HIGH TEMPERATURE ANTENNA POINTING MECHANISM FOR BEPICOLOMBO MISSION

Second Part: Test results

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ABSTRACT

This paper describes the high temperature tests results for a Breadboard model two axis Antenna Pointing Mechanism (APM) with dual frequency (X-Ka bands) Rotary Joint (RJ).

The APM is developed by Kongsberg Defence and Aerospace and BAE Systems, in the frame of the ESA Bepi Colombo mission to the planet Mercury.

The APM with an integrated RF Rotary Joint was tested for:

- Mechanism friction characterisation.
- Functional and RF performance in air at RT.
- Random Vibration.
- TV cycles (6 ea) hot at +250ºC and cold cycles down to -30ºC with functional and RF tests and life endurance for APM 10.000 cycles.

The test were performed successfully and the APM proved that the chosen technology and mechanism design will function in a 250ºC vacuum environment.

The X-band performance was close to the analysed performance regarding insertion and return losses as well as the strict transmission phase stability. The Ka-band channel was found to be slightly mistuned.

The APM dynamic pointing accuracy was within ±0,01º as required. The gear hysteresis when reversing the drive direction was shown to be larger than expected.

1. BEPI COLOMBO APA

1.1. Design

The Antenna Pointing Assembly (APA) shall steer the BepiColombo High Gain Antenna reflector in azimuth and elevation axis for precise pointing towards Earth during the satellite cruise, but primarily during the 2 year Mercury orbit operational period.

The APA consists of two almost identical Antenna Pointing Mechanisms (APM) mounted orthogonally onto each other. Each APM consists of a drive unit and a dual channel RF Rotary Joint in X and Ka-band.

The main design driver is the high temperature conditions during Mercury orbit combined with precise pointing dynamics and RF performance.

1.2. Thermal requirements

The APA will see direct sunlight, which is about 10 times higher than for Earth orbits, and also the reflected and radiated heat from the spacecraft panels, antenna, Mercury as well as conducted heat from the antenna interface.

The base line thermal control system is chosen to be a combination of using Multi Layer Insulation (MLI) and Optical Solar Reflectors (OSR).

With such a system providing heat reflection from the APM stepper motors and also RF Rotary Joints, which generates internal heat dissipation, the qualification temperature for the APM elements and structure has been calculated to be below 260ºC.

The APM Breadboard has therefore been tested up to 260ºC in TV.

1.3. Pointing Requirements

The APA needs to continuously steer and point the antenna towards Earth in a predetermined profile with speeds ranging from very slow (±0,01º/s) and up to ±0.2º/s.

In order to maintain a high overall antenna gain factor, the error budget for the APM is very tight requiring an absolute pointing accuracy of each mechanisms of maximum ±0.01º. This puts high demands on friction, stiffness, tolerances and backlash in the drive system when combined with the need to operate in a extremely wide temperature range.

Proc. '12th Euro. Space Mechanisms & Tribology Symp. (ESMATS)', Liverpool, UK,
19–21 September 2007 (ESA SP-653, August 2007)

1.4. RF Requirements

Magnetic and gravitational field variations around Mercury shall be measured by a Radio Scientific Experiment. The variation in the phase shift of the received RF signal shall be accurately measured and used to calculate the MPO position deviations. This puts high demands on a phase stable RF transfer through the High Gain Antenna including the APM RF Rotary Joints.

Also, the losses must be minimized for achieving the overall gain requirement for the system.

Therefore the APM Breadboard was tested for phase stability and losses during the test campaign.

2. APM BREADBOARD

2.1. Design

The high temperature APA for BepiColombo is developed by Kongsberg Defence and Aerospace and BAE Systems, in the frame of the ESA BepiColombo mission to the planet Mercury.

The APM and RF Rotary Joint structures are mainly made of Titanium Alloy (Ti6Al4V) and stainless steel. All ball bearings are 440C stainless steel with special heat treatment and dry film MoS_2 lubrication performed by ESTL.

The stepper motor and gear head were specially prepared by CDA Intercorp (US) for the high temperature operation with lubrication provided by ESTL using their MoS_2 sputtering process.

The overall mass of the APM Breadboard with the RF Rotary Joint and a dummy high precision position sensor is 3.6 kg.

2.2. Assembly and RF integration

The APM Breadboard was assembled by KDA and accurately measured, weighed and characterised for friction before integration with the RF Rotary Joint (RJ).

The RJ was built by BAE Systems in Great Baddow in UK and characterised there before a final integration into the APM was performed by BAE Systems engineer.

The RJ is an integral part using the APM main rotary shaft and bearing as its main support. The mechanical interface between the two units is carefully shimmed for the final correct fitting. Both assemblies showed to be very accurate within the specified extremely strict tolerances and no problems were encountered.

All external surfaces of the APM and RJ were painted with a heat resistant black paint for increased heat transfer by the IR heating to be used in the TV chamber for high temperature heating.

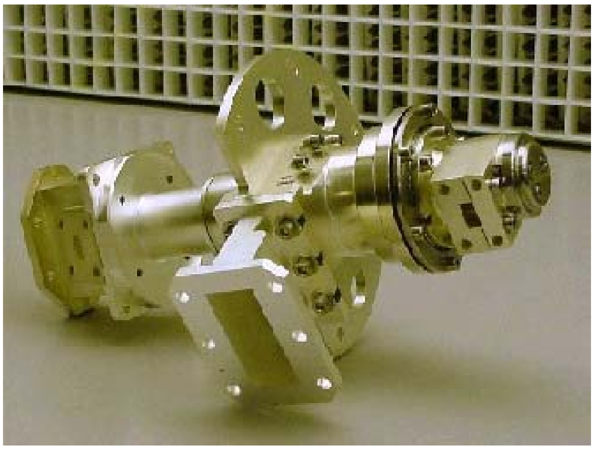

Figure 1. RF Rotary Joint.

Figure 2. APM Breadboard without RF Rotary Joint and drive actuator.

Figure 3. APM Breadboard.

3. BREADBOARD TEST

3.1. Mechanical Functional Test

The assembled APM was first functionally tested in air at room temperature. Due to the dry film lubrication with MoS2 and its sensitivity to moisture, the mechanism was located into a closed fixture (also used for vibration) with continuous purging of dry nitrogen (N_2) gas.

The APM was functionally tested for:

- Detent torque and stiffness, power off
- Static torque and stiffness, power on
- 360° deployment verification
- End stop verification
- Angular repeatability test
- Dynamic response
- Stall Torque test
- Stall torque

The APM shaft position was measured by a Renishaw Laser M10 which provides dynamic angular measurements in a sector of up to 40º and with a resolution of about 0.001º.

The APM delivered torque was measured by a load cell located tangentially to the large flywheel acting as a stop while the Renishaw laser measured the angular displacement in order to calculate the torque stiffness of the APM.

The APM shaft was dynamically loaded by a flexible flywheel of 25 kg simulating the first eigen frequency of the antenna system. The flywheel weight was not offloaded, but fully supported by the APM shaft. This was not considered a problem when considering that the APM bearing is pre-loaded to as much as 1200 N and has a very large load capacity.

In order to detect the stepper motor motion and verify stepping, or not, a small angular (space qualified) potentiometer with a 300º measuring range and allowing continuous rotation, was attached to the motor shaft via a flexible connection. This gave valuable information of the motor step accuracy (electrical lag and step smoothness) and status (stalled or not). The potentiometer was also used successfully in the TV chamber for hot and cold cases. However, the potentiometer friction introduced a small uncertainty and a reduction in the real torque margin of the system due to its friction load onto the motor shaft.

In conclusion, the APM met all design requirements and predictions besides the pointing hytseresis when reversing drive direction which showed to be about double above the required level for pointing accuracy:

APM torque and stiffness:

- Torque stiffness > 3200 Nm/rad at low loading.
- Holding torque, power OFF > 13 Nm
- Holding torque, power ON > 39 Nm
- Stall torque > 34 Nm.

APM pointing accuracy and speed/acceleration:

- Hysteresis/backlash < 0.055º (required < 0.02º)
- Dynamic accuracy within ±0.01º for rates up to about 0.1°/s.
- All demanded speeds and acceleration requirements met up to 2º/s.

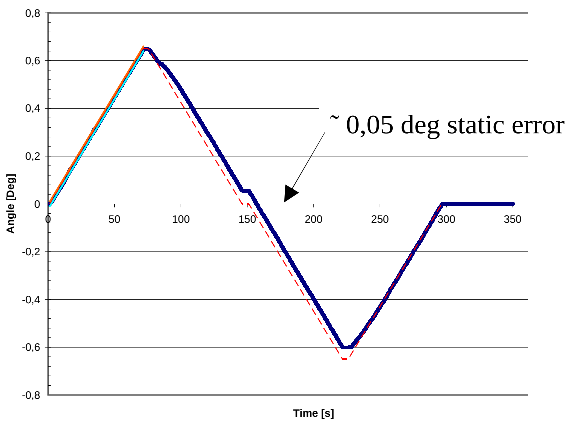

Figure 4. APM pointing performance (blue curve is measured shaft position, red is theoretical by commanded motor steps.

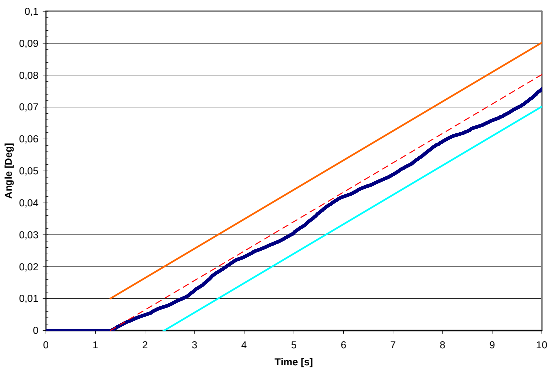

Figure 5. APM dynamic pointing at 0.01º/s rate.

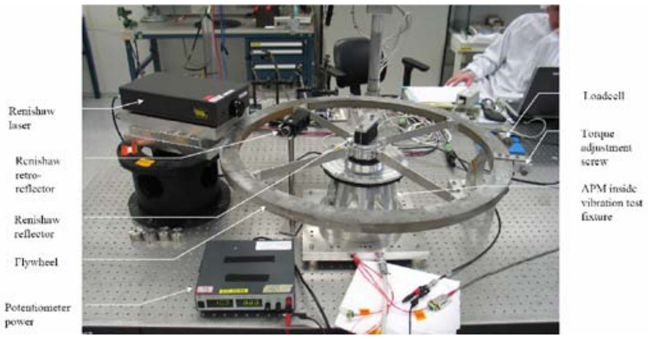

Figure 6. APM Functional Test.

3.2. RF Functional Test

The main objective for producing and testing this model was for demonstrating the mechanical feasibility of the technology and the stability of the performance over a wide temperature range and in this respect the programme has been successful. The RF design was carried directly to manufacture from the finite element modelling. No facility was incorporated for manual tuning of the performance.


Figure 7. APM during RF functional test in air.

The rotary joint s-parameters were measured under ambient conditions, prior to and following integration with the pointing mechanism.

Figure 7 above shows the integrated rotary joint during measurement. The results showed that the integration introduced no significant changes to the measured performance. Generally, the ambient measurements showed that there was a resonance on the x-band channel at 7.45GHz, unpredicted by modeling and has since been identified as originating in a quarter wave choke. This will be removed or minimized by design, should the programme proceed to flight. The resonant frequency was situated between the transmit and receive bands, and though it did not significantly influence the insertion and return loss in those bands, it did effect the transmission phase stability.

The Ka-band channel return loss had a performance degraded from the calculated result, most likely associated with imperfections in the manufacture of the waveguide to coaxial transitions, but in other respects the results were successful. The rf test results are summarized in Table 1 below.

Table 1. A Summary of RF performance in Thermal Vacuum

Parameter	Freq Band	Units	Spec	Amb	TV Amb	TV Hot 240°C	TV Cold-25°C
Return Loss	X1	dB	-20	-25.6	-23.0	-25.5	-23.7
Return Loss	X2	dB	-20	-22.1	-22.3	-22.2	-22.4
Insertion Loss	X1	dB	-0.1	-0.1	-	-	-
Insertion Loss	X2	dB	-0.1	-0.1	-	-	-
Transmission Phase WOW	X1		1°	1.6°	1.8°	1.5°	-
Transmission Phase WOW	X2		1°	0.5°	0.5°	0.7°	-
Return Loss	Ka1	dB	-20	-19	-18.5	-21.7	-18.5
Return Loss	Ka2	dB	-20	-13	-12.7	-12.5	-12.8
Insertion Loss	Ka1	dB	-0.4	-0.25	-	-	-
Insertion Loss	Ka2	dB	-0.4	-0.41	-	-	-
Transmission Phase WOW	Ka1		1.4°	0.9°	1°	1°	-
Transmission Phase WOW	Ka2		1.4°	1.3°	1°	1°	-
Inter-channel Isolation	Ka1 & 2	dB	TBD	<-75	<-75	<-75	<-75
Turning Torque	N.m		TBD	<0.0 025	-	-	-

For the RF testing in thermal vacuum, the static waveguide ports of the rotary joint were connected by waveguide to ports in the vacuum chamber wall, which were sealed with RF vacuum windows. Each waveguide contained a section of flexible guide to minimise the force on the waveguide interfaces, caused by differential thermal expansion between the waveguides and the chamber. The rotary joint waveguide ports on the rotary side of the assembly were terminated in RF terminations. These were specifically manufactured from silicon carbide load elements to obtain high temperature performance.

The outside RF connections from the vacuum chamber were connected to an Agilent E6384B PNA vector network analyser. Each port of the VNA was dedicated to the one channel of the rotary joint. In this way, the connection in circuit path to the rotary joint remained unbroken.

The rotary and high temperature nature of the testing prevented two-port transmission measurements in the thermal chamber. Due to the criticality of the transmission phase stability with rotation, and at the request of ESA, BAE Systems developed a technique for synthesising transmission data from a set of 1 port measurements, terminated with the normal calibration standards of a precision termination, a short and an offset short.

Rather than attempting to calibrate the RF measurements at high and low temperature, all calibrations were performed at ambient. This technique relied on the performance of the test equipment remaining relatively consistent over the course of the thermal cycling and this proved generally to be the case. Calibrations were made in the TV chamber at the plane of attachment to the rotary joints using a standard 1 port precision waveguide calibration kit.

During parts 1 and 2 of the thermal vacuum test sequence, conventional return loss measurements were performed with both channels of the rotary joint terminated with the high temperature compatible waveguide loads.

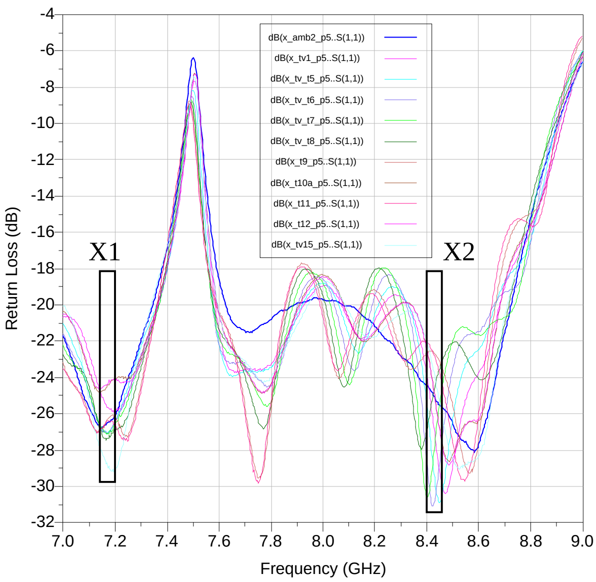

Figure 8 Effect of Temperature on X-band Return Loss Compared to Ambient Non-chamber Plot

Figure 8 shows a comparison of X-band return loss measurements for one position of rotation measured over the TV temperature range, along with an ambient laboratory measurement, shown as the bold line. The latter being a well terminated measurement, has no ripple.

The thermal vacuum measurements have ripple associated with the higher reflection coefficient of the high temperature termination. This ripple was present in the chamber measurement at ambient conditions. From inspection of the data, it can be seen that during the temperature excursions, it is only the ripple that is significantly changing and not the underlying performance of the rotary joint. Undoubtedly addition processing could minimize the effect of the termination.

However even with the effects of the load included the return loss remains within specification over the measured temperature range.

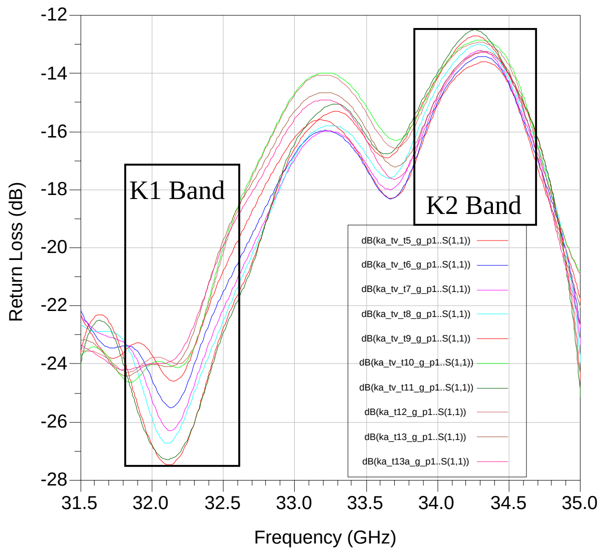

Figure 9 Effect of Temperature on Ka-band Return Loss

The Ka-band reflection measurements benefited from the ability to use the gating function on the VNA to display only the rotary joint reflection and exclude the effects of the rest of the circuit.

Gating could be used on the Ka-band due to the greater electrical length between the rotary joint and the rest of the circuit. Consequently the return loss results seen in Figure 9 show little of the ripple visible in the x-band measurement.

There is more apparent change in performance of the Ka-band channel and this is perhaps to be expected due to the smaller dimensions of the hardware. There is a worst case reflection coefficient change of 0.04. Assuming that this will still be representative of a better matched model, this would require an ambient performance of better than 24.5dB to remain in specification over the temperature range. Modelling shows that will be a demanding specification and will require close control of manufacturing tolerances, and a manually tuned matching element is likely to be required.

Following the main test sequence, two additional high temperature cycles were performed for reflection measurements, one with the rotary joint terminated with a short circuit and the other terminated with an offset short circuit. Again this was done for both channels. This data was then used to synthesise the transmission phase variation with rotation data for both channels at ambient and maximum test temperature.

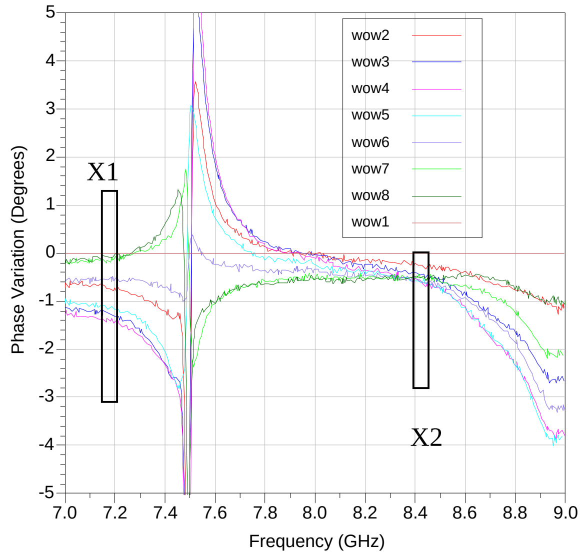

Figure 10. Wideband Plot of X-band Relative Transmission Phase Variation for 360º of Rotation at 240ºC

It should be noted that though in theory this technique can produce good quality results, it is of course dependent on the quality and consistency of the input data. Due to the many practical limitation associated with such a test, i.e. variation of thermal conditions between cycles, imperfect test loads, no calibration at temperature etc, the test data did not produce accurate absolute transmission data.

However the *relative* rotational phase data proved to be extremely good showing excellent correlation between the normal laboratory data and TV chamber data, measured at ambient conditions. It should also be noted that the basic 'double pass' data from the short circuit measurements, did not produce accurate relative transmission phase data, without the synthesis calculations.

Figure 10 shows the high temperature phase variation for the X-band channel and is generally quite similar to the ambient response. Considering the sensitivity of the resonance to minor mechanical alignments, this indicates favourably for a design with the resonance suppressed.

The synthesised Ka-band channel transmission phase variation is shown in Figure 11. The calculations were performed using un-gated data, so there is ripple in this plot from the load mismatch. It can be seen that the variation is within the specification of 1.4º

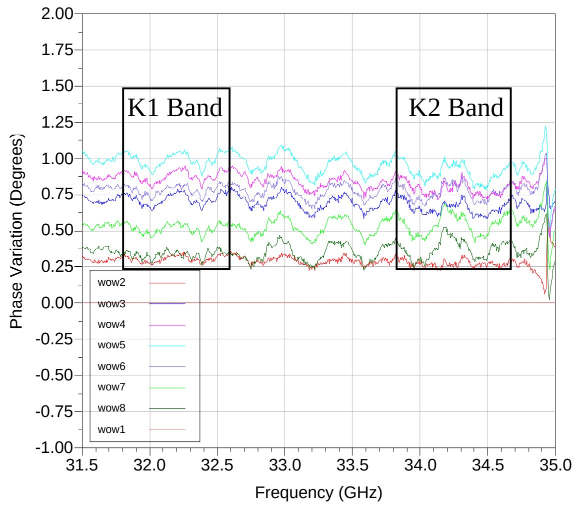

Figure 11. Wide-band Plot of Ka-band Relative Transmission Phase for 360º of Rotation at 240°C

3.3. TV tests, Part 1

The APM was mounted into the TV chamber with RF feed through on the TV chamber walls for both the Ka and X band single port analysis. The unit was instrumented with 10 thermocouples for mapping the APM temperature distribution.

The APM was thermally isolated from the bottom plate and fixture by mounting it on 6 titanium rods. The unit was radiation heated by 6 each 900W IR lamps with variable and individual power adjustment. Cooling was provided by a bottom plate with liquid N_2 circulation capable of lower than -130ºC.

The whole unit was shielded inside the TV chamber by aluminium foil in order to reduce the heat exchange with the surrounding chamber walls. This set-up proved to work very well and there was little problems obtaining the required temperature.

In average each lamp provided about 50 W for obtaining the qualification temperatures of between 200 to 255ºC on the APM and RJ structures. The lamps proved to be a very effective means for controlling the temperature. The stepper motor self heated to its final peak temperature of maximum 255º on the windings.

The thermal vacuum was maintained below 10^{-6} mbar throughout the tests.

During the TV test, the stepper motor correct stepping was measured and verified by the potentiometer which was held at lower temperature. The APM was run without the dummy antenna inertia and laser position measurement due limitations by the vacuum chamber set-up.

In all 4 thermal cycles with functional checks of the RF and mechanism) where performed successfully in vacuum before opening the chamber for performing random vibration. This sequence was performed in order to obtain some TV tests before risking any damage due to random vibration (which proved not be a risk)

The functional check of the mechanism showed normal behaviour. The motor winding resistance maintained stable throughout the testing except for thermal variations which increased the resistance by a factor of about two at the Hot Case condition compared to RT.

- **Motor start current** (static resistance in mechanism) changed little during thermal vacuum test:
  - RT before TV: 0.08 A
  - Hot case: **0.06 A**
  - Cold Case: **0.09 A**
  - RT after life test: **0.09 A**

- **Cold Case Torque margin** was slightly negative when including ESA safety factors but influenced by the motor shaft potentiometer friction.

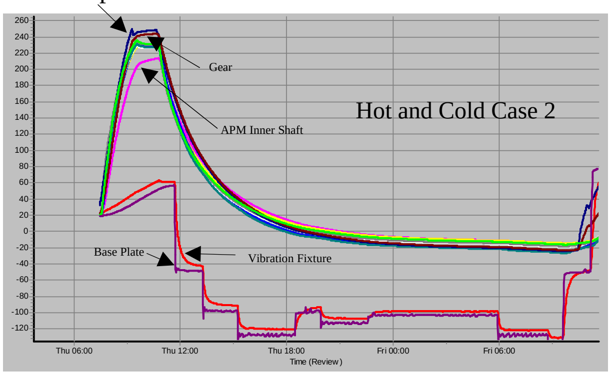

Figure 14. Temperature curves for Hot and Cold case.

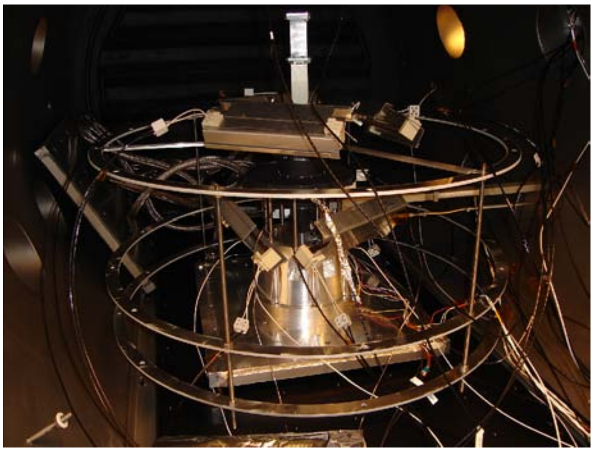

Figure 12. APM Breadboard with IR lamps and RF connections in vacuum chamber.

Figure 13. APM Breadboard isolated by aluminum foil in vacuum chamber.

3.4. Random Vibration

The APM was removed from the TV chamber, instrumented with accelerometers, bagged (for particle protection) and mounted onto a large shaker for vibration in axial direction as first step.

The unit was exposed to low level sine sweep before and after the random vibration in order to map any changes in characteristics. The random vibration was applied in increasing levels until full level of 18.3 gRMS was applied for 2 minutes.

A strong resonance at about 700 Hz was detected during the initial sine sweep for the aft end of the RF Rotary Joint and it was decided to notch the random level at this frequency in order not to risk premature damage to the unit.

Following the axial direction was random vibration in lateral direction to 11.8 gRMS. Again, the level in the RJ resonance frequency was decided to be notched to avoid any premature damage.

In conclusion, the vibration showed:

- No failures or noticeable degradation.
- No signs of loose parts or high alarming noise levels.
- The APM shaft remained in position (in free position, not supported).
- Resonance frequencies and Q-factors were stable, little sign of any non-linear internal friction.
- Tests of the mechanisms and RF performance did not shown any signs of change.
- Only problem identified is high Q-factor for the aft end of the RJ Ka band which required notching.
- Reason and remedy RJ high Q-factors will have to be studied further.

Figure 15. APM Breadboard bagged on vibration shaker.

3.5. TV tests, Part 2

After vibration and a functional check, the APM was again mounted into the TV chamber for the remaining two Hot and Cold cycles including endurance testing of the mechanism to 10.000 nominal life cycles (but with reduced amplitude in order to compress the test time) divided into the last Hot and Cold cases.

The life cycles were completed without any motor step problems and a final functional check of the RF and mechanical performance was performed at RT in the TV chamber before opening.

3.6. Final Functional Test

The final functional test of the mechanism in air (with N_2 purging) revealed that there was apparently some increase of friction in the order of 35%.

The most important result was that the system drive and pointing characteristics had not changed precision after TV and random vibration.

However, the larger than expected static hytseresis of 0.055º needs further design attention to resolve. The major part of the hysteresis is due to that the drive actuator is a very slight gapping of the pinion in lateral and tangential direction which was measured after test with an accurate clock.

The APM is being modified by stiffening the gear head pinion in lateral direction by adding a secondary support bearing.

4. CONCLUSION

In conclusion the test campaign has proved that the chosen technology and mechanism design will function and meet the major requirements within the extreme temperature range between Cold and Hot Case up to 260ºC in a vacuum environment.

Some more design tuning and verification remains before the complete APM is ready for a final C/D-phase development and flight manufacture and test.

Also technology used in components not covered in the this test campaign must be verified covering mainly:

- Position Sensor.
- Twist Capsule with electrical wire transfer.
- Thermal Control system materials.