TEST & INSPECTION CAMPAIGN OF SURREY SATELLITE TECHNOLOGY LTD FIRST GEOSTATIONARY WHEEL

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ABSTRACT

From January 2015, Surrey Satellite Technology Ltd (SSTL) had the opportunity to develop a wheel for a SSTL GEO mission. SSTL is under contract with prime contractor Airbus Defence and Space (ADS), who are supplying the flexible payload for the spacecraft. In September 2015, SSTL held a Test Readiness Review with key personnel from ADS and the European Space Agency (ESA) for an ACM (Actuator Confidence Model) in order to de-risk the mechanism as early as possible in the program. A qualification test program on the ACM proceeded, comprising full EVT and then six months confidence life tests designed to put the mechanism through harsher profiles than normal operation, followed by complete disassembly and inspection down to bearing component level. The inspection revealed a few secondary findings within the mechanism (not within the bearings) that required explanations and a solution and SSTL resolved these such that a final sign off of the ACM from was completed in June 2016. Since the start of the main development phase in 2015, the mechanical structure, a new speed measurement encoder, a new motor, completely new radiation hard electronics to Class 1 and firmware has been designed and developed by SSTL, in preparation for the Engineering Qualification Model (EQM).

This paper will discuss the test and inspection campaign of the Actuator Confidence Model (ACM) wheel, the challenges of obtaining the required level of confidence for a mechanism that is required to operate successfully in excess of 15 years and the resultant conclusions and lessons learnt/recommendations for future.

1. INTRODUCTION

Table 1 lists the main requirements of the GEO wheel.

Table 1. SSTL Main GEO Wheel Requirements

Requirement	Specification
Torque	>=200mNm to +/-4200rpm
Momentum	12Nms
Speed Range	+/-5000rpm
Operational revolutions	20 billion
Zero crossings	32580
Lifetime (orbit)	15.25 years
Power consumption	~150 Watts at full torque ~13 Watts at 4000rpm
Mass	<6kg
Volume	~240 diameter x 95mm high
Temperature	-20 to +50°C (operating) -30 to +60°C (survival)
Vibration	High sine : 50g Random : ~11 to 14 grms
Shock	100Hz (20g) to 10000Hz (1000g)
Unbalance	Static < 4.5gcm^2 Dynamic < 20gcm^2 (post EVT)

1.1. Model Philosophy

Table 2. SSTL GEO Wheel Model Philosophy

Model	Quantity	Status
Life Test Model (LTM)	1	Operating indefinitely > 14 billion revolutions >32,000 zero crossings
Actuator Confidence Model (ACM)	1	Testing complete
Engineering Qualification Model (EQM)	1	Testing commencing Q3 2017
Proto-flight Model (PFM)	4	Testing commencing Q1 2018

As shown in Table 2, the model philosophy consists of a Life Test Model (LTM) that was originally developed for a Giove-B ESA program in 2008. SSTL's new GEO wheel development utilises a very similar core mechanism to the former LTM with regards to general arrangement of bearings, oil type, preloads and bearing spacing. Since the LTM started testing SSTL has developed significantly with its oil lubricated wheels, including advancements in bearing processing as well as new design features to increase robustness and reliability around the mechanism level. It was therefore critical to the success of the GEO wheel to build on the LTM and give confidence to ourselves and our stakeholders in the revised design and processes. The ACM (shown in Figure 1) therefore consisted of a core mechanism utilising SSTL's knowledge and processes learnt from prior wheel developments and the LTM, a redesigned structure along with a motor and encoder from SSTL's other LEO (Low Earth Orbit) wheel product lines and a completely new mechanical structure based as closely as possible on the final wheel specifications. The electronics were only commencing development at this time and so the module utilised a dummy Printed Circuit Board (PCB). The Engineering Qualification Model (EQM) and subsequent PFM (Protoflight Model) are described in section 5.2.

Figure 1. SSTL's Actuator Confidence Model (ACM)

2. TEST CAMPAIGN

2.1. Test Approach

Unlike other space mechanisms where the entire life can be tested in a practical duration a space qualified wheel has the challenges of significant revolutions where it is almost impossible within practical timescales to demonstrate the required life. In this instance a pragmatic approach needs to be adopted that is in agreement with all relevant parties. In this instance SSTL used an approach that Airbus Space and Defence (ADS) has often adopted with other wheel suppliers. It involves six months life test duration (not including EVT) where the wheel is purposely tested outside its normal operational mode, followed by a complete disassembly and inspection of the wheel to mechanism and bearing level. This differs to SSTL's previous wheel life test approach which is to operate either one or two qualification models indefinitely and obtain at least one year of ground operation (life testing), usually at slightly elevated test levels from expected operation (i.e. speeds, zero crossings). This approach has been adopted in the past, because the main contributors to wheel mechanism failure are oil migration from the bearings. Oil can migrate from bearings without suitable protection extremely rapidly (i.e. < 1 week) so any weak points in this defence are likely to be seen within the first year of operation. For previous SSTL missions this gave confidence in the mechanism by Flight Readiness Review (FRR). Although the 6 months approach has been used here it does also to some degree rely on previous SSTL experience of wheel manufacture, existing life tests and confidence from external stakeholders on SSTL's ability. For example, if this was SSTL's first wheel development with little understanding of designing and manufacturing reaction wheel mechanisms it would be hard to then be able to adopt this approach first off.

2.2. Qualification Process Flow

With the test approach set the ACM qualification tests as detailed in Table 3 were agreed with ADS and ESA. The EQM will follow a similar approach, but it will be considered qualified post TVAC. It will therefore not include the full 6 months phase testing but a small subset of these tests. It will then undergo inspection to bearing assembly level (i.e. not bearing disassembly) which the ACM has gone through. It will then be put on an internal SSTL indefinite life test outside of the contract.

Table 3. Qualification Process Flow (ACM/EQM)

Test / Check / Operation	Comments
TEST READINESS REVIEW (External)	External review with ADS and ESA
Bearing cartridge testing	Preload, low speed dynamometer and frequency analysis characterisation
Initial functional & mechanism characterisation/performance	Initial check of drive electronics, speed & current modes, torque capability and internal losses characterisation
Initial rotor balance	To baseline requirement
Initial thermal cycling	Checks prior to vibration and TVAC
Internal evacuation (EQM only)	Mechanism now in a vacuum
Micro-vibration	Characterisation
High Sine	50g
Random Vibration	11 to 13 grms
Post vibration mechanism characterisation/performance	Torque capability and internal losses characterisation
Micro-vibration	Characterisation
Rotor balance	Identify any shifts
Robustness	Wheel mounted 45°, 90° & 135°
Shock	100Hz (20g) to 10000Hz (1000g)
Post shock mechanism characterisation/performance	Torque capability and internal losses characterisation
Rotor balance	Identify any shifts
Internal evacuation (ACM only)	Mechanism now in a vacuum
TVAC	Four cycles
TVAC (Thermal Transient)	
TEST REVIEW BOARD (External)	External review with ADS and ESA
Confidence life test phase 1 (ACM only)	Boundary operation
Post phase 1 mechanism characterisation/performance (ACM only)	Torque capability and internal losses characterisation
Confidence life test phase 2 (ACM only)	High speed operation

Test / Check / Operation	Comments
Post phase 2 mechanism characterisation/performance (ACM only)	Torque capability and internal losses characterisation
Confidence life test phase 3 (ACM/ only)	High torque zero crossings
Post phase 3 mechanism characterisation/performance (ACM only)	Torque capability and internal losses characterisation
High torque operation (EQM only)	To ensure the secondary issues observed post ACM testing are resolved.
Internal pressurisation	Mechanism now at atmospheric pressure
Rotor balance	Identify any shifts
TEST REVIEW BOARD (External)	External review with ADS and ESA
Wheel disassembly	To sub assembly level
Bearing cartridge mechanism testing	Preload, low speed dynamometer and frequency analysis characterisation
Bearing cartridge mechanism disassembly & inspection	
Bearings disassembly & inspection (ACM only)	
FINAL INSPECTION REVIEW BOARD (External)	External review with ADS and ESA

2.3. ACM Qualification life test phases

With the majority of testing stated in Table 3 being generally in line with space industry expectations it makes sense to highlight the three confidence life test phases that were introduced to operate the ACM wheel 6 months after completing TVAC (Thermal Vacuum) and prior to disassembly and inspection. Phase one as shown in Figure 2 is designed to operate the bearings in the boundary lubrication region where the fluid film thickness is effectively null and metal to metal contact occurs. Two short re-lubrications a day were designed in by moving into Elastic Hydro Dynamic (EHD) lubrication region. Three months in continuous boundary operation was seen as unrealistic without having any re-lubrication and certainly far in excess of any mission duration expectation in the boundary region.

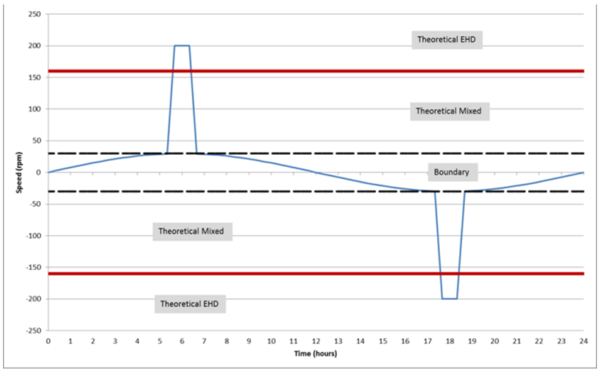

Figure 2. Phase 1 testing – boundary operation

Phase two as shown in Figure 3 is designed to operate the bearings at high speed and at an elevated temperature where the fluid film thickness is thinner. This allows time for the oil to be dispersed to thin the fluid layer further. Note - at the time of the test the full thermal profile was not known but it was not believed the wheels would generally operate hotter than 35°C.

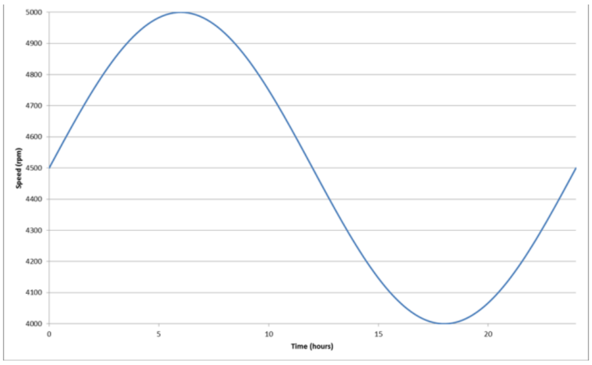

Figure 3. Phase 2 testing – high speed profile (35°C)

Lastly, phase three as shown in Figure 4 is designed to operate the bearings at high torque through the boundary lubrication region, where all the required high torque crossings could be tested to meet the 15 year life of the wheel.

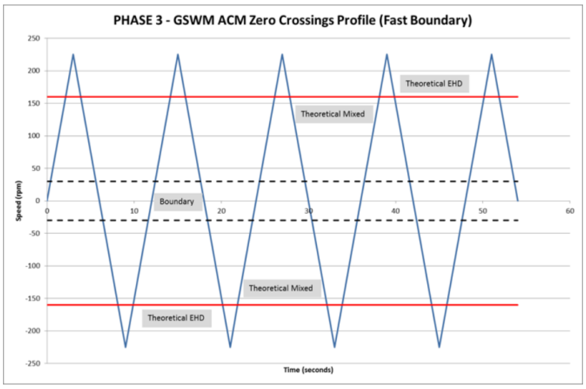

Figure 4. Phase 3 testing – high torque zero crossings

It was decided not to mix the above three tests into a single daily profile as keeping them separate would demonstrate worst case testing.

3. CONCLUSION - ACM TEST CAMPAIGN

The results of high sine, random vibration and shock are not discussed in this paper. Results were as expected and the unit passed all the requirements derived from the Structural Qualification model (SQM) levels. Some further notching was required for the out of plane tests but the wheel was effectively qualified above (SQM) levels. TVAC tests resulted in expected behaviours and higher initial friction losses during cold start-up and initial running.

For the 6 months test campaign, the graphs in Figure 5 represent the key coast down tests (pre and post the different test phases) from +/-5000rpm to zero, plotting the torque loss over the speed range whilst the wheel is allowed to free spin. The x-axis is speed (rpm) and the y-axis is torque (mNm). The red line indicates 25mNm.

This effectively gives around 3x margin on the required torque made available by the wheel to AOCS (Attitude Orbit Control System). Torque losses and fluctuations only needed to be characterised for a maximum torque loss over the full operating temperature, rather than characterisation at particular speeds and temperatures. The reason being that if the wheels are operated in speed mode the wheels internal closed loop controller can cope with torque fluctuations and in torque mode, torque estimating is carried out by AOCS. As shown, over the 6 months testing there is no significant change or measured degradation of the losses within the mechanism. Figure 6 extracts out the low speed part and demonstrates the coulomb friction.

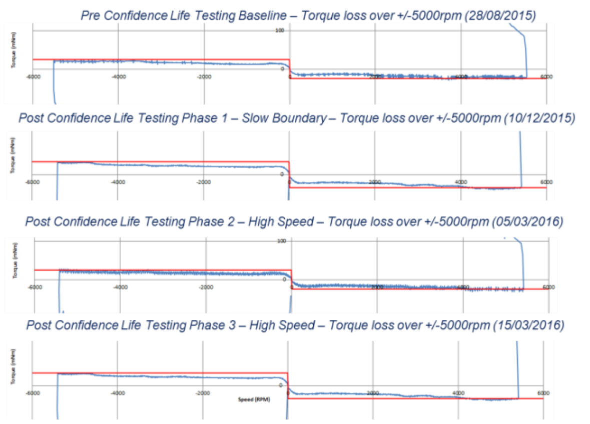

Figure 5. ACM torque loss

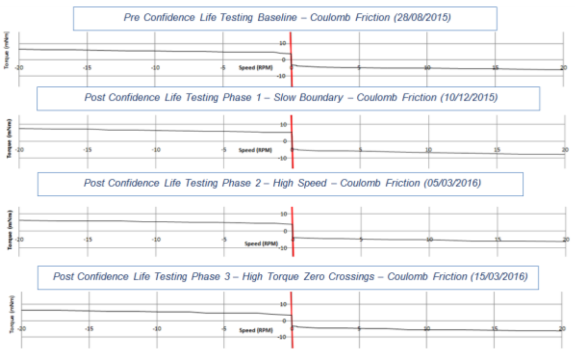

Figure 6. ACM coulomb friction

4. DISASSMEBLY & INSPECTION

4.1. Initial disassembly & bearing cartridge level tests

Following testing and review of the results, at wheel level, the ACM post testing as shown in Figure 7 was disassembled and inspected down to its sub-assembly constituents. There was no evidence at sub-assembly of any failures or issues observed. From bearing cartridge level testing, the bearing preload revealed slight reductions, but this was in family with the LTM and various new processes have been introduced since to stabilise this for subsequent builds. However, even this reduced preload is not a concern for the successful operation of the mechanism at the LTM has seen over 13 billion revolutions. Low speed dynamometer tests revealed there were no cage hang ups at the start and end of life. Coulomb friction had reduced by 9.5% which is likely due to a slight preload reduction and smoothing of the tracks during phase 2 tests in particular. A FFT (Fast Fourier Transform) analysis revealed no changes or unexpected behaviour thus no defects in the bearings.

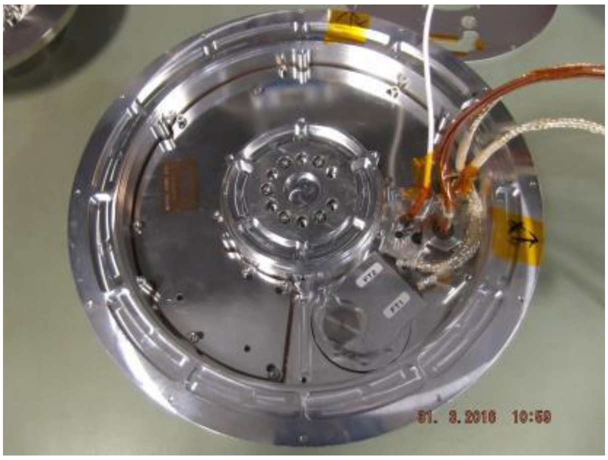

Figure 7. ACM ready for disassembly (mechanism still in vacuum)

4.2. Bearing cartridge disassembly & inspection

An initial strip examination of the bearing cartridge assembly was carried out by SSTL and the European Space Tribology Laboratory (ESTL) at ESTL with key personnel from ESA present.

All bearing cartridge fixings were still torqued and locked and all the anti-creep barriers were inspected and photographed under UV. They were all intact and within the positions originally applied. On removal of the two bearings, the lower bearing seat was in good clean condition and appeared normal. Using a plastic fine tip instrument the oil could be disturbed on surfaces where it is expected to be and seen as a visible track on the oil film, although photographic evidence on lightly oiled surfaces is exceptionally difficult to capture. Even though there are external shields for the bearings, the gaps have to be large enough to prevent oil droplets forming and creating a viscous brake, therefore it was expected that some oil would be expelled during initial run up and vibration and this was contained within expected areas. There is however, no observed evidence of oil migration through the oil surface barriers due to capillary action and the amount of oil remaining within the bearing was significant and the quantities expected.

The good condition of the lower bearing seat was in contrast to the upper bearing seat which had darkened oil as shown in Figure 8 in positions 'X' and more heavily present in position 'Y'. Figure 15 shows the typical cross section that details locations of 'X' and 'Y'.

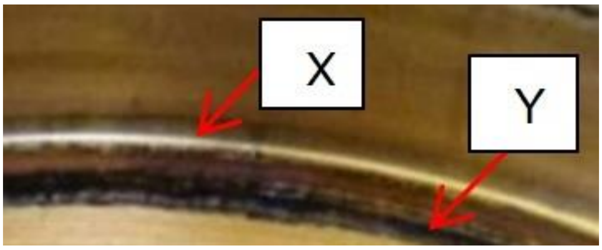

Figure 8. ACM upper bearing seat

This darkened oil was still wetting the surface of the bearing seat and did not appear dry or functionally degraded. Energy Dispersive Analysis X-Ray (EDAX) revealed particles in the oil as shown in Figure 9 and indicated the presence of Cu, consistent with transfer from Be-Cu bearing seat.

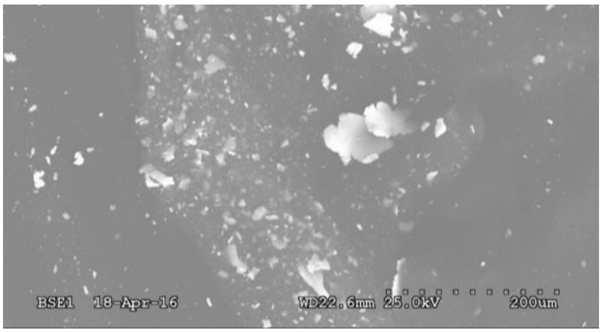

Figure 9. Darkened oil under SEM

During initial inspection it was not understood how these particles were formed especially as there is purposely a presence of an oil film locally which would to some degree provide an oil film barrier between the housing and the bearing which was also expected and found during inspection in the lower bearing.

This secondary finding of the upper bearing seat was then conducted by SSTL at SSTL and took several months to conclude. On further investigation a thin piece of swarf was found almost 360° around in the corner of the bearing seat in position 'X'. A closer image of the swarf along is shown in Figure 10. All initial assembly photos do not highlight this being present which was expected as the component goes through a rigorous cleaning regime, however at this point a potential hypothesis was that some debris from component machining was not dislodged during cleaning.

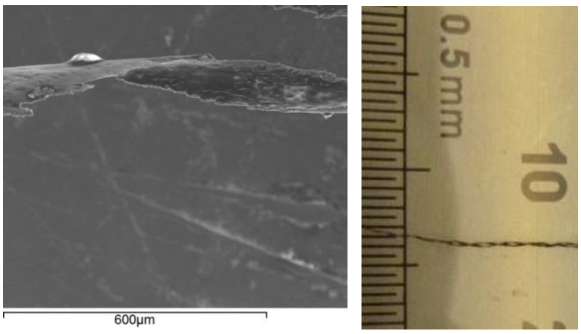

Figure 10. ACM upper bearing seat swarf found

The swarf is approximately 115µm in width, 10 µm thick with a total length of all pieces of 90mm. Based on the initial hypothesis, new swarf was purposely generated after the above discovery whilst duplicating the original machining speeds, feeds, and material. This material is shown below in Figure 11 and was carried out to rule whether it was generated prior to assembly. However, the swarf generated by machining the material resembles a very different form to that which was found and it soon became conclusive that this swarf was not present during assembly and in fact the part was clean and free from debris from the start. It therefore must have been created during or post assembly of the mechanism.

Figure 11. Swarf generated during machining operation

With suggestions that the swarf could not be generated from machining, rotation of the bearing in the housing was investigated. Two nonstructural clamps are implemented to prevent rotation of the bearings outer race. After conducting some outer race rotation tests (both upper and lower bearings) and investigation of both bearing clamps, it has been revealed that outer race rotation has occurred in the upper bearing only. Test results of torques required to rotate the bearings are within the reaction torque exposed during initial run-in when the vicious losses in the bearings are at their highest. Further investigation into the tolerance analysis revealed an error such that no clamping could occur. If the upper bearing clamp (with or without lubrication) was shimmed to simulate a "clamped" interface no rotation is possible. Following a further tolerance analysis against measurements of the actual ACM these results suggested that clamping would have been a light touch, but was further hindered from a thread locking compound that was expelled from the top of the fixing holes causing an additional shim of material, i.e. an uncompressible fluid. This resulted in the clamp not sitting low enough.

With rotation of the upper bearing outer race having taken place, the upper bearing was also investigated further as it was not known how the almost perfect piece of swarf had been generated. The bearing inspection revealed as shown in Figure 12, a small manufacturing defect on the perimeter of the outer race. Figure 15 shows the relative position.

There is no feasible method for the generation of this during bearing processing or assembly. Also can be seen is the build-up of housing material on effectively the "cutting edge". Therefore, during slow rotation of the bearing cutting edge peeled off a slice of the bearing seat and deposited it into the seat corner. Further swarf was generated which was trapped in the fluid layer between the bearing and the bearing seat, where it has disintegrated under vibration and during initial rotation.

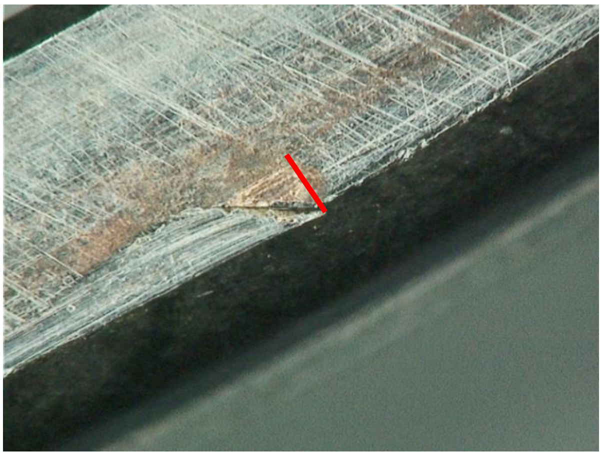

Figure 12. Bearing defect

With the above evidence found the associated bands height profile found on the bearing seat as shown in Figure 13 and Figure 14 were captured using a confocal microscope and the positions and sizes appeared to match.

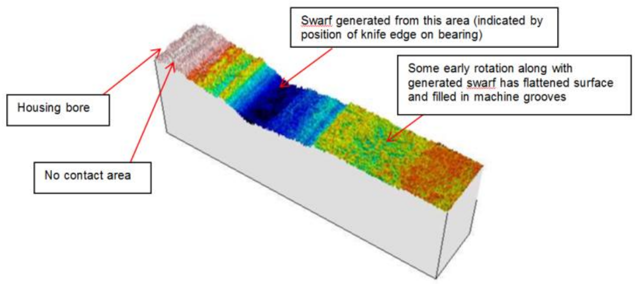

Figure 13. 40x amplification 3D profile of a slide of the bearing seat

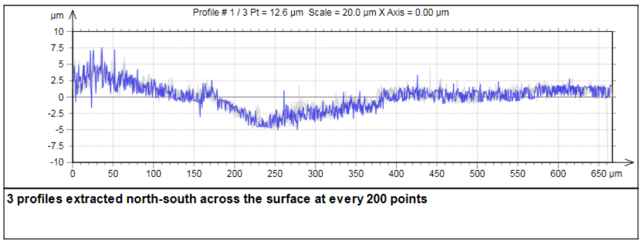

Figure 14. Approximate width of groove shown of 150µm

The removal of part of the bearing seat material by the cutting action and the rotation of the bearing has also produced a fine powder of particles that has mixed with the oil. The combination of moisture and air in the oil film on the bearing seat during initial bench tests (i.e. before evacuating to a vacuum) has caused these particles to oxidise and results in the darkened oil found.

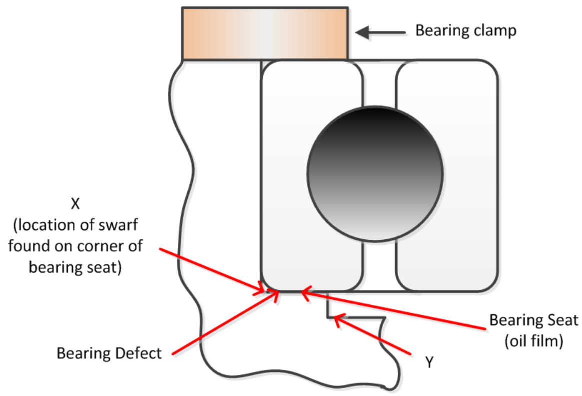

Figure 15. Bearing setup showing locations of findings

4.3. Recommendations from secondary issue

With the findings conclusive it was important to note this was a secondary issue that did not affect the health of the ACM during its 6 months testing, and in no way affected the bearings operation but it must be avoided. There are several simple recommendations that have since been implemented to eliminate this issue for the EQM and subsequent PFM units without compromising the ACM qualification.

Firstly, revisit and increase the clamp distances to take into account tolerance stack ups as well as potential for small amounts of thread lock. Secondly, as part of the assembly procedure for both clamps, take accurate measurements to ensure positive clamping always takes place for every unit manufactured. Thirdly, as part of the assembly procedure use a dummy bearing tool that can be initially assembled with the flight hardware to confirm that a sufficient torque applied does not give rise to any rotation in any direction. Lastly, although 100% inspection of bearings takes place before assembly; close critical inspection only takes place on the balls and bearing races. The rest of the bearing receives a lower magnification inspection. The assembly procedure is to now include 100% inspection of the bearings at higher magnification, looking also for external manufacturing defects.

4.4. Bearing disassembly and inspection

The ACM bearing inspection was carried out at ESTL by SSTL, ESTL and ESA. Both bearings were in good condition with no evidence of marks on the bore or on the outer diameter. No oil meniscus was observed between the cage and land indicating that although oil was present in the bearing, there was not sufficient quantity to bridge the gap between lands and cage. The ball bearings were disassembled and the component parts were examined using a low power microscope and a digital microscope. The bearing raceways were in good condition and the ball running track was evident as a slightly dulled or frosted region just off the center of the ball groove as shown in Figure 16. The balls show a visible orbital track as shown in Figure 17, suggesting the ball spin axis is generally constant and not prone to problems such as skidding leading to multiple orbital bands. Significant oil was still present on the raceway and lands. No evidence of misalignment or variations in width or position of the ball track was observed. The running tracks were parallel to the ball groove and were of even width, as expected for a bearing which operated without misalignment or other anomalies. From bearing analysis, the semi-major axis at the ball to inner race contact was 0.16mm. On this basis, the ball track can be expected to be 0.32mm. Although this prediction was less than the maximum estimated track width measurement of 0.5mm, the track could be wider if we consider thermal effects and axial movement causing small variations in track position. Note that it would require a thermal gradient of 12°C to increase the effective preload such that the contact ellipse semi-major axis was 0.25mm. A thermal gradient of this magnitude is unlikely in fluid lubricated ball bearings. Therefore, contributions from variations in axial ball positions during operation could also result in widening of the ball track. We could expect some degree of axial movement due to variations in ball loading (wider track if some balls more heavily loaded). In addition, micro pitting could result in some steel particles mixing with the oil and being pushed to the side of the ball-raceway oil meniscus and being deposited as a fine brown band outside the contact ellipse, giving the impression of a wider ball track than analytically predicted.

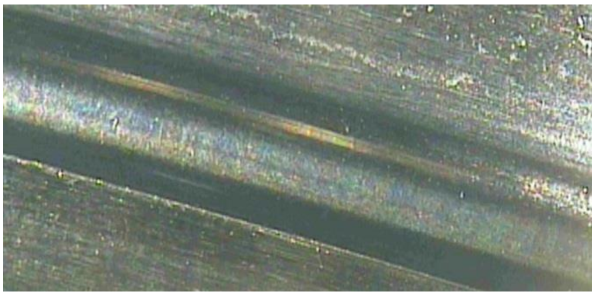

Figure 16. Bearing race showing running track

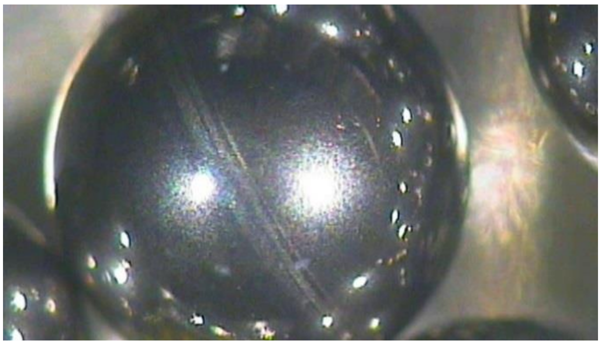

Figure 17. Ball with single orbital track

One ball from each bearing was cleaned and placed in a SEM (Scanning Electron Microscope) so that the surface textures and degree of micro pitting could be compared. There was very little difference, although the ball from one bearing appeared slightly more micro pitted.

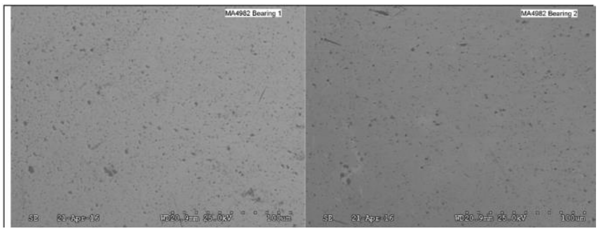

Figure 18. Micro-pitting of balls (SEM)

Cages appeared visually to be in an almost new condition.

5. CONCLUSION - ACM DISASSEMBLY & INSPECTION

The bearings are considered to be in good condition with sufficient oil present. Stable cage mass measurements indicate that they are fully impregnated. The darkened oil and swarf generated is fully explained and future mitigation is simple to implement without affecting the qualification of the ACM or to warrant further testing. The oil maintained in the bearings post testing is as expected and gives confidence for the 15 year mission. The key operational requirements below have also been de-risked as much as practically possible.

1. The wheel mechanism meets the requirements of the mission with regards to vibration, shock and TVAC.
2. AOCS system design expects momentum build up to 8Nms per wheel before offloads (3333 rpm) – equating to 20.1 billion revolutions (50% margin). *The LTM has currently achieved >13 billion revolutions and still operating. The ACM achieved >0.5 billion revolutions before inspection.*
3. Wheel will be operated in the boundary zone for each offload at high torque. As worst case expect a 2 day period between consecutive offloads for part of the year after worst wheel failure. *LTM - 33,000 zero crossings at high torque ACM phase 3 - 46,000 zero crossings at 200mNm*
4. For a 3 wheel operational case (wheel failure) the strategy in case 3 cannot be applied. Worst case 14 hours in boundary zone for wheel 3. Cumulative time in boundary zone of 16.7 out of 365 days. *ACM phase 1 – 22 hours in boundary zone per day for 90 days at a low torque of 0.002mNm.*

The combination of testing, inspection and proposed improvements gives good confidence for the operational life of the mechanism and hence the ACM was considered qualified for the mission.

5.1. Lessons learnt

There have been many minor lessons learnt with regards to the design, development, manufacturing, processing, analysis, testing etc. What really stands out above anything else is the approach used. It seems obvious that all mechanisms should be inspected post life testing, but for most mechanisms it is possible to achieve if not 100% then a significantly high percentage of the life test in a practical time schedule. But for a wheel of course this is different. Therefore the importance of disassembly and inspection with a new wheel development, where it can often be too easy to just leave it on life test indefinitely to accumulate as many of the required many billions of revolutions as possible is tempting. However, the secondary issue observed here during inspection could never be picked up by telemetry data unless of course it had migrated or assisted in the starvation of the bearing of oil and this may have taken years. Of course by which time the wheels would likely be integrated into the satellite and possibly already launched. Therefore, for critical mechanisms where the lifetime can never be completed in the time frame of a project it is imperative that there is always a qualification model available that can be fully disassembled and inspected to a detailed level. Data alone returned from wheel telemetry or external measuring equipment will not always identify a problem buried deep within the module.

5.2. EQM & FM Design Summary

Although not discussed in this paper it is useful to summarise the final wheel design (EQM/FM) which has further evolved by SSTL from the Actuator Confidence Model (ACM) and significantly (except mechanism) from the LTM. This is shown in Figure 19. Since the LTM, the redesigned structure now separates the mechanism completely from the main electronics in its own vacuum (during ground testing also) whilst taking up less mass and volume. The wheel incorporates its own internal Class 1 radiation hard drive electronics and FPGA that provides a full range of telemetry and automation as well as a bespoke motor and encoder. The wheel can be commanded in either current (torque) or speed mode. The rotor part of the motor is directly connected to a mechanical structure which is supported by a series of bearings to allow rotation, whilst the stator remains fixed. In turn the rotor is connected to an inertia mass (effectively a flywheel) which spins up to +/-5000rpm. Speed feedback is either via hall sensors or via an optical encoder which gives more accurate feedback. As with all SSTL wheels during deceleration they act as a generator and sent power back to the spacecraft bus.

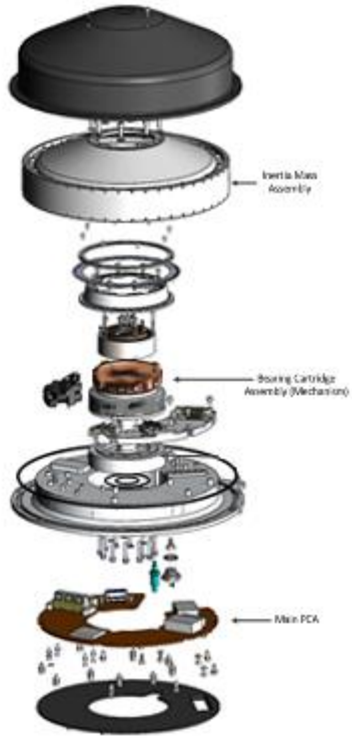

Figure 19. SSTL's First Generation Geo Wheel

The EQM wheel is on track to complete testing in 2017 with many of the FM subassemblies already in production.

6. REFERENCES

1. None

7. ACKNOWLEDGEMENTS

1. European Space Tribology Laboratory for supporting the disassembly & inspection in particular Mike Anderson for his help with the bearing inspection and associated report.
2. Airbus Defence & Space and the European Space Agency for supporting the development, the reviews and ESA for supporting the mechanism inspection activities also.
3. The University of Surrey for the use of their materials/microscopy laboratory during some of the investigations.