STUDY, DESIGN AND COMPONENT TESTING OF AN ADVANCED SCAN MECHANISM INCLUDING POWER AND DATA TRANSMISSION FOR A MICROWAVE RADIOMETER

B. Heinrich[(1)], M.J. Anderson[(2)], M.E. Humphries[(3)], P. Spycher[(1)], R.B. Watters[(2)]

[(1)]Oerlikon Space AG, Schaffhauserstrasse 580, 8052 Zürich, Switzerland
Email: beat.heinrich@oerlikon.com
[(2)]ESTL ESR Technology Ltd., Whittle House, 410 The Quadrant, Birchwood Park Estate, Warrington WA3 6F, UK
Email: mike.anderson@esrtechnology.com
[(3)]Sula Systems Ltd., Old Crown House, Market Street, Wotton-under-Edge, Gloucestershire GL12 7AE, UK
Email: mhumphries@sula.co.uk

ABSTRACT

The study presented is of generic nature covering all possible types of scanner applications such as Large Conical, Cross-Track and Millimetre Wave Radiometers. It included a component and technology survey on which one of the main objectives was to identify new technologies suitable for the use on future scanner mechanisms. Moreover, the requirements for all different types of scanners were identified and a possible design solution of a large conical scanner typically suitable for the use on the Global Precipitation Measurement Mission (GPM) is outlined.
New technologies comprising power transfer via ball bearings (fitted with lightweight, ball-riding composite cages), and capacitive signal transfer devices were more closely investigated and breadboard tested in vacuum.
Furthermore the paper presents a mechanism that allows slip ring brushes to be lifted from, and re-engaged with the slip ring tracks. This so-called smart slip ring provides 'true' redundancy as the redundant brushes are not in contact with the tracks and are therefore not prone to wear during regular operation. The function of the smart slip ring was tested under vacuum as well.

1. INTRODUCTION

Due to programme delay of the European Global Precipitation Mission (EGPM), Oerlikon Space has been selected and teamed up with ESTL ESR Technology and Sula Systems to study and breadboard an advanced generic scan mechanism (including electrical power and signal transfer) to form technical input for a future mission. EGPM is an Earth Explorer Opportunity Mission intended to improve the rainfall estimation accuracy and the detectability of light rain and snowfall for a wide range of scientific studies and applications. The main objective of this mission is to provide a European contribution to the international Global Precipitation Mission. This would be accomplished by providing one element in a constellation of satellites that will provide frequent global rainfall observations for an extended operations period. However the study presented herein was not limited to conical scanning radiometers such as EGPM only. In order to offer a broader application area, the following types of scanner were considered as well:

- Millimetre wave and sub-millimetre wave limb-sounders
- Geostationary millimetre-wave radiometers
- LEO visible IR imagers
- GEO IR imagers

The main objective of the study was to provide a versatile design that can in principle accommodate a range of many other future scanning system applications.

2. DESIGN DRIVERS

There are a number of important differences between the applications in terms of size and dynamic performance. For the large conical scanners, the size of the bearing (required to support the large payload on ground and on orbit) is much larger than that required for the small I.R. scanners.
For past cross-track scanners it has been sufficient to use the far lower efficiency direct drive systems which does offer some chance of commonality with the conical scanners (as the latter have a relatively low torque demand). However, with the larger apertures required for the next generation, there is a strong probability that a higher efficiency gear driven system will be needed (to avoid problems with peak current/power).
The applications that require the use of ball bearing are likely to face the problems of long life (high revolution count), which leads to major issues associated with lubrication and preload control.
For both the X-track scanner there are high moment stiffness requirements coupled with axial envelope constraints which favour a pan-cake bearing configuration.

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

Motors

Applications using motors will need to consider issues such as:

- High mass/power efficiency
- Low cogging torques
- Efficient, reliable and low noise commutation
- Inclusion of redundancy

The majority of the applications will probably favour a direct drive system purely due to minimising the rev count at the motor. However, for the cross track scanner, some level of gearing would yield very important benefits. Given that the life issues related to bearings are expected to be addressed then this should become a practical proposition.

Position Sensors

Virtually all the scanners will require rotary position transducers and these will need to match the demands of the future which are likely to be:

- High resolution with extreme accuracy
- Axial compactness and provision of a large through bore (for some applications)
- High reliability and compact inclusion of redundancy
- Insensitivity to internal contamination

Power and Signal Transfer

For the forthcoming generation of Imaging Microwave Radiometers such as EGPM there is a fundamental design technology issue related to the reliable transfer of signal data and power between the rotating instrument equipments and the spacecraft bus. This is particularly critical where the required number of revolutions is high. For the EGPM mission for instance the total number of revolutions is expected to be over one hundred million.

The currently available contacting technology is not well suited to this type of application with respect to reliability and life (typical life capability is less than one million revolutions, with no redundancy).

For signal transfer, a contactless technology is envisaged due to the susceptibility of contacting technologies to wear at the very high number of revolutions.

Exported Forces/Torque

It is foreseen that control of residual torques and forces will be achieved by providing good static and dynamic balance. Should this not prove to be achievable then there are two options for eliminating this effect:

- The implementation of active static and dynamic balance
- Compensation of residual torques and forces by using dedicated reaction wheels or other force/torque generators.

There will also be a significant residual momentum vector which may also need to be compensated and this could be achieved by electrically slaving a momentum wheel directly to the output of the scan mechanism.

3. MODULAR DESIGN CONCEPT

If a future generic scanner is to take account of all of the potential applications in a single mechanism then the designer faces an almost impossible task. This is mainly due to the diverse nature of some of the most critical design drivers.

The biggest conflict in requirements and most favoured implementation approach is between the continuous scanners and the reciprocating devices this is mainly due to the fact that the latter can best be implemented as follows:

- Custom built flexures to support the payload – rather than bearings
- Limited angle actuators for providing motion – rather than convention motors
- Flex harness systems for power and signal transfer – rather than slip rings or contact-less devices
- Dedicated hold-down devices to support multiple axes - rather than conventional bearing protection systems

It is recognised that some commonality could be found for some of the above mentioned types of scanner applications but this is not considered to provide an optimised configuration which the programmes would require. It is therefore unlikely that a single design can meet both of these applications and therefore there will need to be a decision on which applications one should target the scanner towards.

It therefore seems logical to take a modular approach to the overall mechanism architecture. An architecture that takes a building block approach should allow newly developed state of the component and processes to be utilised and it is possible to develop a number of scanner modules that can be configured in various ways to meet the demands of most applications. This approach was proposed by Oerlikon Space as it appears to be the only approach that can lead to a truly generic advanced scan mechanism.

The proposed modules to be considered at this stage of the study are as follows:

1. Main Bearing unit
2. Main Sensor Unit – plus - (2a conditioning electronics)
3. Direct Drive Module
4. Gear Drive Module

5. Stepper Drive Module
6. Signal Transfer Module
7. Power Transfer Module
8. Smart Slip-ring
9. Torque Compensation Unit
10. Launch Protection System

By combining the above modules in various ways it should be possible to establish a number of mechanism configurations which could address the main applications identified in this document.
The only exception is the applications using high precision long life reciprocating scan mechanisms. It is likely that these will use customised flexures rather than bearings and voice-coil/limited angle torquers rather than conventional motors. Although it should be noted these applications would still benefit from the availability of high resolution/accuracy angular position sensors and associated electronics. It is also possible that one axis of such scanners (requiring line increments) could benefit from a geared stepper configuration.

Below are some examples of how this module system may be used to address some of the identified applications:

1. Large Conical Scanner - would be composed of module 1,2, 3 and 10 plus 6 or 7 or 8 or 9

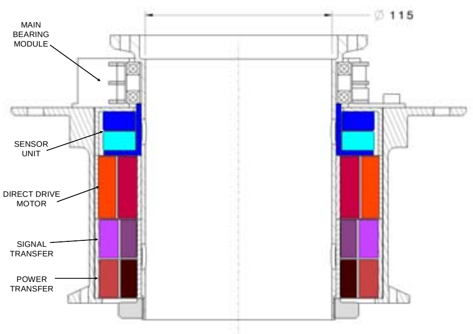

Figure 1. Large Conical Scanner Configuration.

2. Cross-Track Scanner - would be composed of modules 1,2 and 3 or 4 and 9 (if required)

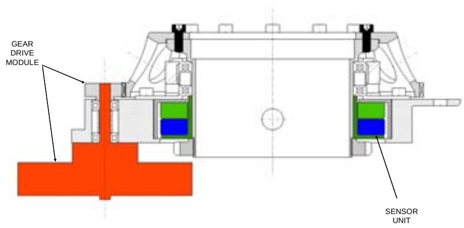

Figure 2. Cross-Track Scanner Configuration.

4. BASELINE DESIGN DESCRIPTION

4.1. General Design

The baseline described in this paper incorporates a single axis scan mechanism for providing the across-track earth scan (conical scanning). A possible implementation of this mechanism for large conical scanning such as EGPM is presented on Fig. 3 below.
The design currently employs a fixed reflector which includes higher reliability, better reflector alignment and greater possibilities with respect to minimising the need for active balancing.
As shown on the figure below, the baseline for a large conical scan mechanism typically suitable for EGPM consists of the following main sub-assemblies:

- Scan Drive Mechanism (SDM)
- Smart-Slip ring (for grounding purposes)
- Launch Protection System
- Torque Compensation Units
- Reaction Wheels

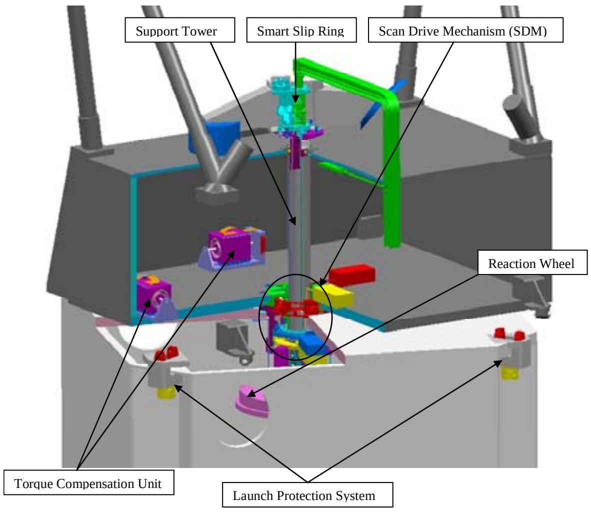

Figure 3. Baseline Design of Large Conical Scanner.

4.2. Scan Drive Mechanism

The scan drive mechanism as shown on Fig. 4 is composed of the bearing module (including power to be transferred across the ball bearings), sensor unit, direct drive and signal transfer modules.
Since one main objective of this study was also to identify new technologies, electrical power will be transferred via the ball bearings.

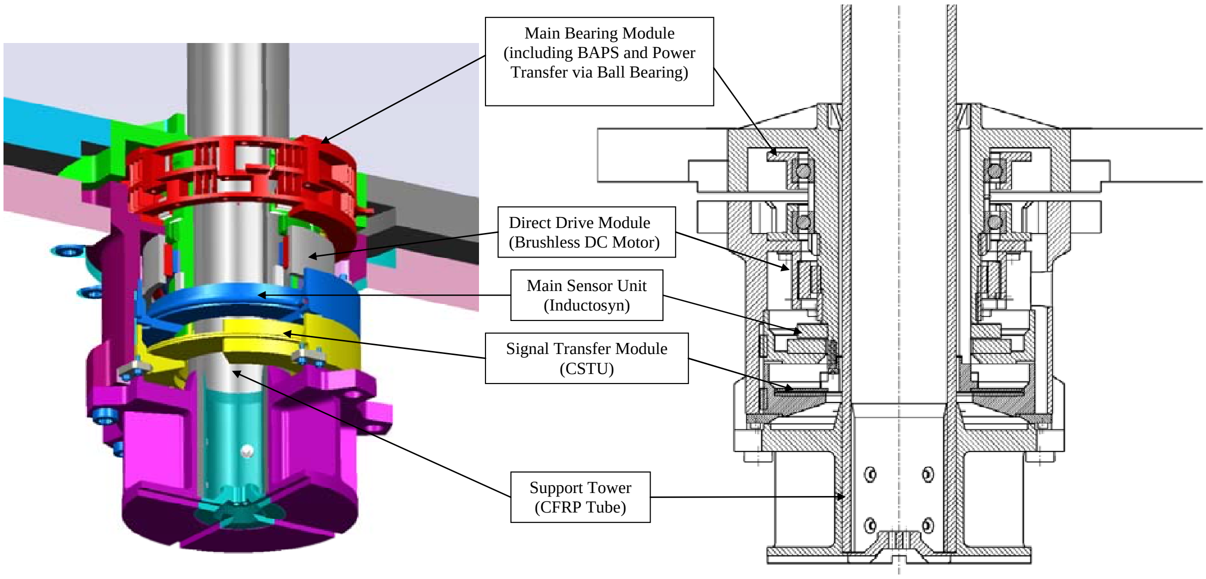

Figure 4. Scan Drive Mechanism (SDM).

Bearing Module

The bearing module employs a so-called bearing active preload system (BAPS) as shown on Fig. 4.

The BAPS concept [1] which is under development has a number of very attractive features which make it eminently suitable for an advanced generic scan mechanism (AGSM). This system employs a bi-stable flexure system to allow the bearing to be set with a high and rigid preload at launch and once one orbit the preload can be switched to a predetermined lower level. The ratio of the high to low preload is about 10 to 1.

This mechanism allows to have a low on-orbit preload. This maximises the bearing life and avoids high Coulombic (load dependent) torque and therefore minimises exported torques and motor power. To meet the launch constraints the bearing system will be pre-loaded via the SMA actuator.

The ball bearings have been chosen to satisfy both functions, provide rotary support to the scanner payload and to allow current to be passed through.

Figure 5. Ultra-lighweight Ball Bearing Cage.

The baselined bearing assembly consists of thin section angular contact ball bearings (type SEA 95) fitted with an ultra-lightweight hybrid cage based on a carbon reinforced cage with lead bronze inserts as shown on Fig.5.

Since one main objective of this study was also to identify new technologies, electrical power will be transferred via the ball bearings.

The notion of transferring electrical power across rotating ball bearings is both innovative and radical.

Motor Drive

The relatively high inertia means that the scan requirements are less challenging given that high inertia tends to stabilise the rotation rate.

Therefore direct drive motors using conventional brushless motor technology is expected to be quite adequate.

Main Sensor Unit

The base-lined position encoder for the AGSM is a 512 pole (256 speed) semi-absolute Inductosyn® having once per revolution redundant hall effect sensors loacated 180° apart from each other. The 512 pole pattern with 10 bit cyclic interpolation yields in 18 bit overall resolution and easily achieves a speed of 40 rad/sec with a properly set up DDC converter. This option gives a very good cyclic error performance because the basic cyclic error of the transducer is less and the higher electrical speed reduces the error contribution of the electronics. On the negative side, this option will be more sensitive to once-per-revolution error increase due to mechanical mounting deviations.

However, if redundant windings could not be accommodated within the specified inner and outer diameter, the Inductosyn will be built as a sandwich, i.e.

the rotor disk having windings (main/redundant) on either side will be fitted between two stator disks.
The rotor is excited via a rotary transformer, so that no direct electrical connection to the rotor is required, i.e. no slip rings or brushes. Therefore as only non-contacting technologies were used the lifetime requirement is feasible to be met.

Signal Transfer

The data transfer rates are not particularly demanding but of course high reliability and low noise/cross torque are required. The rolling element solution using existing U.S. technology is an option that has been pursued in the past but with mixed results. Therefore, based on the trade-off performed, a capacitive signal transfer unit (CSTU) is currently considered as the best solution.
Capacitive transfer of signals has been demonstrated and this can be implemented in a very efficient manner, provided that the signals are packaged and multiplexed which allows the transfer to be achieved through just one or two capacitive interfaces. The contact less capacitive transmission seems to be the best alternative to overcome the lifetime issue, mainly because no debris is generated. Advantages of this technology are wear-resistance, high noise immunity combined with excellent EMC-qualities, high reliability and bit error rates of $<10^{-13}$.
It is assumed that a COTS available capacitive signal transfer unit could be accommodated for space applications. However, some open points will be investigated during the breadboard test campaign. One point is the power dissipated by the electronics mounted on the capacitive disks. Furthermore at the moment it is also unclear, if the HiRel space electronics will still fit into the specified envelope as the electronics of the of the off-the-shelf product do. A possible solution to solve both problems, the envelope and power dissipation could be to integrate the electronics into the S/C and the scanner payload.

4.3. Smart Slip Ring

The purpose of the smart slip ring is to provide an electrical connection between the satellite and the rotating payload, in detail for:

- Grounding
- Minimum power and signal transfer when the S/C is in the power-off state

The smart slip ring module could also be used to provide redundant signal and power lines.

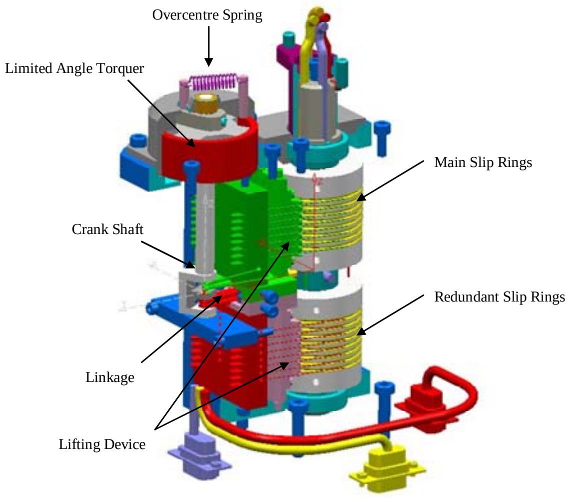

Figure 6. Smart Slip Ring.

In general, the main problem with slip rings is mechanical wear due to friction at the contacts. After a period there is no more contacting material at the brushes/wires and the isolation barriers between the lines are contaminated by dust from the brushes. So lifetime of conventional mechanical slip rings is limited.
However, the ‘smart’ slip ring concept minimises these issues. Firstly, the slip ring is placed on top of the support tower as shown on Fig. 3 which minimises the sliding distances due to the reduced diameter. Secondly, the smart slip ring comprises an actuator to allow the main and redundant slip rings to be engaged respectively disengaged.
Additionally, it can be an option to disengage both the main and redundant wires at the same time in order to extend the slip ring lifetime even further. However this is not foreseen at the moment in the current design as it is assumed that grounding must be applied over the whole lifetime.
The engagement respectively disengagement is achieved by a linkage system acting on a lifting device.
The wires are lifted-off by driving the linkage into the dead centre which keeps the system in a labile position.
In order to avoid a premature engagement of the redundant slip ring during launch respectively vibration, the system is made stable at the end position (bi-stable) utilising an overcentre spring.
The linkage is driven by a 120° Limited Angle Torquer from Aeroflex
The slip rings are supported by two ball bearings which allow to build the wire arm less stiff and therefore less mass intensive and reduces alignment problems. In addition this makes the smart slip ring independent from the rest of the structure which is fully in-line with selected modular approach.

4.4. Launch Protection System

Given the relatively large mass and high inertia it is also expected that a dedicated launch locking system will be required. Therefore, the current baseline is to use a system of radially separating hold-down points as presented on Fig. 3 that remove from the rotating instrument locus. In particular, at this stage is to use a system of four discrete attachment interfaces with their own release device. It is recognized that the normal concern of a multiple hard-point system is the possibility of indeterminate load transfer through the bearing assembly. This risk has already been mitigated, by the introduction of active bearing preload system within the scan mechanism.

The design solution consists of clamp utilising a lever/ spring system for actuation. The launch lock is released using a Qwknut® from Starsys. The design is very mass efficient as the entire load will be taken by the self-blocking lever system. As a consequence, a very small and light Qwknut and release spring could be chosen. Moreover the good mechanical advantage of the levers reduces the force needed to drive the clamp and consequently minimises the shock generated by the spring.

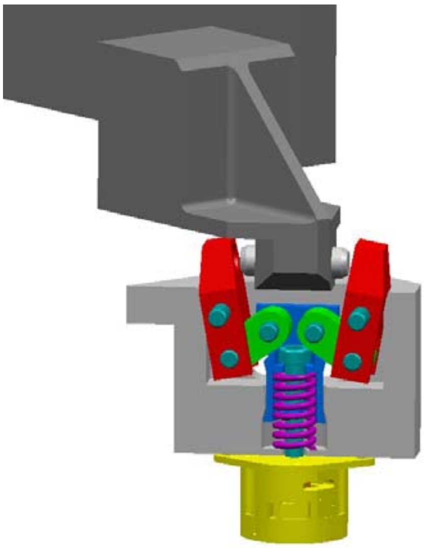

Figure 7. Launch Lock.

This option offers very high stiffness and strength. Moreover it can be realised very light and compact and can be easily integrated into the S/C structure due to its axial nature. The conical design of the clamps is insensitive to effects related to misalignment and tolerances and thus jamming is very unlikely.

The clamps do not introduce forces into the spacecraft structure and therefore the structural performance is independent from the stiffness of the rotating part of the spacecraft. This enables a 'true' generic design.

4.5. Torque Compensation/Balancing Mechanism

To provide the necessary on-orbit modification of instrument rotor mass properties, four balancing mechanism are required. Two mechanisms (one with its axis aligned with the x-axis and the other aligned with the y-axis) are required two be mounted at two different and separated planes. The degree of separation should be maximised and for the purpose of this study it is assumed that the separation distance is about 0.7m (along z-axis)

The basic principle, which is shown on Fig 8, is that of a moving balance mass supported on a lead-screw so that rotation of the lead-screw produces axial motion of the balance mass. By moving the appropriate balance masses by the correct amount, the output from the force sensors can be nulled and on–orbit balancing is achieved. To achieve maximum mass efficiency the motor a stator and its housing provides both the actuation torque and the moving mass. This is achieved by using a static ACME lead screw which mates with a moving ACME nut assembly. The latter is integrated within the motor rotor and itself supports the motor housing through a pair of deep groove ball bearings. This allows the motor rotor and lead screw nuts to rotate with respect to the motor stator and housing but prevents relative axial motion. In order to react the torque generated by the motor, the motor housing/ balance mass is constrained rotationally by a guide rail. This configuration allows the motor housing/balance mass to translate along the lead screw when the motor rotor is rotated. By using a stepper motor discreet axial increments in balance mass position can be achieved by driving the motor in step mode. To provide position status after launch and to monitor balance mechanism operation an absolute axial position sensor is included. As the number of operations is very low then contacting sensors can be used and offer the advantage of simple implementation and minimum electronics. 360 step/rev stepper motor enables open loop operation to provide precise axial motion. The inherent detent torque enables position to be maintained passively (motors not powered).

The base-lined motor is produced by ETEL and is still available for space applications, and is used in the CSA-10 actuator from Oerlikon Space.

Two linear potentiometers are mounted to the light weighted static support structure and provide redundant absolute position data to the balance control electronics.

The motor harness is a flat flex print formed into a rolling loop to provide reliable and low force operation.

The moving mass can be optimised (by sizing and material selection) to suit the expected instrument on-orbit state of balance.

Each mechanism can provide a total mass-movement product of up to +/- 80 kg.mm without effecting the defined mechanism configuration or interfaces.

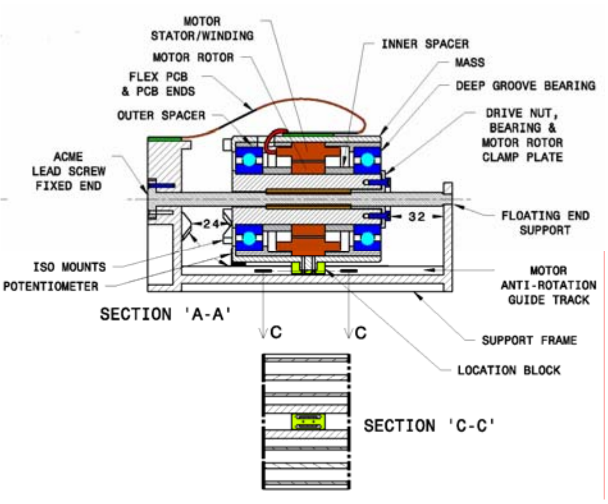

Figure 8. Torque Compensation Unit.

The residual momentum generated by the scanner rotation is best eliminated by electronically slaving a conventional momentum wheel to the motion of the scan mechanism. Numerous space compatible off-the-shelf momentum wheels are available. The HR-14 reaction wheel from Honeywell providing a maximum momentum of 50Nms is taken as baseline. The design features integrated motor drive electronics and thus offers versatile interchangeability which satisfies best the modular approach.

4.6. Support Tower

The support tower constitutes the calibration support structure. The baseline design takes advantage of providing an additional support for the scanner payload on top of the tower, i.e. an additional ball bearing is fitted on a diaphragm to reduce exported loads due to moisture release and CTE mismatch. As the loads during launch are mainly taken by the launch protection system (launch lock) and the BAPS, the upper bearing is slightly soft preloaded (via the diaphragm) just to avoid hammering of the balls during vibration. The low preload helps to minimise the bearing resistance torque and in addition to reduce wear. The advantage of the additional bearing is that the scanner payload structure can be built very mass efficient as the panels have to be less stiff due to the provision of the additional support.
In order to meet the stiffness requirements whilst providing a mass efficient design, the tube is made from CFRP.

4.7. Lubrication

The final selection trade-off has been performed in an attempt to select the best option for this advanced generic scan mechanism. However, the trade off result was not fully conclusive.
One promising option was the hybrid lubrication, and the best implementation of this is based on a combination of lead ion plating and Fomblin Z25 oil. This potentially offers the best life/reliability when taking into account the long on-orbit operation and the significant level of ground testing.
The only drawback is that for ball bearing applications the potential benefits have not yet been fully proven and so there is still some risk remaining related to life/electrical performance for power transfer.
Until this decision is finalised (subject to the results of breadboard testing) it is considered prudent to maintain a back-up option, which is pure dry lubrication option based on lead-ion plated races and a leaded/bronze cage. Given this back-up option the impacts of internal contamination need to be taken into account when considering motor and sensor selection.
The final choice between dry and hybrid lubrication would best be taken after the bread-boarding phase and initial testing of the power transfer options as one of the dividing issue between the two is the electrical transfer issue.

5. BREADBOARD TESTING

5.1. Test Item

The item tested was the AGSM breadboard (BBM), which comprised:

- AGSM support bearings which were compliantly loaded SEA95 ball bearings manufactured by SNFA. Preloading was accomplished by means of a semi-flexible housing and the bearings were mounted face-to-face. They were fitted with lightweight ball-riding cages manufactured from carbon fibre and with lead-bronze lubricating pocket inserts (see Fig. 5). The bearing rings were lead-lubricated and the lower bearing contained 1mg of Fomblin Z25 oil.
- The bearings were electrically isolated from the mechanism by the insulating coating (sputtered SiO_2) applied to the housing liners, shaft, spacers and clamping rings.
- Contactless Signal Transfer Unit (CSTU) – capacitive device used to transfer signals across rotating parts of the mechanism. This unit was manufactured by Schleifring, Germany and is a commercial off-the-shelf item.
- Smart slip rings – this unit comprised eight rings with two slip ring brushes per ring. The slip ring brushes (0.5 mm diameter gold alloy wires) could be raised and lowered using a motorised cam arrangement. By raising the slip ring brushes, the lifetimes of the brushes and rings can be prolonged.
- by not using them when they are not required. Parasitic torques at the ring to brush interfaces can also be eliminated. This slip ring unit, except for the cam arrangement to lift the brushes, is also an off-the-shelf-item manufactured by Schleifring and each channel was rated at 5A.

5.2. Description of Mechanical Test Set-up

The AGSM BBM was installed in a 1m diameter vacuum chamber and mounted upon a Kistler piezoelectric torque transducer, whose output is converted to a voltage proportional to torque by a charge amplifier.
Rotation of the central shaft was accomplished by a drive motor located externally to the vacuum chamber and at a rotation rate of 30 rpm. The test set-up is illustrated in the Fig. 9.

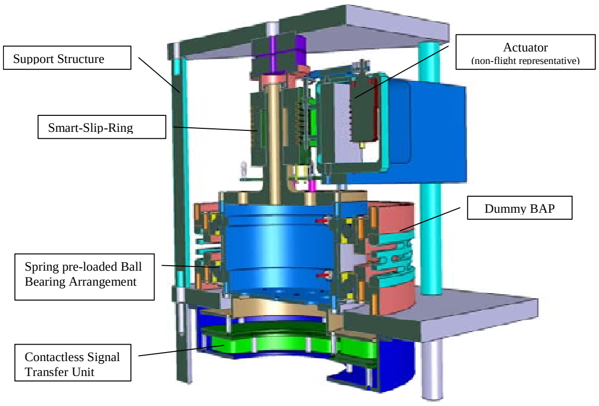

Figure 9. AGSM test set-up.

5.3. Electrical Configuration, Measurement and Monitoring

A schematic diagram showing the current path through the bearings and voltage taps is provided in Fig.10. The bearing supply current was maintained at a constant 5A and was also monitored throughout testing.
Slip rings were used to pass current through the bearings, apply voltages to the CSTU and to monitor voltage drops across the bearings and signals across the CSTU, when activated.

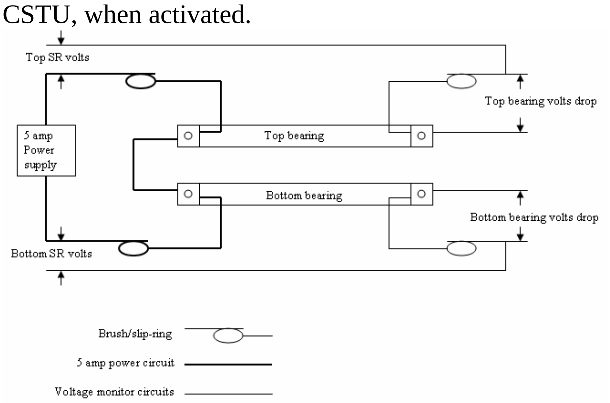

Figure 10. Schematic diagram showing current path through bearings and voltage measurements.

Electrical signals were measured using a PC and LabView software. Signals were monitored continuously at a rate of 200Hz over a window of 30 seconds (15 revs) and the mean, peak and standard deviation calculated and recorded. Every working day, a more detailed high-frequency scan at 200Hz was measured for a 10 to 30 minute period and all data recorded and stored.

5.4. Test Results from Bearing Electrical Circuit

The lower bearing resistance increased considerably from its steady-state value at approximately 300,000 revs.

The upper bearing resistance achieved exceptionally low values and further checks were carried out to check that the current was being passed through the bearings and that an alternative short-circuiting path was not being followed.

The current through the external link between the outer rings was checked and it was found that at least 1A was flowing. This value was less than the 5A expected and it was feasible that current was passing through the housing, in which case the full 5A would have been passed through both bearings, or through the shaft and/or the inner spacer ring. If the insulating coating had degraded and this was happening, then it could account for some of the current loss (maximum of 4A).

Assuming that this had been the case, then the bearing resistance values are as shown in Fig.11.

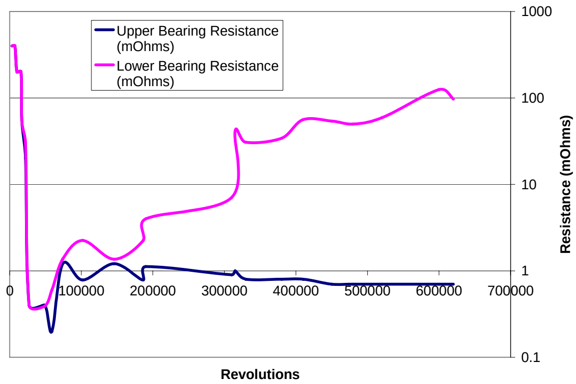

Figure 11. Summary of resistance assuming 1A passed through bearings.

From the bearing measurements, it is evident that the insulating coating was not providing sufficient electrical isolation and it is recommend that an alternative coating is considered for further developments of the AGSM concept.

5.5. Summary of Test Results

From the results, the following findings were evident:

- In air, the bearing resistances were effectively independent of current. However, after a short period of vacuum operation, the bearing resistances became proportional to current. Resistances at the start of testing decreased in vacuum. This finding is consistent with the initial presence of an oxide layer on the surface of the solid lubricant film, which is rapidly removed in vacuum during operation. The bearing torque increased by approximately 20 to 40% during vacuum testing over 624'000 revs.
- A rapid decrease was measured in bearing resistance after approximately 22'000 revs, which could be attributable to current leakage caused by a breakdown of the insulating coating.
- The smart slip ring unit operated successfully in both air and in vacuum and no changes in its characteristics were measured after two weeks of testing.
- The CSTU transmitted signals in air and no performance changes were measured as a result of vacuum testing.
- The resistance of the lower bearing (lead, with Z25) increased by two orders of magnitude during testing. No change was measured in the performance of the top bearing.
- From the bearing torque measurements, there was no evidence to suggest that the lightweight, ball-riding cage misbehaved or was prone to cage "hang-up".

6. CONCLUSIONS

A detailed market and technology survey on scan mechanisms and components was performed. In the frame of this activity, new technologies that could be attractive for a future scanner application (power transfer via ball bearings, Smart Slip Ring) were investigated.
A baseline design concept for a large conical scanner following a modular approach was established.
The power transfer via ball bearings was breadboard tested. Up to now after completion of approx. 600'000 revs, the power transfer via the ball bearing showed very promising results in vacuum, in particular very small voltage drop (resistance) was measured. Moreover, the ultra-lightweight ball bearing cage made from composite material did not show any form of degradation or cage hang-up. Nevertheless, it was found that the lead coating is susceptible to oxidation resulting in poor electrical conductance across the bearings in air. However, once the bearings are in vacuum, the oxide layer disappears very quickly and the electrical performance is restored. The hybrid lubricated bearing on the other hand started to electrically degrade very soon both in air and vacuum. In a follow-on activity it is therefore planned to replace the hybrid bearing with another pure lead lubricated ball bearing and to continue the life-test with this configuration.
The mechanism design of the Smart-Slip-Ring was proven and also the CSTU was functioning very well in vacuum.

7. ACKNOWLEGEMENTS

The authors would like to thank Pierre Vogel from ESTEC for his support, advice and encouragement in this study.

8. REFERENCES

1. Lewis S.D. and Humphries M.E., *An Introduction to Bearing Active Preload Systems – Technology and Performance Benefits,* Proceedings of the 11th European Space Mechanism and Tribology Symposium, Lucerne, Switzerland, 2005.
2. Roberts E.W. (Ed.), *ESTL Space Tribology Handbook*