THE DESIGN, DEVELOPMENT, QUALIFICATION AND DELIVERY OF THE SOLAR ARRAY DRIVE ASSEMBLY (SADA) FOR BEPICOLOMBO MERCURY TRANSFER MODULE (MTM)

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ABSTRACT/RESUME

This paper describes the BepiColombo MTM SADA developed by Kongsberg Defence & Aerospace with RUAG Space as sub-contractor, within the framework of the ESA BepiColombo mission to Mercury.

The MTM is the Mercury Transfer Module, which will carry the two science satellites MMO from Japan (JAXA) and MPO by ESA to Mercury.

The MTM is designed to use electric propulsion for the six years of its interplanetary journey. The electrical propulsion demands high continuous power transfer from the MTM Solar Arrays through the SADMs.

When approaching Mercury with its proximity to the Sun, the Solar Array Sun incident angle is very important for the survival of the Solar Arrays. This requires high position control on the SADA as well as a short reaction time for turning the Solar Array out of the Sun in case of any command error and risk of overheating the Arrays.

The SADA design therefore includes a special Fast Mode for driving the Solar Arrays under high acceleration and rotation speed (max 6°/s) up to 180° out of the Sun within 30 seconds from SADA power turn-on.

The fast mode requires high motor power for accelerating and driving the heavy Solar Arrays (37kgm^2) with up to 40Nm dimensioning reaction torque.

Under normal operation for stand-by or normal driving (<1°/s), the power to the SADMs must be lower in order to not overheat the stepper motors.

In addition, the mechanism must survive extreme cold and hot temperatures during the interplanetary cruise phase with several planet fly-bys in eclipse (cold case).

The program consisted of a 6 months pre-design phase, followed by a C/D phase. This included building a structural/thermal model, followed by a breadboard for early tests at SADA level, as well as higher system level tests, followed by a qualification campaign building and testing two SADM QM's and one EQM SADE partly in overlap and parallel with building and testing the deliverable flight models.

Several technical challenges were encountered with non-conformance setbacks before the flight models were ready for delivery.

1 GENERAL DESCRIPTION

1.1 SADA functions

The SADA consists of two SADMs controlled by the MTM on-board computer (OBC) via the SADE. The SADE communicates via two active and two redundant 1553 buses commanding individually the SADMs via stepper motor drives.

The SADE has several specific functions, which are primarily:

- Start-up and driving SADMs within 0.5s from power ON.
- Receiving speed and desired angular position information every 0.5 seconds.
- Commanding the SADMs in accordance with speed/position commands from the OBC and completing the drive profile with acceleration and deceleration autonomous until the SADM positions are reached, or a stop command is received.
- Reporting each SADM position by the performed step commands as well as the independent position readout by the position sensors.
- Receiving programmable instructions.
- Sending housekeeping data.

Figure 1. BepiColombo MTM SADE

Figure 2. BepiColombo MTM SADM

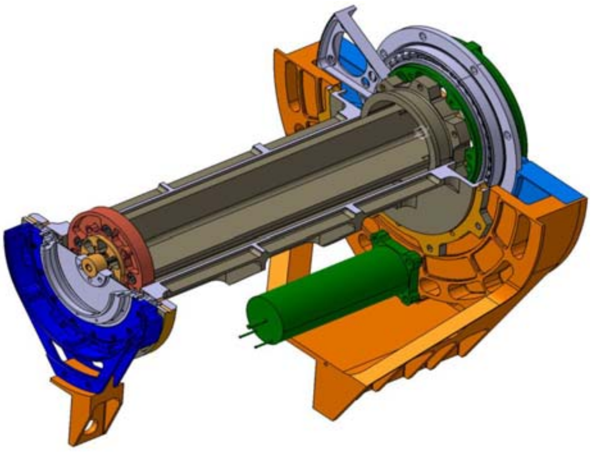

Figure 3. SADM mechanism structural build up

1.2 Slipring

The SADMs uses a hybrid slipring with gold/gold contact technology for 26 tracks with low noise signal transfer from the Solar Arrays and carbon-silver brushes on gold plated tracks for the high power transfer consisting of 2 x 15 tracks, each carrying 12.5A continuous current.

The SADM drive mechanism supports and aligns the slipring shaft as well as the Solar Array loads with a super duplex pre-loaded ball bearing.

In addition, there is a support bearing in the rear of the slipring that provides precise alignment of the rear mounted potentiometers (nom and redundant) as well as load support of the slipring rotor, thereby reducing some of the cross axis bending moment in the front super duplex bearing induced by the Solar Array.

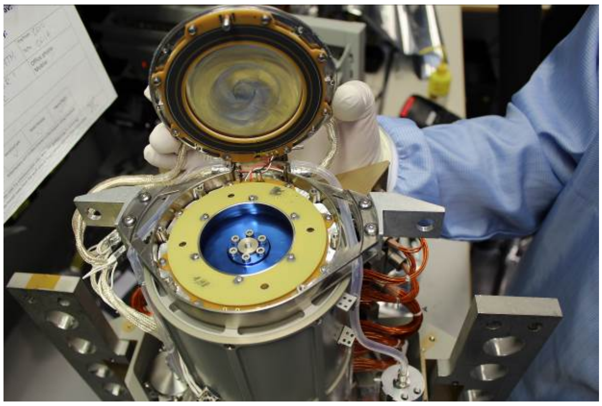

Figure 4. Slipring aft end with potentiometers and (blue anodized) titanium alloy diaphragm providing axial compliance for the ball bearing.

The slipring single row rear ball bearing inner race is mounted into a titanium diaphragm of 0.6 mm thickness, which allows for axial compliance between the slipring shaft and its housing. The diaphragm needs special attention for NDI and is accurately pre-loaded under SADM integration for correct operation and minimising stress and stress cycles in order to be safe against fatigue or potential crack growth under launch and operation in space.

The slipring is designed for high temperatures using high temperature epoxy potting (Duralco 4700) and crimped eye connection with screw attachments for the rotor harness and stator brush wires.

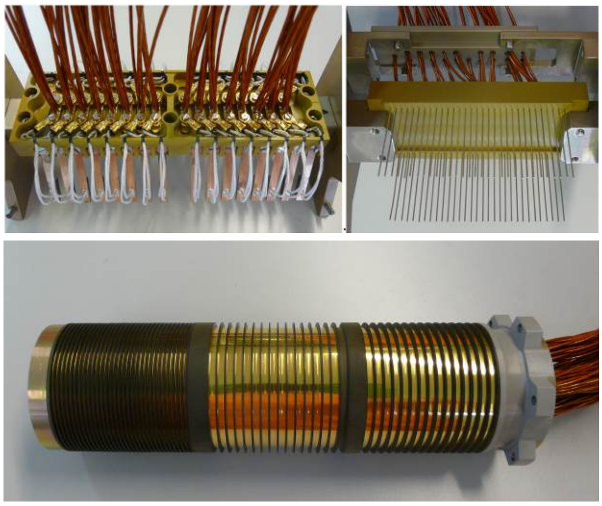

Figure 5. Slipring brush blocks and rotor using hybrid track technology for power and signal

1.3 Drive mechanism

The SADM is driven by a stepper motor and planetary gear unit (actuator) supplied by CDA InterCorp in Florida, US.

The unit was initially developed via an earlier program with ESA for the High Temperature High Gain Antenna Pointing Mechanisms and capable of high temperatures up to 280°C, which proved important for the SADMs as well.

The CDA actuator drives a final stage spur gear (13:1 ratio) with an anti-backlash pinion providing an overall high pointing accuracy of within +/-0.05°.

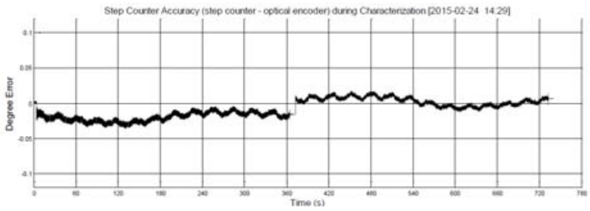

Figure 6. Accuracy between step commands and SADM shaft position measured by an external encoder for 360° step in both directions.

1.4 Position sensor

A potentiometer system is geared off the spur gear running at 13 times the SADM speed (same as the actuator pinion). The potentiometers has a continuous 180° position readout with two wipers are 90° phase angle providing precise 180° saw tooth position readout. Combined with the close to 360° potentiometer in the rear of the slipring, the absolute position is calculated and digitized by the SADE.

1.5 Lubrication

All ball bearings in the drive actuator and the other parts of the SADM, were initially designed and produced with dry lubrication using ESTL's sputtered MoS_2 process and their design of PGM cages produced by JPM of Mississippi in the US. Later in the qualification program, a hybrid lubrication needed to be introduced (refer the test campaign).

1.6 Pressure purging

The SADM was designed to be airtight for avoiding satellite internal air flushing through the unit during pressure drop under launch, but also for being able to purge the SADM internal with controlled flow of dry nitrogen for keeping the MoS_2 lubrication film dry. The external gas flow is distrusted into the SADM via a permanently mounted system consisting of a manifold and PFA hoses feeding into the slipring rear ball bearing, the motor/gearhead and the high-speed potentiometer housing. A PTFE gasket seals the SADM shaft against the housing and the nitrogen gas finally exits via a small hole facing the Solar Array.

2 CRITICAL REQUIREMENTS AND PERFORMANCE

2.1 Temperature

The SADM max and min interface temperatures were initially defined conservatively, and later lowered on the high temperature side, which proved important for reducing the SADM thermal reference point (TRP) from 109°C in the start of testing to 70°C for final qualification.

Still, with high current transfer in the slipring and motor power, the internal parts peak temperatures were high.

The slipring rotor operates in hot case in TV qualification at 115°C with continuous 12.5A feed through all 30 power tracks, while the SADM stepper motor runs on average at about 145°C when running in normal speed mode (<1°/s) and 105°C when in hold mode.

However, when running in fast mode at 6°/s turning away from the Sun in an emergency situation, the motor temperature quickly rises to above 180°C in the motor windings during the approximately 10 minutes allowed for high speed operation with 28W supplied to the motor.

In particular cold case, at -65°C soak temperature, in combination with a large temperature span when including hot case required the use of titanium alloy throughout all the ball bearing interfaces as well as dry lubrication.

Additional friction in cold case is compensated by the increased gross motor torque from increased current under lower resistance with SADE operating in constant power supply mode.

Table 1 SADM Qualification temperatures

Location	Operational		Non operational	
	Cold	Hot	Cold	Hot
SADM TRP				
S/C panel*	-60°C	70°C	-65°C**	70°C
SA yoke	-120°C	120°C	-120°C	120°C

*Panel and inside satellite walls **SADM cold start at -65°C

The SADE temperature was also shown to be critical and driven by the limited conductive heat transfer into the spacecraft panel.

2.2 Drive performance

The nominal required drive mode applying an immediate step rate at any desired speed and direction of the SADMs up to 0.5°/s.

However, in so-called Fast Mode, the SADA needs to accelerate (12°/s^2) the step rate up to the commanded maximum speed of 6°/s in order to be able to handle internal inertia as well as the SA loading.

The SADM position will then lag behind the satellite speed/position commands, which does not necessarily include an acceleration profile. SADE then needs to compensate the lost position (lag) by increasing the speed to catch up on position once the SADM completes its acceleration phase.

SADE therefore controls the SADM in a closed loop control between the step count and satellite commanded position until the difference in commanded and stepped position are equal.

The initial position when the SADA is powered ON is determined by the potentiometer position. The position is read back into the SADE setting the absolute step position.

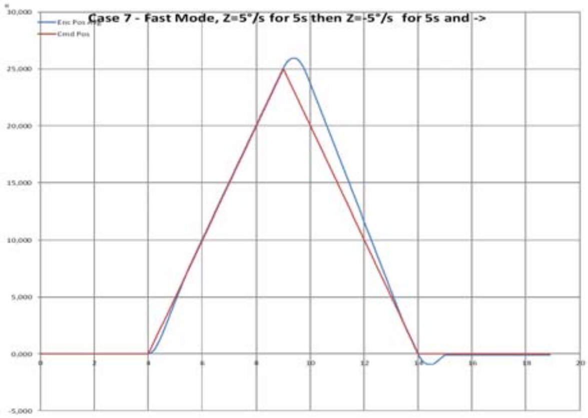

Figure 5. SADM drive profile versus commanded by satellite.

2.3 Absolute position reporting accuracy

The SADM absolute position over 360° is required to be reported via the SADE with an accuracy better than +/-0.2° over the temperature range and operational life.

Due to the temperature range and cost aspects, the position readout was based on potentiometers digitized by SADE. However, in order to manage the absolute position accuracy of +/-0.2°, a multi speed system was required where the high speed potentiometer determines the accuracy, while the single speed determines the number of turns the high speed indicator has performed.

The high-speed potentiometer is geared 13:1 relative the SADM output shaft via the final stage spur gear. The high-speed potentiometer pinion needed also to be split and spring loaded to remove the gear backlash. This was elegantly performed by supporting the anti-backlash part of the pinion via a small ¼ inch flex pivot and producing the gear pinions out of self-lubricating plastic material (Vespel SP3, later changed to Duratron)

In order to manage an absolute position accuracy between the spacecraft panel and the Solar Array, the high-speed potentiometer needed to be ground adjustable at final assembly of the SADMs.

Also, with two systems (nominal and redundant) there is a need for mechanical adjustment between each potentiometer. Finally, to keep the thermal stresses low for optimizing the pointing accuracy and maintain friction torque stable, the potentiometer housing is machined out of titanium alloy.

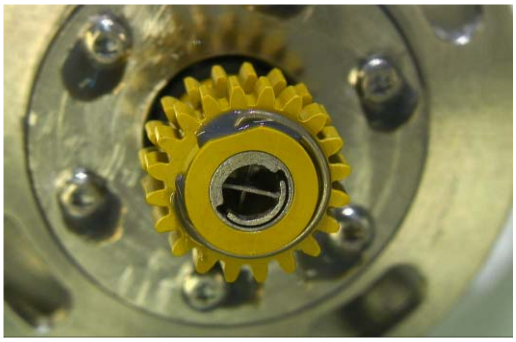

Figure 7. SADM high-speed potentiometer anti-backlash pinion system in Duratron.

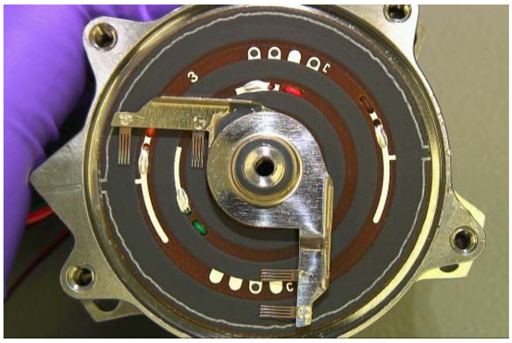

Figure 8. SADM high-speed potentiometer with dual wipers.

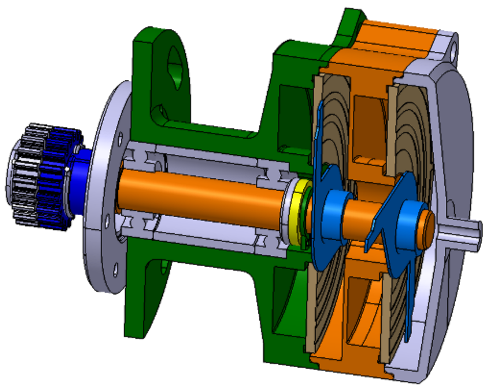

Figure 9. SADM high-speed potentiometer housing in titanium alloy.

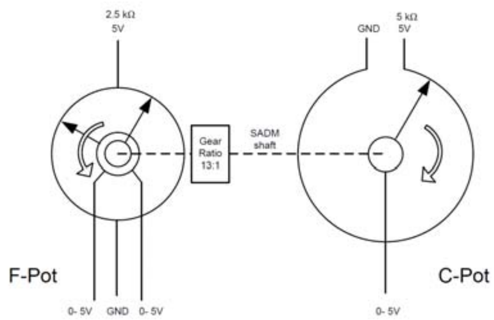

Figure 10. SADM high-speed and slow-speed potentiometer.

2.4 Torque

Due to the high acceleration and heavy Solar Arrays, the drive torque delivered by the SADMs is worst case 40 Nm.

The high load was only identified at the end of the qualification program after it became evident that the Solar Panels could in worst case be commanded in one direction, and suddenly be re-commanded and accelerated immediately in the opposite direction causing more than 3 times the initial acceleration loads from stand still.

A very healthy initial torque budget paid off and proved the power delivered by SADE was sufficient to accelerate the panels with a 40 Nm external resistance including all ECSS required factors.

The SADM torque margin was, for all cases, demonstrated by driving the SADM at reduced current in proportion to the margin required by a dedicated motor driver and data acquisition system for test.

Typically, the SADM will produce 40Nm torque with 375mA, while the SADE will deliver a minimum of 700mA in cold case at worst case 22W power.

3 TEST CAMPAIGN

The qualification and flight acceptance test campaigns were split between the SADM and the SADE, but with a final test of the combined system covering demonstration of the SADE drive algorithm, reading of SA signals, power delivered to the SADMs and EMC tests.

3.1 SADA tests

The first combined test of SADE driving SADM revealed a few system performance errors:

1. Each time the slow speed (coarse) potentiometer passes its dead-band of zero volt, it can read any voltage pending if it samples in the very narrow band (<0.1°) between 5V to 0V. This causes an error in the reported position between 0 to 360°. The impact of this error was minimized by locating the dead-band in a position the Solar Array normally does not operate within and was accepted by the customer.
2. The Requirement Specification specified the SADA to have a maximum speed of 6°/s, but commanded less than 6°/s. The SADE was designed for maximum 6°/s, but for numerical quantification reasons the SADE physical speed proved to be 5.95°/s. When the SADE and SADM were finally tested together at max commanded speed (6°/s), it became evident there was a build-up of divergence of 3° between commanded position and SADM physical position after one minute drive due to the difference in commanded (6°/s) and physical speed performance of 5.95°/s. This problem demanded a re-programming of the SADE FPGA code to allow the SADM to step at a rate giving 6.05°/s.

3.2 SADM QM tests

The SADM Qualification Model test campaign ended up being performed twice for several reasons.

Initially, the first QM was partly damaged in vibration when running into heavy resonance at 100Hz upper sine vibration. The first mode of the SADM with the Solar Array dummy mass of 7 kg 140 mm in front of the Solar Array interface was at approximately 115 Hz and caused heavy response at the upper sine 100 Hz frequency. The SADM ball bearing yielded at the end of the full level sine sweep, which reduced its mode down to 100 Hz causing a fatal sudden response of 200 g acceleration on the dummy mass.

The unit was dismantled and inspected under NRB actions. Finally, the damage was concluded not to be detrimental and in order to save time, the unit was reassembled and the qualification program continued.

3.3 Slipring power tracks contact resistance

The slipring power tracks with carbon/silver brushes showed large increase in static electrical contact resistance after vibration.

Typically, the resistance increased from in average 3 mΩ to an average of 30 mΩ and peak resistance up to 60 mΩ in the position the unit was vibrated.

The risk was that the slipring would overheat in TV if stationary in the position with increased resistance.

A pre-qualification TV test was performed and proved that the brush resistance quickly dropped in a larger rate than the general resistance increase due to temperature when the nominal 12.5A current in all tracks was applied.

The slipring carbon/silver brushes proved never to have a resistive run-away and were very robust throughout the campaign.

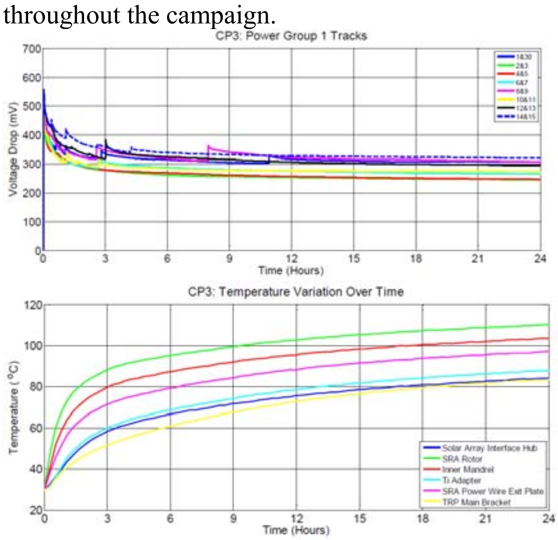

Figure 11. Voltage drop in slipring power tracks at 12.5A and the temperature increase during 24 hours

test in TV with SADM stationary at the position where it was vibrated.

3.4 Failure of high speed potentiometer gear

The high speed potentiometer pinion in Vespel SP3 cracked and broke in shock test and was replaced by Duratron T4203 which is a more ductile material.

3.5 Computer tomography of slipring

Following the heavy overloading of the SADM QM in sine vibration and the areas with substantial increase in contact resistance of the power brushes, it was questioned if the slipring was still mechanically intact.

However, the units cannot be opened for inspection and it was decided that the SADM QM, and later also both flight units, needed to be inspected by use of computer tomography. The SADMs were shipped to ESTEC and inspected using ESAs equipment and expertise. This was an interesting experience but could not reveal any anomaly of the brushes and parts within the resolution of the 3D pictures.

However, it showed the high temperature epoxy, which is very hard and brittle, showed some delamination and cracks in a few locations inside the cavity of the slipring rotor due to shrinkage under curing. High voltage isolation tests showed this had no impact.

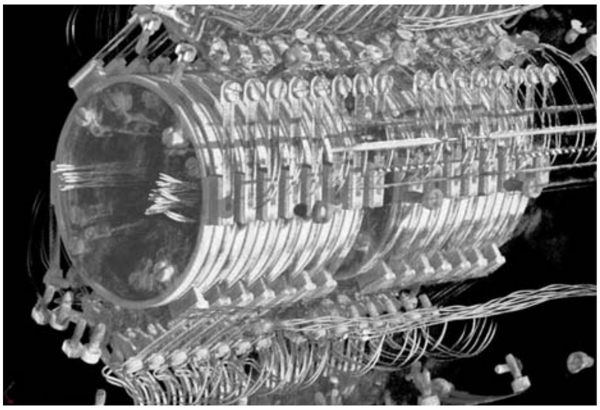

Figure 12. Computer tomography 3D picture of slipring by ESA.

3.6 Lubrication and wear

Inspection of the drive line after pre-mature completion of the first life test due to increased friction in the mechanism showed the motor pinion as well as the final stage anti-backlash pinion system had wear marks in the gear teeth surface. The life was thereby not approved.

This required a second qualification campaign after refurbishment of the SADM QM.

The rebuild included reusing the slipring since this had proven to be robust, while the drive actuator, the spur gear stage and all ball bearings were replaced.

In order to increase the probability of meeting the qualification life of about 800 SADM accumulated revolutions without wearing through the MoS_2 film, a hybrid solution with Braycote 601 grease on top of the MoS_2 coating was chosen for the two critical gear interfaces on the motor pinion as well as the final stage anti-backlash pinion and large spur gear.

Sample pin on disc test were performed at ESTL to prove the hybrid lubrication would not have any unknown negative impacts. The conclusion was that the hybrid lubrication increased the life.

In ESTL conclusion: "*When tested under vacuum at 170°C a lubricant combination of MoS_2 and Braycote 601EF grease yielded an appreciably longer life than the sum of the intrinsic lives of the MoS_2 alone and the Braycote 601EF grease alone.*"

Further studies of the hybrid lubrication have since been performed by ESTL and presented at the "Final Presentation Days" at ESTEC.

Finally, SENER also decided to modify and introduce hybrid lubrication for their APM on the BepiColombo MPO High Gain Antenna.

3.7 Drive torque for rotating the Solar Arrays at high speed

One challenge in the test program was to simulate the significant Solar Array inertia loading and demonstrate torque margin not only in tests outside the vacuum chamber, but also during the thermal vacuum cycling in hot cold and cold non-operational start-up.

Building a dummy inertia of 37 kgm^2 is not very practical or handy to operate. Also, it creates non-realistic loading on the SADM when running accelerated testing of the mechanism above the nominal operational speed of maximum 0.5°/s.

Two solutions were applied. A smaller 2.5 kgm^2 inertia wheel with flexible spokes was applied with approximately the Solar Array fundamental mode at 1Hz for providing a correct mode and loading the SA under accelerated life testing.

For high torque loading under Fast Mode acceleration, a simple and very cost effective method was applied by coupling the SADM shaft to an aluminium rod of the proper diameter and length.

The rod was sized to provide an increase in torque per angular rotation approximately equal to the predicted inertia from the Solar Array when accelerating at 12°/s2 up to 6°/s. When the peak moment in the rod is obtained, sized for about 17Nm, the section yields in a fully plastic condition and the moment stays quasi-constant until the SADM is stopped. The rod is capable of rotating several revolutions before it finally ruptures. Thus, it can be torqued repeated times for short tests over only a few degrees (20° per test approximately).

When using the rod ("Dog Bone") in the vacuum chamber, a mechanical coupling was made between the SADM and the rod allowing the SADM to rotate freely for 360° before engaging the Dog Bone at each end of the turn. Thus, when the stall torque was measured, the SADM was carefully driven until the Dog Bone was engaged. Then stopped, pre-loaded and accelerated up to 6°/s under the load from the aluminium rod.

Very late in the program at the end of qualification and flight units acceptance, it was identified that the Solar Array inertia torque could in worst case be more than tripled to 40 Nm if the SADM was stopped and reversed in fast mode. Finally, a stall test was required to demonstrate the required torque margin.

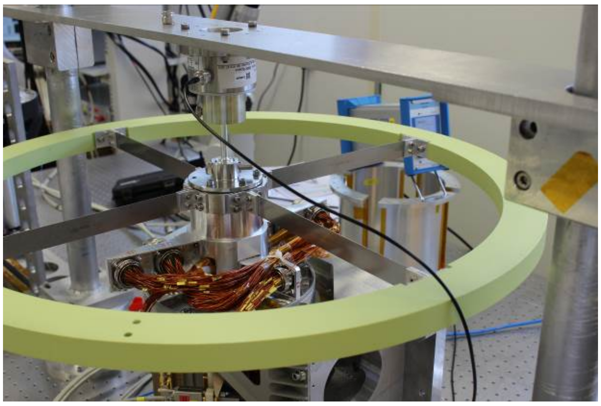

Figure 13. 2.5 kgm^2 dummy inertia load and aluminium torque rod that yields in torsion simulating higher torque loads.

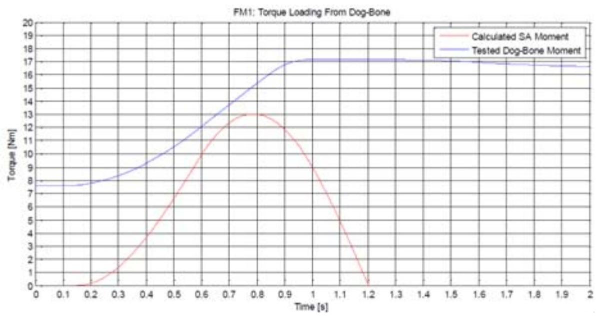

Figure 14. Moment in aluminium rod under acceleration of SADM to 6°/s with 12°/s2 overlapping calculated inertia loading from Solar Array.

3.8 Thermal Vacuum test

Thermal vacuum tests included a test set-up enabling heating and cooling of the spacecraft interface as well as the Solar Array via radiative coupling.

It also included continuous power of the slipring while the individual voltage drop of each track could be monitored. Also, four point measurements of all the power brushes track contact resistance could be measured.

The SADM position was measured by an externally mounted optical encoder with bearings driven by a coupling to the SADM shaft. The encoder needed to be decoupled from the SADM in order not to avoid overheating its electronic read heads.

The SADM was located with the shaft in vertical position with the dummy inertia loading (fly wheel with spokes). Finally, high Solar Array torque loading via the 360° free coupling into the aluminium rod could be performed when needed.

4 LESSONS LEARNED

There were several and continuous lessons learned through long development and MAIT phase over a period of 5 years with a program originally planned for 2.5 years.

The major lesson learned was the complexity of deep space science missions requiring new development of equipment and thereby loss of heritage posing a major development risk, which can only be mitigated by testing on breadboard and Engineering Models and dividing sufficient time for the design phase reduce risk. The SADA program only had room for one SADM BBM and SADE EM, which were both not sufficiently detailed to identify all risk.

System simulation are also a valuable verification of software and hardware performance. Some of the system errors encountered would probably have been identified before first live system tests on the Qualification Models if detailed simulations had been performed.

NCs on Qualification and Flight Models are very time consuming and can cause up to ½ year delay with involvement of all parties. NC design errors should as far as possible be identified and eliminated on BBM and Engineering Models.

On the occasion of immature requirements combined with a lack of clear common understanding at an early stage between the customers at system level and the developer was shown in some major cases to be vital and could have eliminated later misunderstandings which proved costly.

One other major lesson learned is the need to close down and agree systematically on requirements verification through all stages of the design and MAIT phase. Verification of general design and environmental requirements, which numbers up into several hundreds to thousands, needs to be agreed closed at PDR and CDR to avoid open issues after the design is frozen.

The escalation of required verification control matrix details caused a major work task at the end of the program, which should have been closed once the design and test scope was defined.

5 CONCLUSIONS

The BepiColombo MTM SADA C/D program posed a major challenge with a large overrun in development time of several years before final successful delivery of the flight model consisting of one SADE PFM and two SADM FMs including spare kits.

Some major NCs could probably have been avoided with a better early common understanding of the system requirements with subsequent shorter schedule.

Several other NCs were caused by design risk not properly identified at an early stage.

The final conclusion is that all tests showed the system to be robust and meeting the requirements.