA-APM and MGAMA FUNCTIONAL TEST

4.1 Testing in dry conditions

The MoS2 lubrication of gearhead requires running them in dry conditions below 5% of humidity. That is typically achieved by operating them in closed purge boxes with cable feed through or in vacuum chamber. However those solutions are not valid or compatible with the measurement of radiofrequency performance in two ports, that is with waveguide connection in both input and output, and neither compatible with deploying a long boom with hanged with a zero-g device.

To do so a rotating purge box was designed which is a closed envelope with gas inlets installed to be purged continuously with N2 supply but with capability of rotating in both azimuth and elevation. Plastic enclosures have circular slots that allow the movable part to rotate with respect to the fixed part.

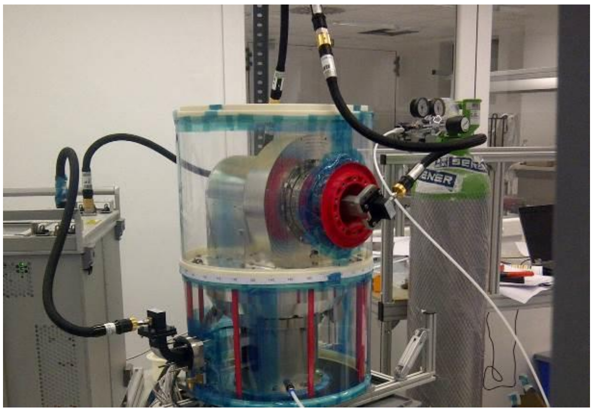

Figure 15 . Purged movable enclosure with RF ports

Elevation shaft is aligned with the output with a set of bearing housed by plastic parts making a labyrinth that may be sealed during the purging previous to motion.

That elevation output allowed the connection to the rotary joint output of radiofrequency ports linked to the network analyser.

For MGAMA the elevation closure is clamped over the boom, so all the boom is outside of the purging box. That allows the connection to the hold-down areas and the connection to the zero-g device.

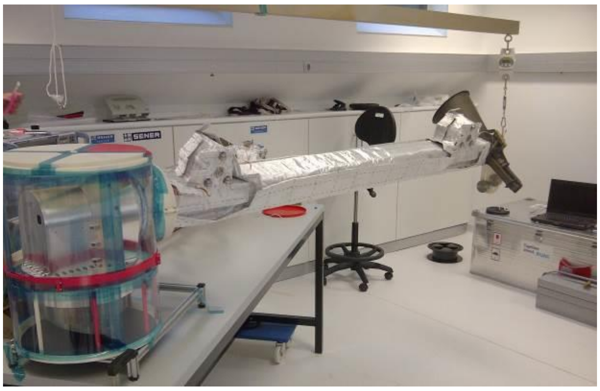

Figure 16 . Movable purge box for MGAMA during functional test with zero-g

The zero-g device allows rotation of the boom in its axis (elevation) and deployment rotation (azimuth). The first degree of freedom is enabled by bearings located at the tip of the boom in the horn antenna. The second degree of freedom is achieved because the self compensating beam hangs from a thin rope with a turn buckle in its hanging point.

4.2 Stability and pointing accuracy

Stability and pointing accuracy test have been performed with the HGA APM EQM and PFM, the pointing is measured externally though a laser tracker which follows targets located on a long bar and provides coordinate which are later correlated and compared with the internal measurement of the APM position sensor.

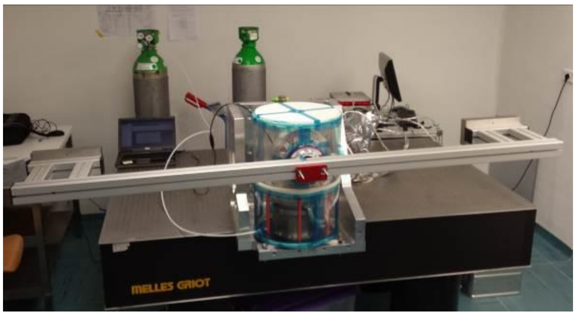

Figure 17 . Stability test set-up

For the stability a representative inertia of the HGA reflector of 20 kgm2 is simulated with an aluminium structure with weights. The first frequencies are analysed and tested to match that of the reflector. The reflector simulator has its centre of gravity in the intersection of azimuth and elevation axis. As a results there are no torques applied to the APM by gravity. Several trajectories are applied with logarithmic increasing speeds in both directions and degrees of freedom to verify that the control loop is stable and there are no major noise amplifications.

5. LIFETEST

During the development of the project several lifetest were performed to verify the mission needs are met. In the frame of SENER participation three motor test took place, which were already reported in a previus paper [1]. A first test achieved 7 million motot revolutions in ambient and 2.8 million in cold before failure. Mitigation actions were taken to avoid cold temperature by self heating and to increase general smoothness drivers of the gearhead motor.

Following test achieved 17 million motor revolutions at ambient temperature, and the third focused on high temperatures achieved 18 million motor revolution (9 hot and 9 ambient).

The cycle figures achieved were enough for the mission definition, through they did not provide large margins. Some improvements were implemented inside the gearhead motors in tolerances, workmanship and configuration.

The lifetest of the qualification model was foreseen in the MGA APM because it has the two motor configurations, that with straight gearhead and the one with right angle gearhead motor .The lifetest was postponed due to schedule constraints to assemble the model in the spacecraft for solar simulation, and the issues of the thermal vacuum cycling in the elevation twist capsuled.

Once returned the equipment was refurbished to replace the damaged elevation twist capsule with the new design tested in a specific test item.

The vibration test was repeated at APM level, and the APM was submitted to a shock test with gearhead motor powered. Then the thermal vacuum cycling was repeated completing the 8 cycles without major issues. After that the life cycling was started in cold conditions in both azimuth and elevation actuators.

As an outcome of previous failed lifetest a pre-heating strategy is followed in the gearhead motors to avoid cold temperatures in the gearhead. There is a one hour heating by holding the motor at the maximum current allowed by the drive electronics (700mA) during that hour the motor winding reach temperatures above 20 degrees and the gearhead interface temperature of nearly zero degrees.

During the lifetest the current is limited to 250mA in order not to allow the motors to produce torques above their rating for life and to allow early detection of increase of resistive torque which would allow exploring and inspecting the problems before they are dramatically disseminated through the whole mechanism.

After just 0.7 million motor revolutions the azimuth gearhead motor stopped, a verification of the current showed that currents above 200mA where required, and little motion was achieved.

For elevation the test was resumed and continued operating up to 4.6 million motor revolutions.

Elevation inspection showed some friction areas but not adding torque above the nominal rating. Threshold torque patterns at APM and at gearhead motor level pointed to a failure of the output stage.

For azimuth stage inspection in the APM was first subjected to a tomography inspection, trying to find problems particularly in the twist capsule which may change its position during disassembly. Nothing was found, neither during APM disassembly.

During gearhead motor inspection the gearhead motor showed a different wear pattern in the pinion that previous experiences. Typically wear and depletion of the MoS2 was found but with more regular pattern. Misalignment of the motor was a possible contributor.

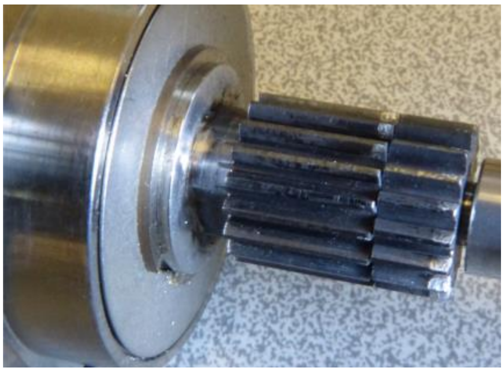

Figure 18 . Azimuth output pinion (main & anti-backlash) wear pattern

Figure 1. Elevation output pinion (main & anti-backlash) wear pattern

A following dimensional inspection of the azimuth housing showed just slight lack of coaxiality of the motor support and the anti-backlash support bearing (0.12 mm) but in radius compatible with meshing. However internal constraints between main and ABL pinion may have not allowed the absortion of that mismatch and may have created and inclined ABL configuration.

Other potential factors considered for the life failure are:

- Shock testing in powered conditions which may have created very high peak torques. As a mitigation action it was agreed and seen possible to consider the APM unpowered during the event creating the shock
- Long stall test against end stops, performed both at gearheadmotor and at APM level, which may be reduced in accordance with FDIR logic.
- Double qualification vibration test campaing in this unit

As a way forward in addition to the mitigation action mentioned above is the use of hybrid lubrication adding grease over the MoS_2. This kind of application has also been applied in other application of this mission.

However for the high temperatures the APM requires a very high temperature grease. Braycote 803 is seen as the most promising solution and would be investigated and validated to check if it may have auto catalytic effects as those reported in [2] or if it may improve the situation as the case of Braycote 601.

An early test with the two spare gearhead motor that follow the above mitigation actions and with hybrid and dry lubrication will provide the comparison and way forward.

Then a qualification lifetest will be done with the selected solution in new gearhead motors with part produced compatible with both options.

6. REFERENCES

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