

HIGH TEMPERATURE ANTENNA POINTING MECHANISM FOR BEPICOLOMBO MISSION

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ABSTRACT/RESUME

This paper describes the two axis Antenna Pointing Mechanism (APM) with dual frequency (X-Ka bands) Rotary Joint (RJ) developed by Kongsberg Defence and Aerospace and BAE Systems, in the frame of the ESA BepiColombo mission to the planet Mercury.

The extreme environmental conditions induced by Mercury's proximity to the Sun (up to 14.500 w/m² direct solar fluxes, up to 5000 W/m² infrared flux and up to 1200 W/m² albedo shine from the planet surface), have dictated the need for a specific high temperature development of the pointing mechanism and of its integrated RF Rotary Joint.

Global thermal analysis of the antenna predicts qualification temperature for the elevation stage APM between 250°C and 295°C.

In addition, the mechanism shall survive extreme cold temperatures during the interplanetary cruise phase.

Beside the harsh environment, the stringent pointing accuracy required by the antenna high frequency operations, and the extreme dimensional stability demanded by a radio science experiment (which is using the antenna for range and range rate measurements), have introduced additional, specific challenges to the mechanism design.

Innovative solutions have been deemed necessary at system architecture level, in the design of the mechanisms critical areas and in the selection of high temperature compatible materials and processes.

The very high working temperature of the mechanism ruled out use of aluminium alloys, which is replaced by Titanium alloy and stainless steels. Special heat treatments of the steel are applied for minimum loss of hardness. The structures are optimised for minimum mass.

To handle thermal stresses and distortion, a very compact design of the APM was performed integrating the bearings, position sensor and drive chain within minimum structural length.

The Rotary Joint is a unique design tailored to the APM using a common main bearing support. Special manufacturing processes have been tested and applied

for manufacture of the very compact RJ being the first of its kind (dual X-Ka band) in European space development. The twin channels are arranged concentrically, permitting continuous 360° rotation. Maximum use of waveguide has been made to minimise the loss in the Ka-band frequency channel and this leads to an unconventional design of the X-band channel.

A specific effort and extensive test program at ESTL in the UK have been put in place to identify suitable high temperature solutions for the RJ and APM bearings lubrication.

The high temperature demands the use of a dry lubrication system. High working loads due to thermal stresses puts extra challenge to the life duration of the dry film lubrication. Lead lubrication was initially the preferred concept, but has later in the program been substituted by MoS₂ film. A design life of 20,000 cycles at 250°C and elevated load has been demonstrated for the bearings with MoS₂.

Special attention has been paid to the materials in the stepper motor using high temperature solder material and MoS₂ dry lubrication in the bearings and gear train.

The APM is designed for use of a high accuracy inductive based position sensor with remote signal and amplifier electronics. Electrical signal transfer is via a high temperature Twist Capsule.

The activity has included the design, manufacturing and testing in a representative environment of a breadboard model of the APM and of its integrated radio frequency RJ. The breadboard does not include a position sensor or the Twist Capsule.

The breadboard tests will include functional performance tests in air, vibration tests and thermal vacuum. The thermal vacuum test will include RF testing at high temperature combined with APM pointing performance.

1. GENERAL DESCRIPTION

This study presented here is performed as a part of a ESA Contract for study of the complete Bepi High Temperature High Gain Antenna System with KDA as

prime contractor. The Pointing Mechanism and Rotary Joint are developed under KDA and BAE Systems respectively. ESTL has been contracted by KDA for lubrication studies and tests.

The High Temperature High Gain Antenna (HTHGA) System consists of 1.5 meter reflector antenna for X- and Ka-band RF transmission and shall be used on the Magnetic Planetary Orbiter (MPO) which is one of two spacecrafts in ESA's BepiColombo programs for exploration of Mercury.

The MPO is three-axis stabilised mainly devoted to Mercury remote sensing and Radio Science experiments.

The HTHGA shall be mounted on the space craft Z-panel facing outwards from Mercury. The antenna will be stowed against the panel during launch and released once into Earth orbit. After an interplanetary cruise phase of 4.35 years, the MPO will enter Mercury orbit and shall be operational for a period of maximum 2 years with an orbit time period of about 2.3 hours. The polar orbit is elliptical with a perihelion altitude of 400 km and aphelion altitude of 1500 km above Mercury.

The antenna will be fully exposed to the sun and Mercury planet shine giving high temperatures as well as low temperature transients in eclipse during the Mercury orbit period.

The antenna shall have more than hemispherical pointing capability for continuous earth tracking with high accuracy by a two axis Antenna Pointing Assembly (APA).

The two Pointing Mechanisms (PM) of the APA are separated by a 0.7 meter long composite circular boom. The elevation axis PM is located close to the antenna reflector. The azimuth axis PM is mounted into the spacecraft Z-panel. This concept, compared to a tripod arrangement, was found to give the best stiffness/mass ratio by minimising the dynamic mass and give acceptable launch loads in the APM's.

Also, the thermal conditions for the azimuth Pointing Mechanism, which is protected in the spacecraft Z-panel, are by this arrangement much less severe reducing the overall risk and making the transfer of all electrical controls for the elevation PM less critical.

This paper deals in particular with the design and development aspects of the Antenna PM for the elevation axis.

2. CRITICAL REQUIREMENTS AND PERFORMANCE

2.1 Temperature

The main critical requirement is the high temperature experienced for the Antenna reflector as well as the elevation Pointing Mechanism.

The PM sees not only direct sunlight, which is at maximum about 14.4 kW/m^2 when closest to the sun,

but sees also the reflected and radiated heat from the spacecraft panel, antenna, Mercury as well as conducted heat from the antenna interface.

The high solar flux puts high demands on the thermal protection and its thermal optical properties for the mission life in order to avoid serious degradation.

A long series of thermal studies of the complete antenna system on the MPO have been performed by Dutch Space as part of the team.

Different thermal control concepts have been studied. For the elevation stage PM, the best solution for reducing the maximum temperature is found to be a combination of using Multi Layer Insulation (MLI) and Optical Solar Reflectors (OSR).

The OSRs are used in particular to reduce the temperature on the electrical stepper motor, which dissipates about 6 W when energised. The OSR's advantage compared to MLI is the ability to achieve a low ratio for sun absorption compared to IR radiation α/ϵ of about 0.25 / 0.85. When utilising a good heat conductive path from the motor to the OSR covered surfaces, as well as avoiding sunlight on all radiative surfaces simultaneously, a cooling effect is achieved. Special attention is paid to the attachment and arrangement of the OSRs for achieving optimum heat reduction.

Table 1 APM Qualification temperatures

APM sub-units	Qualification temp [deg C]
Rotary Joint rotating part X- and Ka-band	295
Rotary Joint static part Ka-band	285
Drive shaft, outer part (antenna interface)	284
APM support bracket (boom interface)	274
Drive shaft and inner races of main bearing	266
Housing Rotary Joint static part X-band	261
Inductosyn rotor	260
Housing and main bearing outer races	257
Stepper motor	256
Gear head	253
Inducosyn stator	253

With this thermal control system, the qualification temperature of the APM is ranging from 253°C to as high as 295°C as shown in Table 1. The most critical is the stepper motor temperature. The motor soldering material has a melting point at about 310°C and the organic insulation materials has increased dielectric breakdown rate at temperatures above 260°C. Note that the qualification temperature is 40°C above the calculated values adding uncertainty and a qualification margin.

2.2 Mass

The APM has an allocated 4.5 kg mass budget. This is a strict budget when considering that traditional aluminium alloys can not be utilised due to the temperature.

The main structures driving mass are the titanium alloy (Ti-6Al-4V) housing and brackets. These structures are optimised with ribs and lightening holes in compromise with machining complexity.

The Breadboard mass budget is shown in Table 2. For a flight model, additional items must be added, mainly:

- Support bracket between the boom and the APM.
- Thermal control system.
- Twist Capsule.

With these components added, the flight model mass is predicted to be slightly above the target of 4.5 kg.

Table 2 APM Breadboard mass budget

APM sub-item	Material	Mass [kg]
Motor and gear	SS	0.430
Inductosyn plates	Titanium	1.014
Main bearing pair	SS	0.436
Rotary Joint incl shim	SS	0.410
Drive shaft	Titanium	0.282
Housing	Titanium	0.866
Drive gear	SS	0.138
Mechanical stop mechanisms	SS	0.013
Fasteners	Ti/SS	0.050
APM breadboard model		3.639

2.3 Pointing accuracy

The pointing accuracy of the APM shall be better than $\pm 0.01^\circ$ for a tracking rate up to $0.2^\circ/\text{s}$. To obtain this accuracy, the gear ratio must be high and the gear backlash kept to a minimum. In addition, an anti-backlash system on the final stage is applied.

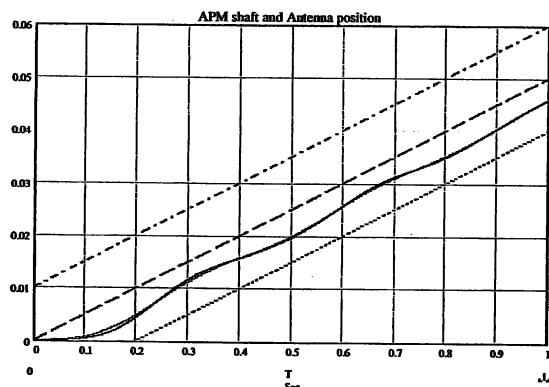


Fig. 1. Pointing prediction for $0.05^\circ/\text{s}$ rate.

In order to reduce the stepper motor torque disturbances, which triggers eigen modes in the

system, 64 micro steps per each motor 30° whole steps is applied.

2.4 Disturbance torque

The disturbance torque from the antenna onto the spacecraft shall be less than 0.05 Nm at tracking rates up to $0.2^\circ/\text{s}$.

Predictions show that this low disturbance can only be obtained at lower tracking speeds below $0.05^\circ/\text{s}$ pending antenna inertia and the system stiffness. Simulations of the antenna Earth-tracking shows, however, that the average speed is most of the time below $0.05^\circ/\text{s}$.

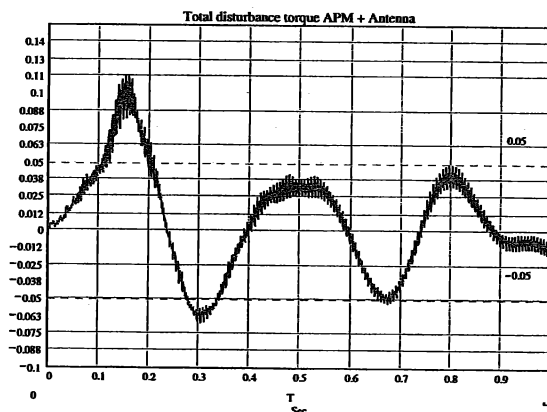


Fig. 2. Disturbance torque onto spacecraft from antenna system at $0.05^\circ/\text{s}$ pointing rate.

2.5 RF Requirements

It is a fundamental requirement of the APM that it passes the RF signals with as little disruption as possible. All the RF components in the rotary joint have been optimised for the specific X and Ka-frequency bands, in order to minimise signal reflection and transmission phase variation with rotation.

The transmission phase variation, critical for the Radio Science Experiment (RSE) with a specification of 1° and 1.4° for the X and Ka-band respectively, has proven to be the most demanding parameter to achieve. Finite element analysis of all rotary channel components under worst case misalignment, has lead to the introduction of mode suppression slots in the quarter wave choking, and this has significantly improve the phase stability.

3. DESIGN CONCEPT

3.1 APM general concept

The Antenna Pointing Assembly general concept is shown in Fig. 3. Two almost identical Antenna Pointing Mechanisms are applied with main elements:

- An outer housing in titanium alloy Ti-6Al-4V.

- Hollow drive shaft in Ti-6Al-4V with interface for the RF Rotary Joint.
- Mechanical end stops and deployment latch mechanism.
- Side mounted stepper motor with gearbox running onto a main gear wheel.
- A main gear wheel, made of 17-4PH corrosion resistant steel.
- The pinion onto the gear wheel is equipped with an anti backlash system.
- Position sensor.
- Twist capsule for electrical signal transfer.

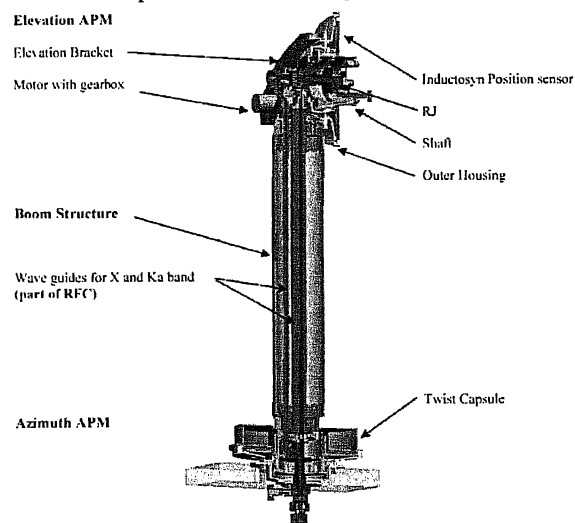


Fig. 3. APAconcept.

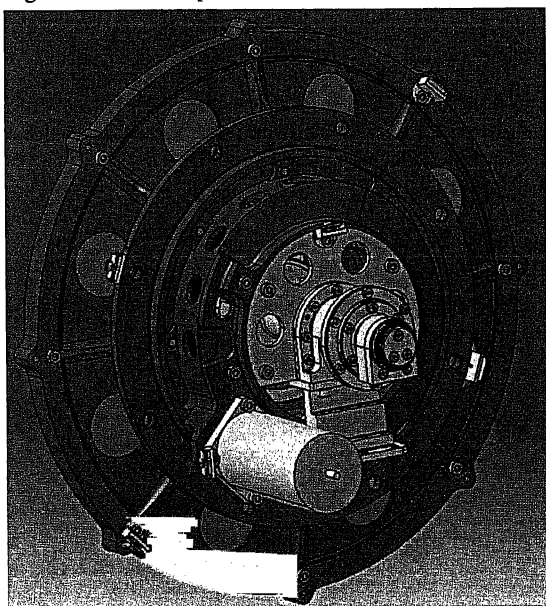


Fig. 4. APM Breadboard model showing static side of RF Rotary Joint and stepper motor.

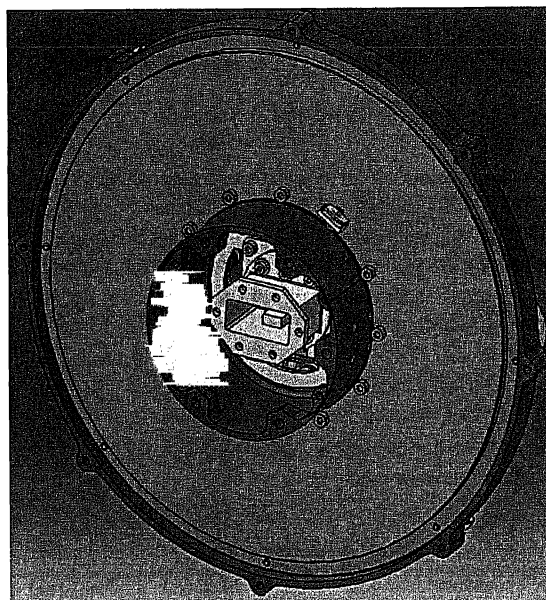


Fig. 5. APM Breadboard model showing rotational side with wave guide interface and position sensor plates.

3.2 Motor and gear

The motor gear is delivered by CDA InterCorp (USA). the stepper motor is a dual wound, 30° whole step, with Samarium Cobalt permanent magnets. KDA has experience with this motor from the Rosetta and Mars/Venus Express SADMs as well as in an earlier TRP study for high temperature APM with dual RF channels.

The motor has by design a high temperature capability and only the wire solder material and lubrication is specially modified for Bepi APM Breadboard model.

The gearhead is a 3 stage planetary type with ratio 200:1 made in stainless steel and supported by ball bearings for all gears. The backlash is very low: Less than 4 arc minutes.

The motor and gear ball bearings are 440C stainless steel. The bearings and gears are lubricated with MoS₂ sputtered thin film applied by ESTL.

3.3 Final stage gear

The motor gearhead drives a final stage gear wheel attached to the APM drive shaft with straight cut involute spur gears. The gear wheel is made in 17-4PH martensitic stainless steel and also lubricated with MoS₂ sputtered film applied by ESTL.

The drive pinion on the gearhead output shaft is split and preloaded by a torque spring for anti-backlash function.

3.4 Integrated APM and Rotary Joint bearing

A super duplex angular contact ball bearing pair supports the APM drive shaft. The bearing assembly is initially developed by ADR, France, for the Rosetta APM and SADM. It is a very robust and stiff bearing with an inner diameter of 85 mm allowing room for the RF Rotary Joint inside the dive shaft.

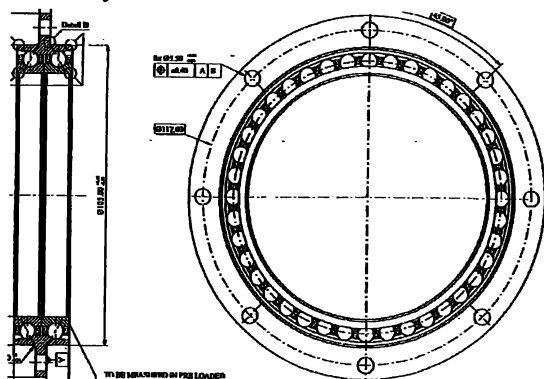


Fig. 6. APM Main Bearing pair.

The bearing is pre-loaded to 1200 N in order to maintain stiffness in deployed mode and avoid gapping during launch loads. At max operational temperature the thermal stress causes an equivalent pre-load of about 2700 N (1650 MPa Hertzian stress in race).

In order to save mass and avoid additional thermal stress in the bearings for the RF Rotary Joint, the APM main bearing assembly also functions as the Rotary Joint main support bearing.

This has been a challenging design task involving a close co-operation in the development between BAE Systems designing the RF Rotary Joint and KDA designing the APM.

The result is a highly integrated design with very low thermal distortions and stress and thereby increased thermal margins for the structure and bearings.

In all, the APM with the Rotary Joint, excluding the motor/gear unit, applies only three pairs of bearings for antenna axis support and the Ka and X-band RF rotary transfer.

3.5 Rotary Joint

The rotary joint, shown in Fig. 7, has two physically separate channels to transmit the X and Ka-bands signals, which are mounted concentrically, with the Ka-band input waveguide passing through the centre of the X-band channel.

The X-band channel though larger in diameter than compared to the Rosetta design, is not overmoded, but operates with a lower coaxial line impedance.

The Ka-band uses conventional style waveguide to coaxial transitions to give good performance, but

which are usually associated with lower frequencies of operation.

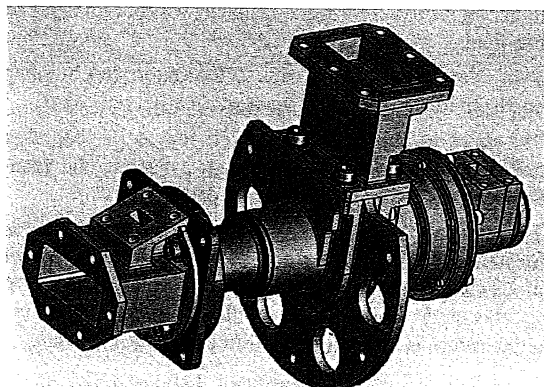


Fig 7. X and Ka-band RF Rotary Joint.

4. BEARING LUBRICATION TEST PROGRAM

4.1 Lubrication candidates

One of the main challenges designing the high temperature APM is finding a ball bearing lubrication system surviving the load and life duration.

To accomplish this, an extensive ball bearing lubrication test program was performed under contract to ESTL. The program included an initial trade-off study for the best-suited candidate lubrication systems and definition of the bearing designs to be tested.

The two critical bearings for the integrated APM/RJ were applied for the test:

- The APM main bearing pair (super duplex) by ADR, France.
- The Rotary Joint secondary support bearing pair by MPB/Timken: ID 7.938 mm, OD 12.7 mm.

The operating temperature of about 260°C precludes the use of any fluid lubricants due to outgassing and evaporation.

A solid lubricant is therefore required and two options were evaluated in the test programme:

- Sputter-deposited lead, 0.2 to 0.5 microns thick, applied to the raceways in conjunction with lead-bronze cages fitted in the bearings was investigated.
- Sputtered MoS₂ 0.2 to 0.5 microns thick, applied to the raceways and operated in conjunction with self-lubricating polymeric cages manufactured from PGM-HT, a composite of PTFE, glass fibres and MoS₂. For the Main Bearing pair, sputtered MoS₂ was also applied to the balls.

4.2 Test set-up

The bearings were tested in vacuum at 250 to 300°C using a test rig developed by ESTL, Fig. 8.

The bearings are installed in a test housing and flexibly preloaded to enable the bearing arrangement to be able to accommodate thermal expansion without changes in pre-load.

Two heater blocks are fixed to the outer ring housing and each heater block is thermostatically controlled.

The drive motor is situated externally to the chamber and drives the inner rings through a ferrofluidic feed-through connected to the bearing drive shaft.

Torque is measured on a piezoelectric transducer and is located at a distance from the bearings and heater blocks and thermally insulated by a ceramic stack of spacers and is also water-cooled to ensure that the temperature is maintained within its operational range.

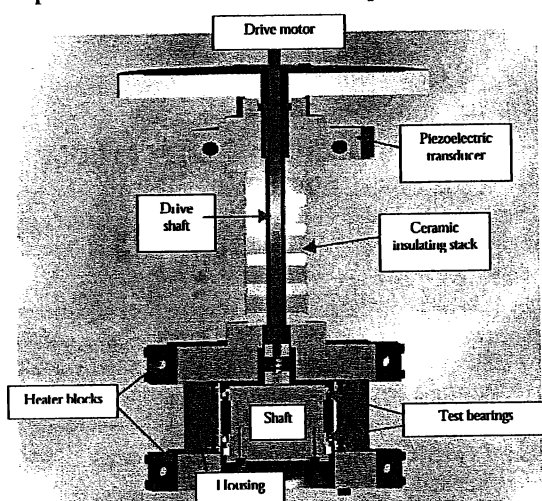


Fig. 8. Schematic diagram of high temperature rig.

The dimensioning life covers in all 20.000 oscillation cycles. Increasing, decreasing amplitudes were applied in steps performing 100 oscillations for each amplitude. The profile in Fig. 9 was repeated 10 times. The test was accelerated by running at an average speed of about 108°/s (18 RPM) in stead of an average pointing rate of less than 0.05°/s during operation.

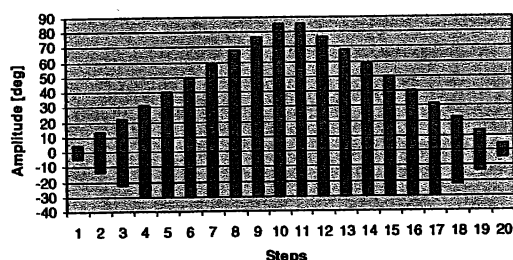


Fig. 9. Amplitude profile for bearing life test.

The tests followed a defined sequence:

1. Check of bearing torque with oil in laboratory air at ambient temperature.
2. Dry lubricate bearings and run-in in air. For MoS₂-lubricated bearings, the run in was shorter than for the lead lubricated.
3. For lead-lubricated bearings, after running-in, remove and rinse bearings with solvent to remove excess lead particles generated during running-in.
4. Heat bearings and check torque at room temp., 50, 100, 150, 200 and 250°C.
5. Perform oscillatory testing at 250, 275 and 300°C, as appropriate.
6. After testing, cool bearings and check torque at room temperature in vacuum.
7. Remove and examine bearing components after disassembly: Rings, balls, cages, with emphasis on lubricant and cage condition following testing.

Table 3 Test sequence for bearing and lubricant combinations.

Test bearing	Bearing lubricant	Cage
Trial bearing test.	Lead on raceways.	Lead-bronze.
Rotary Joint 1.		
Main Bearing 1.		
Rotary Joint 2.	MoS ₂ on raceways.	PGM-HT.
Main Bearing 2.	MoS ₂ on raceways and balls.	

The cages for the Lead and MoS₂ lubricated bearings were all one-piece full ball pocket types designed and manufactured under ESTL's responsibility. Special attention was paid for cage/race clearance allowing operation at room temperature and up to 300°C.

The bearings were pre-loaded to 40 N for the Rotary Joint bearing pair and 2700 N for the Main Bearing pair which simulated the maximum thermal stress for hot case operation in the APM.

4.3 Summary for lead lubrication

In summary, the initial Trial and Rotary Joint 1 bearings with lead lubrication performed acceptable.

The most notable finding was that the mean and peak torque increased at 250°C compared with their room temperature values. Upon returning to room temperature, the torque decreased to its original value.

The torque traces were characterised by high transients upon reversals of direction, although this effect was not always present. The Main Bearing tests showed torque peaks and hang up problems during the initial oscillatory tests. The test stopped due to high torque after about 9000 oscillations.

Following the testing of the MB, it was evident that the torque of the lead-lubricated bearings was higher than anticipated and that the lead film was depleted on the bearing raceways. It was therefore agreed that the

alternative approach with MoS₂ would be required for lubricating the MB assembly.

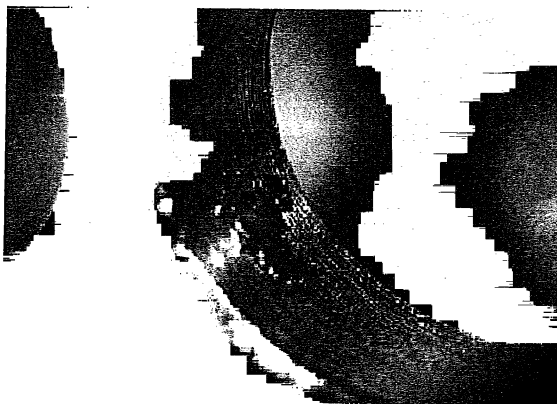


Fig. 10. Lead patches in the MB cage ball pocket.

4.4 Summary for MoS₂ lubrication on RJ

The MoS₂-lubricated rotary joint bearings performed better than the equivalent lead-lubricated bearings with the mean torque being, typically, 30 to 40% less and the peaks being 50% less.

After testing at temperatures up to 300°C, it was found that the cages were slightly distorted. However, the torque performance was satisfactory during testing at 275 and 300°C and upon returning to room temperature.

Table 4 Sum of torque for the RJ bearings with MoS₂.

Temp. [°C]	Mean torque [gcm]	Pk-Pk torque [gcm]	Comments
250°C	6.7	48	Good trace – no evidence of hang-up or high loads
275°C	7.4	44	Good trace
300°C	8.0	50	Slight hang-up
Room temp after cooling from 300°C	8.3	48	“Wobble” present – could be due to cage behaviour.

Following test completion, the bearings were removed and inspected. The following observations were apparent:

- The MoS₂ film on the bearing raceways was intact and in good condition, with no indications that wearing out was imminent.
- The cages were in excellent condition, with barely discernible marks present in the ball pockets. However, the cage was no longer completely round.
- The balls were in good condition.

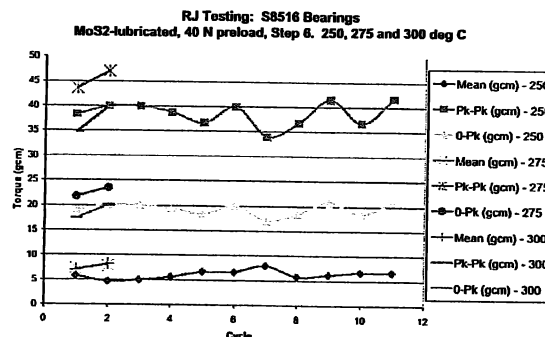


Fig. 11. Rotary Joint bearing with MoS₂ lubrication.



Fig. 12 Rotary Joint bearing showing MoS₂ film in good condition after test.

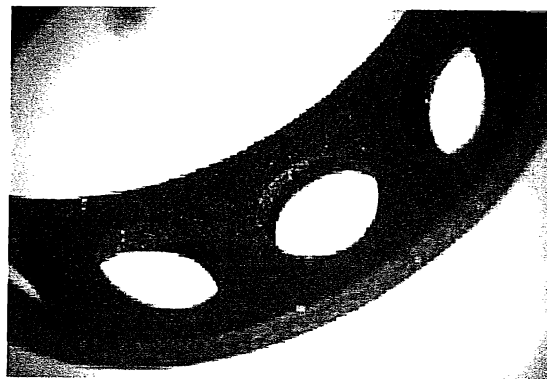


Fig. 13. Rotary Joint bearing PGM-HT in excellent visual condition after test.

4.5 Summary for MoS₂ lubrication on MB

The Main Bearing test and post-test examination demonstrate that the MoS₂ film provides adequate lubrication for the lifetime requirement with some margin remaining.

The mean and peak-to-peak torque is plotted on Fig. 14. Based upon CABARET analysis, the mean torque values correspond to friction coefficients between 0.05 and 0.08 up to 250°C.

At room temperature after test at 300°C, it was found that the bearing could not be rotated. Disassembly of the bearing showed that the cages had reduced in dimensions and there was no clearance left between the cage and inner ring lands, causing the bearings to seize as the cages had become a tight fit.

Table 5 Summary of torque measurements for the Main Bearing with MoS₂.

Temp. [°C]	Mean torque [gcm]	Pk-Pk torque [gcm]	Comments
250°C	1100	3900	0-Peak reduced to 1600 gcm after 10 revs.
275°C	1906	6000	0-Peak reduced to 2250 after 10 revs.
300°C	2000	4186	0-Peak reduced to 2375 after 10 revs.
Room temp after cooling from 300°C		> 5 to 10 Nm	Bearing would not move.

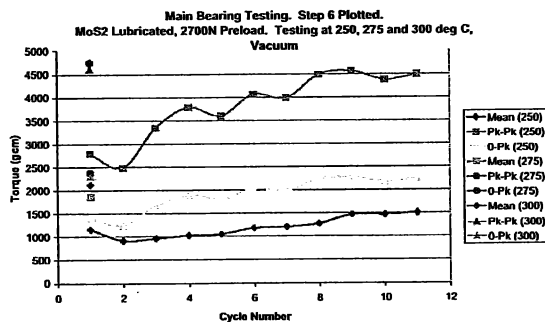


Fig. 14. Main Bearing with MoS₂ lubrication.

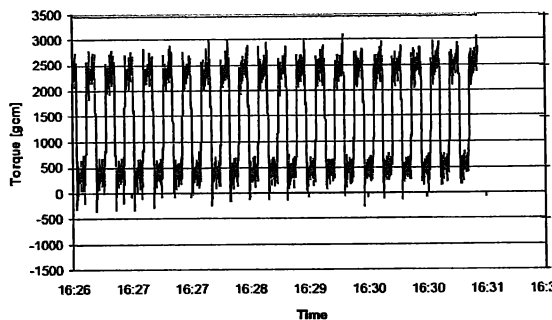


Fig. 15. Example of Main Bearing torque trace at 250°C at start of testing.

4.5 Conclusion for MoS₂ lubrication

It can be concluded that sputtered MoS₂ applied to the balls and raceways is a satisfactory lubricant for the Bepi APM application.

The PGM-HT cage operated well throughout the life test. Problems were only when testing was completed and bearings were cooled to room temperature from 300°C.

It is therefore essential that the PGM-HT material characteristics at 260°C are further investigated and the design optimised or reworked for the next stage for the Bepi-Colombo programme.

The Breadboard test will be performed using a modified PGM-HT cage with larger clearances. The test will be limited to the qualification temperature of about 260°C, and thus the problem of dimensional change is considered less critical.

5. BREADBOARD MANUFACTURE

The APM Breadboard is manufactured under joint responsibility:

- KDA for the Pointing Mechanism (PM).
- BAE Systems for the Rotary Joint (RJ).

Each unit will be assembled and initially tested for characterisation under each responsibility before the RJ is integrated into the PM unit for the main Breadboard tests of the complete APM.

The initial tests cover interface checks, mass weighing and bearing friction characterisation, as well as RF test of the RJ and functional check of the PM. A fixture for handling and tests will support the RJ before integrated into the PM.

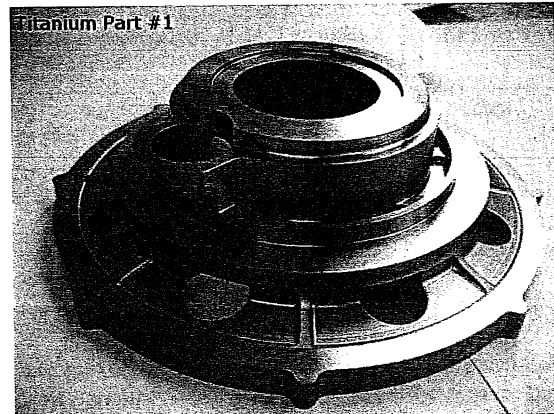


Fig. 16. Pre-machined APM housing in Titanium alloy

6. BREADBOARD TEST PLANNING

The integrated APM Breadboard will undergo the following main test sequence:

Mechanical friction

The torque required to turn the APM drive shaft in air shall be measured and characterised with out the motor/gear engaged.

Detent torque, stiffness and static torque

The APM detent torque and torque stiffness with non-powered and powered motor shall be measured by applying an increasing torque to the APM output shaft.

The static torque capability and margin shall also be measured. The APM motor power shall gradually be increased until a step is achieved and the torque measured.

Angular pointing performance at RT

The APM angular pointing performance shall be verified by running the stepper motor and measuring with high accuracy the position and dynamic response of the output shaft.

The APM shaft will be loaded by an inertia dummy load.

The tests includes:

- Angular repeatability.
- Dynamic response at different angular rates.
- End-stop verification.

Vibration

The APM shall be exposed to sine and random vibration representing a stowed mode condition during the satellite launch. The random level will be 18 g-rms for out-of plane and 11 g-rms in-plane.

Thermal Vacuum test

The APM Breadboard shall be exposed to thermal vacuum cycles between cold and hot case.

RF test and functional operation of the APM pointing at RT and at hot case and after completion of thermal cycles.

The RF check will consist of:

- Return loss measurement for both X and Ka-bands, over transmit and receive frequencies.
- Characterisation of the insertion loss performance at the temperature extremes, using a single port, short circuit technique.
- Inter-channel Isolation

The test shall include a life test of APM at hot case at the last cycle.

7. CRITICAL DESIGN ITEMS

The study program and Breadboard manufacture and test has so far identified some critical areas needing further work in preparation for a final flight model design and development program can be initiated.

These areas are identified as mainly:

- Motor dielectric materials survivability at high temperature during the complete life duration of 2 years avoiding dielectric breakdown.
- Bearing cage design.
- Thermal Control System, development of design details for implementation of OSR's and MLI.
- Development of sub-units not part of the Breadboard for high temperature operation:
 - Twist capsule.
 - Positions sensor.

8. CONCLUSIONS

This study program has shown as expected that it is the high temperature that is the most challenging requirement for the Bepi High Gain Antenna APM.

It has been necessary to optimise and apply unconventional thermal control systems for reducing the temperature as well as finding materials with maximum temperature capabilities within known space materials and procedures.

With the material selection and careful design of the mechanism and RF layout, it is concluded that the Breadboard model has a high chance of success in the coming test program.

Applying the Breadboard experience and performing recommended delta development activities will result in a APM design that will be robust and have a solid margin for high temperature operation above 260°C.