DEVELOPMENT AND QUALIFICATION OF THE EUROSTAR NEO SOLAR ARRAY DRIVE MECHANISM

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ABSTRACT

Airbus have made a transition from their Eurostar 3000 ("E3000") to the innovative Eurostar Neo ("E3Neo") platform in response to the ESA NeoSat program.

One key adaptation was the simplification of the drive electronics used to control the Solar Array Drive Mechanism ("SADM"). To accommodate this change Airbus developed a new Neo Stepper Motor & Gearbox ("NeoSMG"), and planned to qualify this element.

Due to evolving changes at spacecraft System level the scope of modification to the SADM grew, and this resulted in a larger development and delta-qualification than was planned, being just the new stepper motor.

This paper presents the successful development and delta-qualification of the NeoSMG and the Neo SADM equipment, and the lessons learnt.

1 EUROSTAR 3000 AND HIGH POWER SADM

The Eurostar 3000 High Power SADM ("HP SADM") product is a benchmark of reliability and performance for geostationary orbit telecommunications spacecraft.

Figure 1. E3000 High Power SADM

This SADM and its Power and Signal Slip Ring Assembly ("PSSR") – the PSSR is supplied by Beyond Gravity in Nyon, Switzerland − is designed for high power transfer and very high local thermal dissipation (electrical contact heat transfer). It has the capacity to:

- Transfer power of 21 A at 110 V over each of 12 circuits (forward & return), providing a total of up to 27.7 kW per wing,
- Transfer signals of 1 A at 50 V on 35 circuits (single direction lines), and
- Drive large E3000 solar array wings up to some 200 kg and 500 kg.m^2.

The product claims significant heritage, with 30 flight units on 15 spacecraft operating successfully in orbit, and a cumulative life of over 112 years. The first pair were launched in July 2013 and are now more than two-thirds through their design life of 15 years. There have been no in-orbit anomalies.

2 EUROSTAR PLATFORM EVOLUTION

In response to ESA's NeoSat program and the call for a next-generation yet cost-effective geostationary telecommunications platform Airbus developed Eurostar Neo, an evolution of their high reliability and high heritage Eurostar 3000 spacecraft platform product. The HP SADM equipment was selected as part of the Eurostar Neo design baseline and would be considered an off-the-shelf heritage equipment, subject to the following modification.

One key platform adaptation for Eurostar Neo was the simplification of the drive electronics used to control the SADM. On E3000 the HP SADM had been driven in bipolar mode with two motor phases via constant current supply, with 1/8th mini-stepping current levels (linearly ramped), for a total full step size of 0.032°. This control was modified for E3Neo to constant voltage supply with full steps of 0.004°, being 1/8th the previous full step size.

To accommodate the new drive electronics Airbus UK developed the Eurostar Neo variant of the HP SADM, named the Neo SADM. A new Neo Stepper Motor & Gearbox ("NeoSMG") was thus developed by Airbus UK and their supplier Reliance Precision Ltd. (Huddersfield, UK) in cooperation with ESA. This development was part of an initiative to foster new European equipment suppliers, particularly for an SMG.

The NeoSMG featured a new 2-stage orbital gearbox, replacing the incumbent 3-stage planetary gearbox, but maintaining the same 200:1 transmission ratio. The incumbent 8-step permanent magnet stepper motor was replaced by a novel 64-step permanent magnet stepper motor, both 2-phase and driven in bipolar mode. The NeoSMG motor is the first of its kind to market.

The NeoSMG has near-identical mechanical interfaces, volume and mass properties to the incumbent E3000 SMG. The electrical interfaces are similar albeit with a change in winding resistance and inductance due to the new motor design.

Other than replacing the E3000 SMG with the NeoSMG there were no changes foreseen to SADM interfaces or environments (mechanical, thermal, etc.).

2.1 Initial Development & Qualification Plan

The SADM was not intended to be modified other than for the new NeoSMG. The NeoSMG in turn was designed to be a direct ‘swap in’ replacement for the incumbent E3000 SMG actuator (from a different supplier). It was thus envisaged to only qualify the NeoSMG sub-assembly and its interfaces; primarily, this is the single spur gear pass drive coupling to the main shaft of the SADM, although other interfaces (e.g. electrical, etc.) and their impacts were also considered.

The initial development plan comprised the following:

- Full design & analysis of the NeoSMG at sub-assembly level, using environmental boundaries and inputs generated from SADM-level analysis and measurements made during the HP SADM qualification testing (and flight family data),
- Full qualification of the NeoSMG on a simple SADM-representative test bed, using the above environments and inputs, and providing appropriate rotational inertias and damping to satisfy the needs of the NeoSMG operation.

The SADM-representative test bed mentioned above would comprise only necessary elements needed to support testing of the NeoSMG, and would not be classed as ‘hardware under test’ itself.

2.2 Changes to the Neo SADM Development

As previously stated, the SADM was not planned to be modified other than for the new NeoSMG. However, there were a series of further changes to the architecture, interfaces and environments that occurred both prior to and following release of the equipment’s requirements specification. Some of these changes resulted in a protracted detailed design & co-engineering phase effectively held concurrently with the Critical Design Review (“CDR”).

Additionally, during the Neo SADM’s development phase it was also baselined for use on OneSat, another new and innovative spacecraft platform product being developed by Airbus. Use on this other spacecraft application presented some small deltas in environments and operation. In order to avoid a second full qualification and life test, these deltas were incorporated as much as was deemed feasible, into the Neo SADM qualification.

2.3 Final Qualification & Life Test Scope

The net result was a far larger delta-design and delta-qualification scope at SADM level than was planned. A full SADM-level Engineering Qualification Model (“EQM”) was assembled, comprised of an available flight-standard HP SADM unit which was converted with appropriate modifications to become sufficiently representative of the Neo SADM design & configuration. This Neo SADM EQM was fitted with the Qualification Model (“QM”) NeoSMG provided by supplier Reliance Precision Ltd.

The Neo SADM EQM (with NeoSMG QM) was subject to the following qualification campaign, where the set of tests captured any deltas from the existing qualification and life test heritage; the tests included:

- Mechanism functional testing throughout the test campaign, including minimum running torque (via start-up voltage measurement), performance of slip rings, datum sensor and potentiometer, and exported “disturbance” torque,
- Electrical measurements throughout the test campaign, including circuit resistance, insulation resistance and bonding resistance,
- Electromagnetic coupling capacitance and the resulting cross-talk between the new NeoSMG and the signal slip rings,
- Solar array interface half-cone angular error, including under a high cross-moment load,
- Stall torque measurements,
- Performance measurements driving ‘large’ rigid and flexible test inertias of at least 30 kg.m^2,
- Qualification mechanical environments, including high-sine, quasi-static and random spectra vibration, and shock,
- Qualification thermal environments in vacuum with 7 qualification plus 17 life test thermal cycles, as well as an electric orbit raising phase,
- Operational life (revolutions) to ECSS under an in-air environment, including revolutions under a high cross-moment load,
- Operational life (revolutions and other types of motion – see Section 3.5) to ECSS under thermal vacuum conditions, with an acceleration of 200x.

The testing listed above was carried out successfully.

3 EVOLUTIONS IN DESIGN, INTERFACES & ENVIRONMENTS

The suite of additional changes and evolutions are detailed within this section. Each change is described and then the resolution is presented, be it a design modification or a new or modified verification need (via analysis and/or testing).

3.1 Solar Array Harness Form and Connectors

The geometry of the solar array yoke was modified between E3000 and E3Neo. Fig. 2 illustrates these harness forms where E3000 (left) used either a ‘straight’ or ‘Y’ shape and E3Neo (right) uses a ‘V’ shape. The lengths of each harness bundle vary between the various configurations shown.

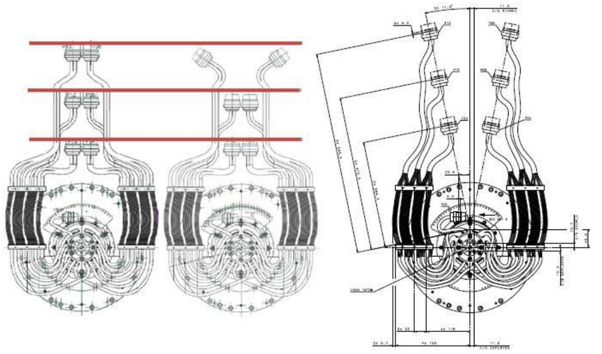

Figure 2. E3000 & E3Neo Solar array yoke shapes

Additionally, the type of electrical connectors on the solar array side harness were modified. On Eurostar 3000 the six electrical connectors on the solar array side were fitted with three sets of mechanical keying (angle of the keyway relative to the pins) such that the different harness lengths combined with the different keying prevented incorrect mating of any one connector to the solar array. For simplification on Eurostar Neo the three keying configurations were harmonised to a single design.

These changes were deemed to have no impact onto qualification at SADM level. For example, that section of the harness is located past mechanical fixation points on/over the deployment hinge and is effectively decoupled from the main mechanical environment applied to the SADM.

However, these changes did affect ground support equipment. New build fixtures (‘wiring jigs’) needed to be designed and manufactured. Electrical test harnesses were no longer compatible, which again required new harnesses to be designed and manufactured. This represented a significant non-recurring (hidden) cost and non-trivial lead time for development, procurement and validation prior to use on / interface with the flight hardware.

3.2 Removal of Potentiometer Position Sensor

The E3000 HP SADM featured two position sensors at the output stage of the transmission:

- An absolute angular position sensor in the form of a potentiometer (fully redundant with offset deadbands) fitted to the ‘top’ of the PSSR – potentiometer supplied by Exxelia in Paris, France. This sensor provides angular information of the solar array wing relative to the main body of the spacecraft.
- A low-resolution relative position sensor which is used to track a specific datum point (at the 0° output position) and then the general rotation around it; i.e. in which hemisphere the output is located, with the objective of finding the shortest distance to reacquire the sun when the spacecraft is in its emergency operational mode. This sensor is embodied by an infrared opto-coupler (fully redundant pairs of light-emitting diodes and photo-transistors) with a rotating shutter that passes between the transmitters and receivers. The shutter has different patterns of apertures over the 180° arcs on either side of the datum.

The need for absolute position information (provided by the potentiometer device) was removed for Eurostar Neo with revised architecture for Guidance, Navigation and Control (“GNC”). It was consequentially requested that the potentiometer device be removed from the SADM assembly.

Removal of the potentiometer from the SADM assembly is not complicated as it is essentially a ‘bolt on’ to the end of the PSSR. The device has minimal contributions to motorisation (low running torque from friction), does not draw any significant power and does not generate any significant thermal dissipation. Removal of the point mass also improves loads generated on the PSSR during mechanical environment, particularly with respect to cantilever modes.

Thus, removal of the potentiometer device could be mistaken for a simple change with little impact on flight use, or even with some small but beneficial impacts. However, impacts on ground use need to be considered. The test methodology for the HP SADM is heavily reliant on the provision of absolute angular information at a reasonable precision (resolution down to motor step level); for example, to perform start-up voltage tests and for verification of cold start up. Historically, the flight potentiometer device has been used to provide this test telemetry rather than a separate test sensor such as an optical digital encoder.

After some assessment a decision was reached to continue to fit the potentiometer for use on ground. The device would be installed onto the SADM as per normal process, used during testing and would then be removed from the SADM following completion of the acceptance test campaign. The potentiometer device would then be re-used on a different SADM unit and so on and so forth. This approach offered the following benefits:

- No major change to build and test processes, with regards to routing, detailed works instructions and declared materials & processes,
- No impact on heritage test methodology, with no additional risks that might have arisen due to a change in test setup and methodology,
- Continuity of test data for the purposes of family assessment and trending,
- Enlarging the qualification envelope of the potentiometer device (as used on the SADM) and effectively maintaining qualification of flight use of the potentiometer on the SADM for possible future variants or specific mission needs.

3.3 Thermal Environment

The original qualification of the E3000 HP SADM (due to some post-life test observations) placed a constraint on the minimum temperatures of, and corresponding temperature gradient across, the main duplex bearing pair of the Power & Signal Slip Ring Assembly (“PSSR”). Consequently, this placed a design and operational constraint on the spacecraft conductive boundary, to be no less than -20°C.

At a late stage of the E3Neo platform development it was found that there was insufficient power available to the thermal control subsystem in order to meet this constraint during the Electric Orbit Raising phase (“EOR”). The minimum operational temperature for the spacecraft conductive boundary was found to be at -28°C during this phase of the mission.

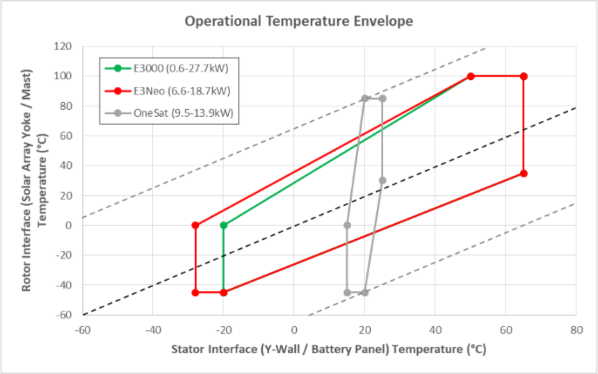

Figure 3. E3000, E3Neo & OneSat thermal envelope

Unfortunately, no options existed at spacecraft system level to resolve this exceedance. Instead the low boundary temperature was resolved by implementing active thermal control within the SADM itself. Two heaters circuits of 20 W capacity each (primary and redundant) were added as well three additional flight thermistors at an appropriate location for the temperature reference point.

Implementation of the 20 W heating (operated below saturation with respect to duty cycle) was sufficient to maintain the temperature of the PSSR bearings within their previously established temperature limits.

It is important to note the onward impacts to the larger SADM equipment, with implications onto design analyses and verification tests, changes in electrical routing and connecter pin allocation, updates to declared materials and processes, etc. In order to validate the revised thermal balance of the SADM this modification triggered the need to perform a delta-qualification at SADM level itself (not just the NeoSMG).

Also note modifications needed for ground support equipment such as electrical test harnesses, which represent a significant non-recurring cost and lead time for development, procurement and validation.

3.4 Shock Input Spectra

The shock input spectra for both Eurostar Neo and OneSat presented exceedances with respect to the shock input spectra for Eurostar 3000, as shown below in Fig. 3. This exceedance represented a limitation of the HP SADM qualification for these new applications.

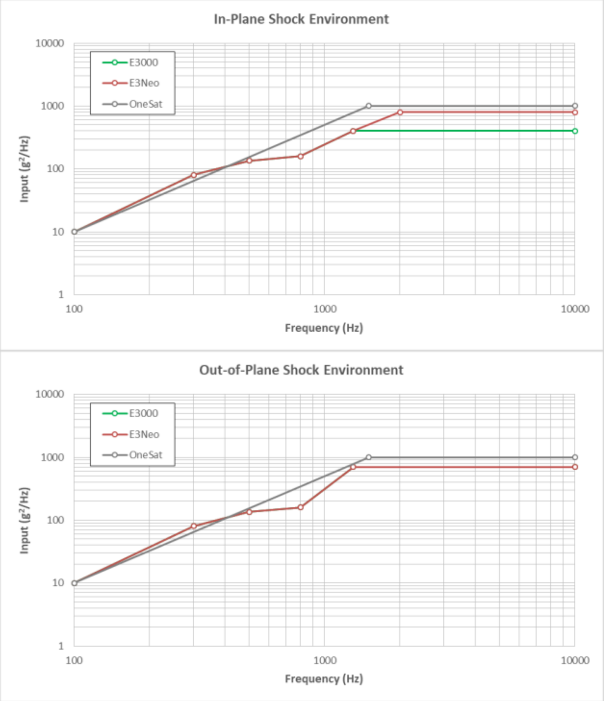

Figure 3. E3000, E3Neo & OneSat shock spectra

As a result, there was a need identified to delta-qualify the SADM and its subassemblies and elements, not just the NeoSMG, via dedicated shock testing. The increase in the shock environment also triggered the need to delta-quality the operational life of the SADM main bearings and of the PSSR bearing set (or at least to 'validate' the previous life test).

3.5 Electric Orbit Raising Phase

Eurostar 3000 was the first large geostationary orbit telecommunications platform to demonstrate electric orbit raising ("EOR") to reach its operational altitude. The Eurostar Neo and OneSat platforms have continued the strong Airbus heritage of EOR missions and have made some further improvements with regards to efficiency of this transfer phase.

During electric orbit raising each orbit increases the spacecraft altitude. The motion of the SADM during each of these orbits is described as a 'boost cycle,' a sinusoid of amplitude up to approximately ± 25°, operating between 0 and 19.2 revolutions per day, with an incremental change in position of approximately 1°/day. This profile is shown below in Fig. 4.

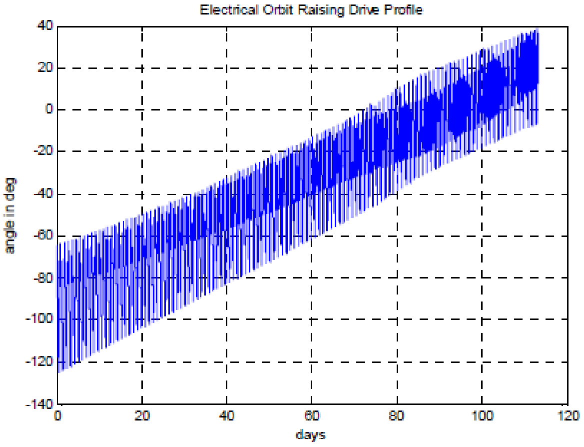

Figure 4. Electric orbit raising boost cycle drive profile

As part of the EOR profile for these new platforms some orbits feature a relatively low altitude perigee, which passes through the upper atmosphere. In order to reduce atmospheric aerodynamic drag the solar arrays are turned 'into the wind' such that their plan area is considerably reduced. During the atmospheric crossing the solar arrays are also trimmed by ± 3° to support GNC needs.

This low perigee manoeuvre thus comprises the following sequence of motions:

– + 90° rotation	Turn into wind
– ± 3° motion	Trim
– - 90° rotation	Return to sun tracking

As expected, operation during the EOR phase is more heavily defined by directional reversals ("inversions") than by total driven distance. This is the opposite of on-station life where there are few-to-no inversions but many thousands of continuous full revolutions. An illustration of the overall EOR motion is presented below in Fig. 5.

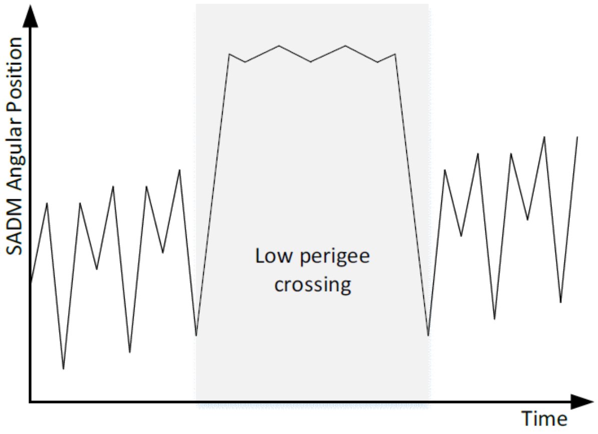

Figure 5. Electric orbit raising profile (approximated)

Note also that EOR for OneSat requires a higher quantity of low perigee crossing manoeuvres, which was included in the EQM qualification & life test.

Subject to the varying aerodynamic pressure and solar array plan area a cross-moment (bending) load of maximum 86 Nm is applied to the solar array interface of the SADM. This loading, applied during SADM rotation, is higher than the 23 Nm seen during EOR on Eurostar 3000 and is also applied over a higher SADM distance travelled. Consequently, there was a need identified to make performance measurements and to perform operational life whilst under this high cross-moment load.

A cross-moment load results in a higher angular deflection of the SADM main bearings (and thus the solar array output plane) as the load acts against the cross-moment stiffness. Additional measurements of the solar array output plane half-cone angular error were made and these demonstrated a higher angle but remained compliant to specified limits.

A cross-moment load changes the axial loading across the SADM main bearings, with the balls/races on one side experiencing an increased load and Hertzian stress, and the opposite side balls/races experiencing a decreased load and Hertzian stress. With regards to the practical considerations of life testing, it was found that the ground support equipment used to generate the cross-moment load was incompatible with the volume of the thermal vacuum chambers used for SADM testing. Additionally, it would not have been practical to recover the chamber to ambient pressure and then re-pressurise in order to change the external loading during the thermal vacuum life test.

Thus, life revolutions under this cross-moment load were performed in the in-air environment. This environment is furthermore worst case due to the oxidation effects onto the solid lead layer lubrication used on the SADM gears and bearings. Additional revolutions in vacuum (without the cross-moment load applied) were still performed in order to meet the ECSS factoring on revolutions in the vacuum environment.

4 QUALIFICATION ANOMALIES

4.1 Coupling Capacitance

Electromagnetic coupling capacitance was measured between the NeoSMG circuits and the signal slip rings (at both ends of the signal section of the PSSR). Unfortunately, the measured performance exceeded the specified limits.

Extensive work was carried out to assess any commonalities in harness runs, shielding, grounding, etc. It was found that there were no significant differences between the Neo SADM and HP SADM designs. Considerations were made towards the spectral characteristic of the NeoSMG operation, being up to only approximately 50 Hz, noting that coupling capacitance typically acts as a high-pass filter.

Finally, characterisation testing was performed to measure electrical cross-talk, which is the actual performance which coupling capacitance affects – cross-talk is effectively the amount of electrical noise imparted onto the signal slip ring circuits due to electromagnetic cleanliness effects. It was found that despite the high measured coupling capacitance there was negligible (too small to be measured) impact on the electrical performance of the signal transfer circuits.

A deviation was raised against the respective requirement, and this deviation was subsequently incorporated into an up-issue of the Neo SADM requirements specification.

4.2 Potentiometer Failure in Vibration

Following the vibration test some anomalous operation of the potentiometer angular sensor was observed. The electrical characteristic was indicative of damage to the resistive (forward) track.

It was found that the qualification level random spectra applied onto the Neo SADM EQM was high at the location of the potentiometer device, with grms reaching levels seen on some previous qualification tests at Airbus. On those occasions similar failures were observed and were confirmed to be due to fretting of the electrical wipers with the resistive track.

Since the potentiometer is no longer a flight device on the Neo SADM (and can be considered as a test sensor) it was removed and replaced. For future use as a flight device, or at least for future qualification unit testing, it was noted that appropriate notching would be required.

5 QUALIFICATION SUMMARY

The qualification and life testing was carried out successfully with only minor anomalies raised, as previously discussed. Both the NeoSMG and Neo SADM itself demonstrated excellent performances throughout life and environments, and the qualification was agreed as successful and closed by all parties (Airbus UK supplier and Airbus internal customer, and external commercial customers and ESA).

Some points of interest regarding the qualification are discussed below.

5.1 Life Factoring Approach

The Neo SADM, via its requirements specification, is subject to commercial life factors (1.5x) and with functional testing to provide the metrics for success. There is a caveat that life testing continues up to ECSS life factors (as per the ECSS Mechanisms Standard) after which there is a strip down and inspection; here the success criteria is for wear debris, etc. as per the ECSS Mechanisms Standard.

The success criteria after performing life to ECSS factoring was agreed to be include both functional performance (50% increase in friction) and strip down & inspection, as per the ECSS Mechanisms Standard.

By the Life Test Readiness Review ("LTRR") the need date for the Neo SADM flight units (and thus the completion of the qualification) was not too distant. There was a consensus within the NeoSat joint project team (industry & agency) to ensure that there were protections on schedule. A pragmatic approach was taken towards factoring the various types of motion.

– On-ground revs. (In-air & vacuum)	ECSS factoring (4x)
– EOR motion	1.5x factor
– EOR revolutions	ECSS factoring (10x/4x/2x)
– GEO revolutions	ECSS factoring (10x/4x/2x)

Furthermore, for the flight revolutions in vacuum the factoring was applied at the NeoSMG output shaft level rather than at the SADM main shaft level. Given that the revolutions at NeoSMG output shaft level are 7x those at SADM main shaft level, a greater proportion of revolutions fall into the 2x factor bracket instead of the

4x factor bracket. Consequently, the total number of factored revolutions is lower (2.07x instead of 2.37x).

This approach was considered to be sufficiently robust due to the NeoSMG needing a full initial qualification whilst the SADM itself was only a delta-qualification and/or a re-validation of its heritage qualification.

The final *as-tested* factor at SADM level ended up as 2.23x, almost perfectly in the middle of the above values, and equating to 35.6 years simulated in test.

5.2 OneSat Thermal Gradients

For the application of the SADM on the OneSat spacecraft platform the thermal environments presented an interested dilemma. Both hot and cold temperature extremes were far more benign than for Eurostar 3000 or Eurostar Neo. However, the temperature gradients between the spacecraft and solar array interfaces were higher. These gradients in the conductive boundaries cause high temperature gradients across the SADM main bearings.

Whilst the absolute hot and cold temperatures were easily accommodated within the Neo SADM EQM qualification and life test the bearing temperature gradients could not be incorporated without presenting significant risk to the Neo SADM and NeoSat program.

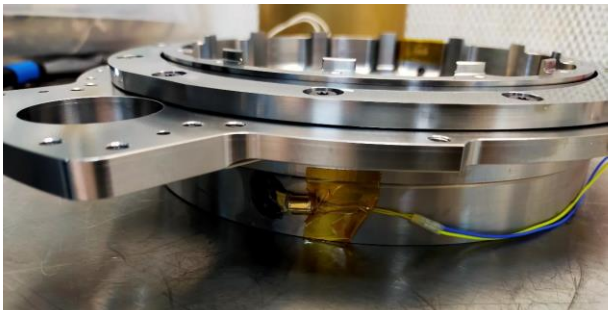

Figure 6. SADM bearing assembly modified by ESTL

In order to delta-qualify the SADM main bearings for OneSat a dedicated test was performed by the European Space Tribology Laboratory (“ESTL”) with a bespoke and novel test setup to accurately measure and control the temperatures across the rotor and stator elements of the assembly.

This bearing assembly-level life test was performed successfully, meeting the criteria specified in the ECSS Mechanisms Standard, and with no anomalies.

6 LESSONS LEARNT

Some lessons learnt from the Neo SADM development and qualification are presented below.

6.1 Ground Support Equipment

The first and most important lesson learnt relates to the impacts, intended or not, on Ground Support Equipment (“GSE”). The reader will have seen examples presented earlier where new mechanical build fixtures and/or electrical test harnesses were needed.

In the example of the change of electrical connector keying, it was requested by the SADM’s customer as a means of cost reduction via standardisation. However, the unintended consequence was that the Neo SADM became incompatible with the existing electrical harnesses. There was a considerable cost and schedule impact.

It is thus recommended to maintain interface similarity between variants of mechanism equipment as far as practically possible.

6.2 Maximum Value from Development & Test

This paper has presented several examples where the needs of the OneSat spacecraft platform were incorporated into the Neo SADM qualification. In particular, note the higher shock environment and additional EOR life needs.

A complete qualification and life test for the OneSat application would have been needed due to the particulars of its environment and life. Subject to a risk assessment against the Neo SADM qualification, some of these aspects were incorporated. The net result was to avoid a repeat qualification and life test activity, but also that the Neo SADM qualification envelope for use on Eurostar Neo was made larger and more robust.

Airbus once again thank our industry and agency customers for their pragmatism and acceptance.

6.3 Testing on a Representative Assembly

The initial qualification plan comprised of testing the QM unit NeoSMG on a ‘light’ SADM test bed. As discussed, the test bed evolved into a full SADM EQM assembly, and provided the following outcomes.

The mechanical environment inputs to the NeoSMG interface were found to be lower than those predicted by finite element stress models, due to additional damping from the full set of SADM components and elements. These more realistic qualification input levels were consequently able to be passed back to the supplier in order to revise the acceptance environment applied onto subsequent flight units.

The fully representative SADM assembly also allowed for correct and detailed characterisation of the electromagnetic cleanliness effects of the NeoSMG onto the signal slip ring circuits; i.e. coupling capacitance and the resulting cross-talk between circuits.

6.4 Life Factoring Approach and Level

As discussed, pragmatic approaches can be taken with respect to life testing. In this case where the commercial requirements are specified and the ECSS Mechanisms Standard is not applicable in its entirety, a balance was found between the needs of industry and agency.

Furthermore, the factoring approach to life revolutions at the NeoSMG output shaft level provided a welcome reduction in the life test duration whilst balancing the respective risks between the new and heritage elements of the SADM.

It is recommended that these types of relaxations should be considered as standard alongside typical concessions of mechanisms life testing such as speed acceleration.

7 CONCLUSION

This paper has presented the evolving yet ultimately successful development and delta-qualification of the Neo SADM product, and the corresponding initial qualification of the NeoSMG.

It has been written not to discuss ‘just another equipment qualification’ but to try capture the experience and lessons learnt during the Neo SADM development and qualification process, and to pass these on to the wider space mechanisms community. In particular, note the considerations of delta-qualification and industrialisation of a new variant of an existing high reliability and high heritage equipment.

The project has drawn from significant qualification and flight heritage of the HP SADM product and from the width and breadth of expertise within the Airbus transnational Mechanisms Product Group. The Neo SADM development journey has effectively enlarged and strengthened the qualification envelop of the HP SADM family, now consisting of variants for each of the Eurostar 3000, Eurostar Neo and OneSat spacecraft platforms.

At the time of writing there are six Neo SADM (with NeoSMG) flight units on three spacecraft operating successfully in orbit. The first two spacecraft were launched in the fourth quarter of 2022; they have both completed their electric orbit raising phase and are now on-station in their respective slots in the geostationary ring.