Scan Mechanism Design for Large Deployable Reflector

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Abstract

Airbus Defence and Space GmbH Germany is developing the Scan Mechanism (SCM) for the instrument of the Copernicus Imaging Microwave Radiometer (CIMR) Satellite. The CIMR mission will carry a wide-swath conically scanning multi-frequency microwave radiometer to provide observations of sea-surface temperature, sea-ice concentration and sea-surface salinity. Uniquely, it will also observe a wide range of other sea-ice parameters.

The SCM will rotate the Large Deployable Reflector. Its size is approximately 8-m diameter with an arm of approximately 8 m. This results in significant rotating mass, inertia and unbalance which needs to be handled by the SCM in combination with extremely high pointing requirements. This combination is considered unique for the space business. A similar NASA Mission with SMAP[1] (Soil Moisture Active/Passive) is available however with a smaller reflector size of 6 m[1] which is approximately 56% of CIMR reflector surface area.

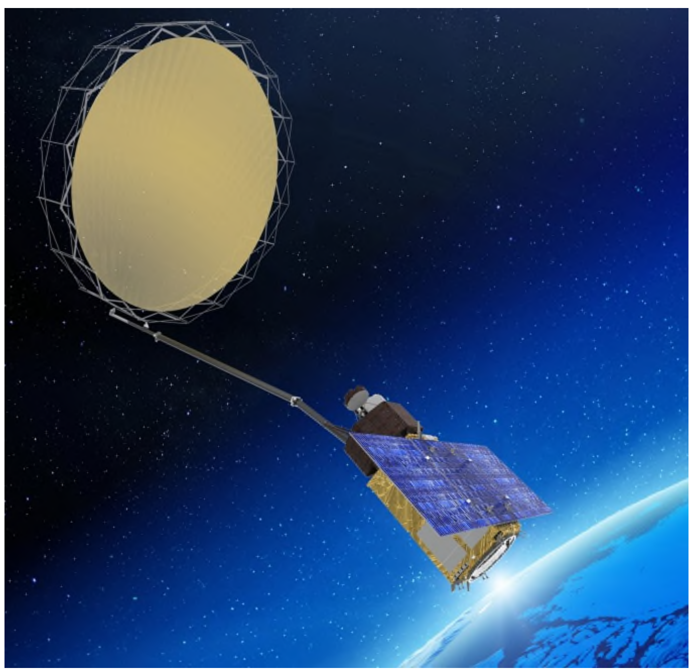

Figure 1: CIMR Image (ESA Homepage, 2021)[2]

Introduction

Many years of experience exists for design development, manufacturing verification and orbit feedback of Scan Mechanisms[3,4,5,6,7] with different requirements. Key requirements are high speed accuracy, specific rotating mass properties, low micro vibration emission, high pointing accuracy and long lifetime. Thanks to

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the modular design, adaptation is manageable; however, the CIMR requirements cause some challenges which are shared in this paper. Furthermore, a design adaptation for the new mission allows implementation of the lessons learned from several Scan Mechanisms of previous MetOP Second Generation projects.

The Scan Mechanism (SCM) is the rotating mechanical and electrical link between the CIMR Platform with the arm and the Large Deployable Reflector. The SCM design consists of a Drive Unit, a Launch Offloading Device (LOD) and a Power and Data Transfer device (Roll-Ring). The LOD is required to decouple the Instrument load from the SCM during launch. The design of the SCM is based on a standardized drive unit design that has been flown on previous missions, such as MHS, MWRI, ADM and which also formed the design baseline for the MWI, ICI, MWS and METImage scanning mechanisms for MetOp-SG and MWRI for FY-3. The main components of the standard drive unit are ball bearings, a brushless DC motor, and a digital encoder. To meet the CIMR requirements, several modifications of the standard design were performed, which are outlined herein. The SCM drives a heavy instrument with the reflector resulting in an angular momentum of maximum 1090 Nms. The scan performance is achieved by the closed control loop included in the Scan Drive Electronics.

Scan Mechanism (SCM)

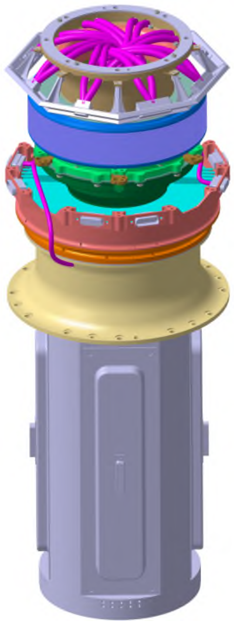

Figure 2: SCM

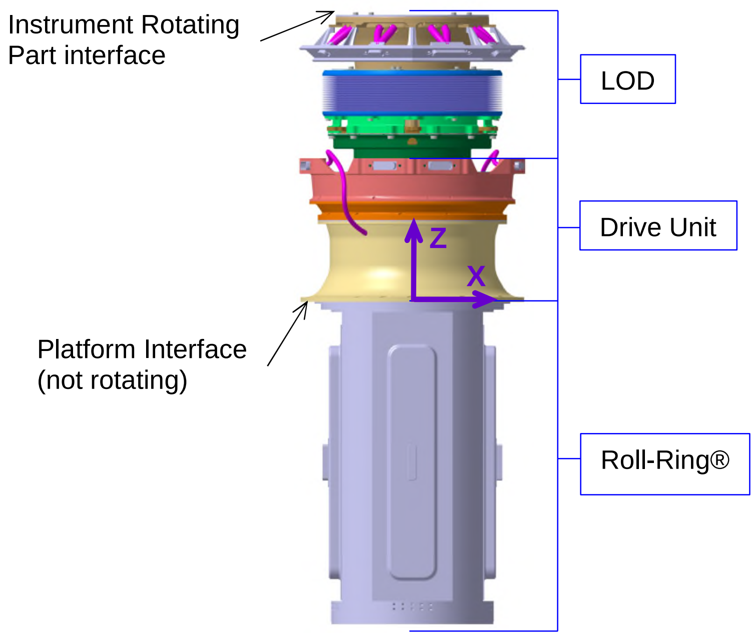

Figure 3: SCM main components and coordinate system

Major design adaptations for CIMR

During the mission, the heavy rotating mass introduces high disturbance moments into the Scan Mechanism mainly due to static and dynamic unbalance, orbit pulsation, and orbit maneuver. High angular stiffness is required for pointing performance of the Scan Mechanism due to the described disturbance and also to achieve the required Eigen frequency of the orbit configuration. In order to increase SCM stiffness, pointing performance and load capability, considerable changes have been done on the drive unit, although maintain applicable previous heritage. For the LOD, the design is upgraded and breadboard activities are currently ongoing for TRL6 demonstration within B2 phase.

Lessons Learned from previous projects

A power and data transfer device is used to transfer the power from the stator to the rotating instrument and the exchange of data between instrument and platform. The data are transferred via Low Voltage Differential Signaling. In the previous project, the selected technology was a Roll-Ring®[1] from Diamond Roltran LLC based on an outcome of a pre-development study. The aim of the study was to evaluate its performance and to demonstrate the feasibility of achieving the required performance over the lifetime and in a representative environment prior to MetOp SG start. The study was successfully completed. Airbus gained a lot of experience during the MetOp SG Project with the Roll-Ring®.

This next generation slip-ring provides low resistance noise, low debris, and long lifetime. The reason is the use of electrical rolling contacts instead of sliding contacts. The life test has shown that the required performance for power and signal is achievable after more than 230 million life qualification revolutions. However, the PDTD development during MetOp SG was not free of issues, which will be described in this paper with improvements implemented for the CIMR Mission in the life test section.

Drive Unit Design Changes for CIMR

To take advantage of heritage, the drive unit uses the same two bearing pairs as in previous MetOP Second Generation projects. Each bearing pair is in an X configuration and supported by a flexible membrane on the housing side. These membranes deliver the required flexibility to handle the misalignment between bearing pairs and thermal induced strains, maintaining the bearing stresses under acceptable values.

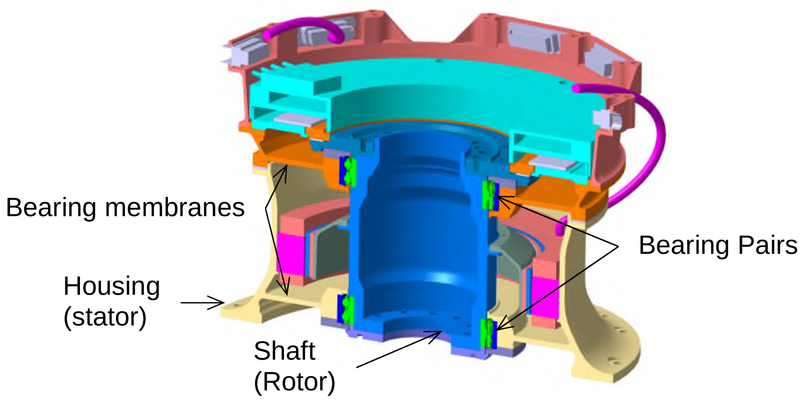

Figure 4: Drive Unit.

On the other hand, high angular bending stiffness is required to achieve the pointing performance of the Scan Mechanism while coping with disturbance torques, and also to achieve the required Eigen frequency of the orbit configuration. Disturbance moments during mission are caused by the heavy rotating mass with static and dynamic unbalance, orbit pulsation, and orbit maneuver. In CIMR project, the rotating mass is 4-times and the inertia 180-times larger than in previous MetOP Second Generation projects.

The following goals:

1. Low axial stiffness between bearing pairs,
2. High angular stiffness of the SCM (extremely challenging to reconcile with previous goal),
3. Acceptable bearing loads (also under wide temperature range and considerable thermal gradients),
4. Low mass,

are expected to be achieved with the following modifications to the previous design:

[1] Roll-Ring® is a registered trademark of Diamond-Roltran LLC

- o Considerable increase of distance between bearing pairs (this increased SCM angular stiffness without changing stiffness between bearing pairs)
- o Increase of diameter and thickness of bearing membranes. This increases the X and Z translation stiffness at each bearing pair, with low change on Z translation and X/Y rotation stiffness, contributing for the reconciliation of goals 1 and 2.
- o Change of shaft and housing material from titanium to stainless steel (this eliminated bearing stresses due to wide temperature range; also allowed to achieve high stiffness in the bolted joints of the shaft where space is the limiting factor)
- o Straightening and shortening of load paths
- o Condensation of functionalities in a reduced number of parts, reducing interfaces in the load path (leading to more complex geometries and demanding manufacturing)

The estimation is an angular stiffness increased of a factor 9 regarding the previous MetOP Second Generation projects, with a mass increase of only factor 1.6 on the parts in the load path (orbit configuration). A trade-off has been performed at requirement level between stiffness and mass and finally the mass and stiffness optimized design is achieved with some effort.

LOD

<u>Concept and challenges</u>
The patented LOD is a coupling which is open during launch and is closed in orbit. The purpose is to interrupt the load path, and so avoid that the launch loads of the instrument rotating part go thru the SCM with the bearings.

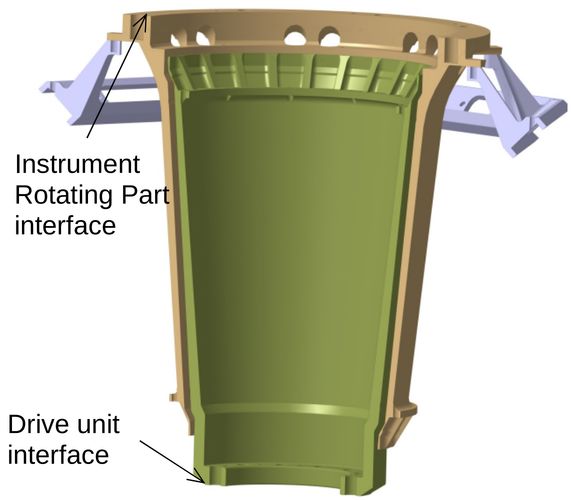

Figure 5: LOD Cones in launch configuration (Open, no contact).

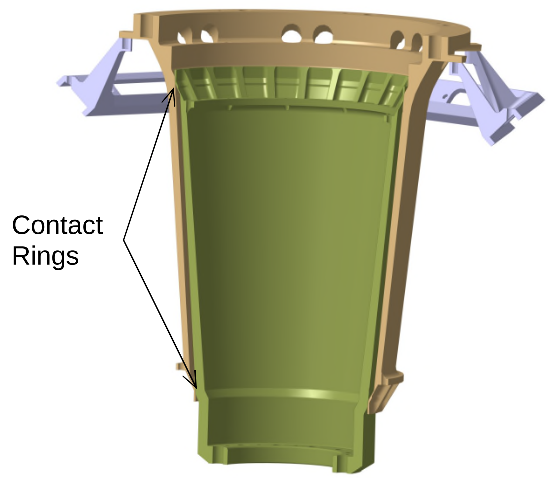

Figure 6: LOD Cones in orbit configuration (Closed, preloaded contact).

The main requirements for the LOD are:
1. Enough clearance during launch, so that no loads are transferred to the Drive Unit (6 DOF free)
2. Reliable transition from launch to orbit configuration (avoid failure modes like getting stuck halfway due to friction or unforeseen clashes, capability to achieve orbit configuration independently of starting conditions)
3. Low energy release during configuration change (the kinetic energy of transition will bend the bearing membranes, and if more than the acceptable values, will cause a clash on the glass encoder disc)
4. 6 DOF locked at orbit configuration, with high load capacity to handle maneuver loads
5. High repeatability (to achieve required pointing performance)

6. High angular stiffness (X and Y), to achieve pointing performance and first Eigen frequency in orbit

<u>Low local stiffness for high repeatability and high SCM stiffness</u>
The current design is the result of assessing several concepts and performing many design-analysis iterations. The cones with 2 contact rings create an over-constrained coupling. This is not ideal because when tolerances are different than absolute zero, it will lead to having contact on one ring only, meaning that: repeatability, load capacity and stiffness will not be achieved.
The way to ensure contact on both contact rings is to elastically deform the contact regions to overcome the manufacturing tolerances. For this, low stiffness in the contact regions and high preload are desired.

To be highlighted the following challenging reconciliations:

a. low stiffness in the contact regions, with high LOD angular stiffness (X and Y),
b. High preload, with low energy release during configuration change (avoiding active components like motors and sensors).
c. Low stiffness in the contact regions, narrow manufacturing tolerances.

Reconciliation "a" is achieved by tuning the contact stiffness value and directions. The idea behind the current geometry is to reduce axial stiffness in the tangential direction (easy change of perimeter), while minimizing the losses of wall bending and shear stiffnesses.

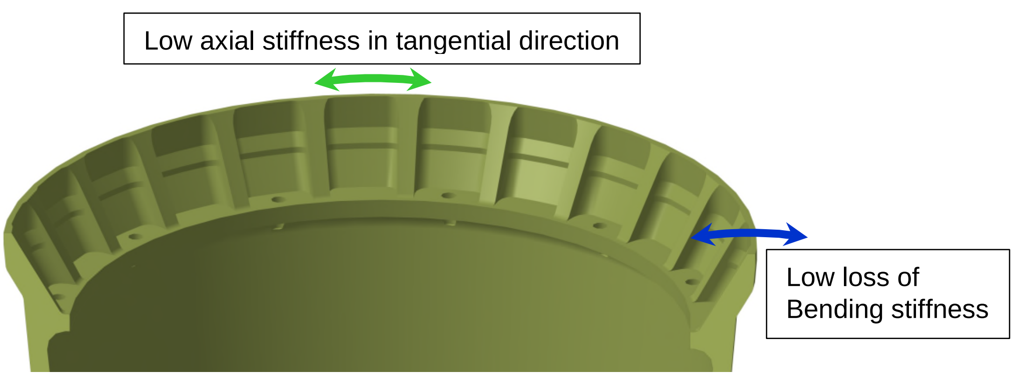

Figure 7: Cone contacts local stiffnesses.

Reconciliation "b" is achieved by actuating the configuration change with a spring delivering low force, as constant as possible thru the stroke (low stiffness spring). In parallel, permanent magnets are used to increase the closing force at the end of the stroke.

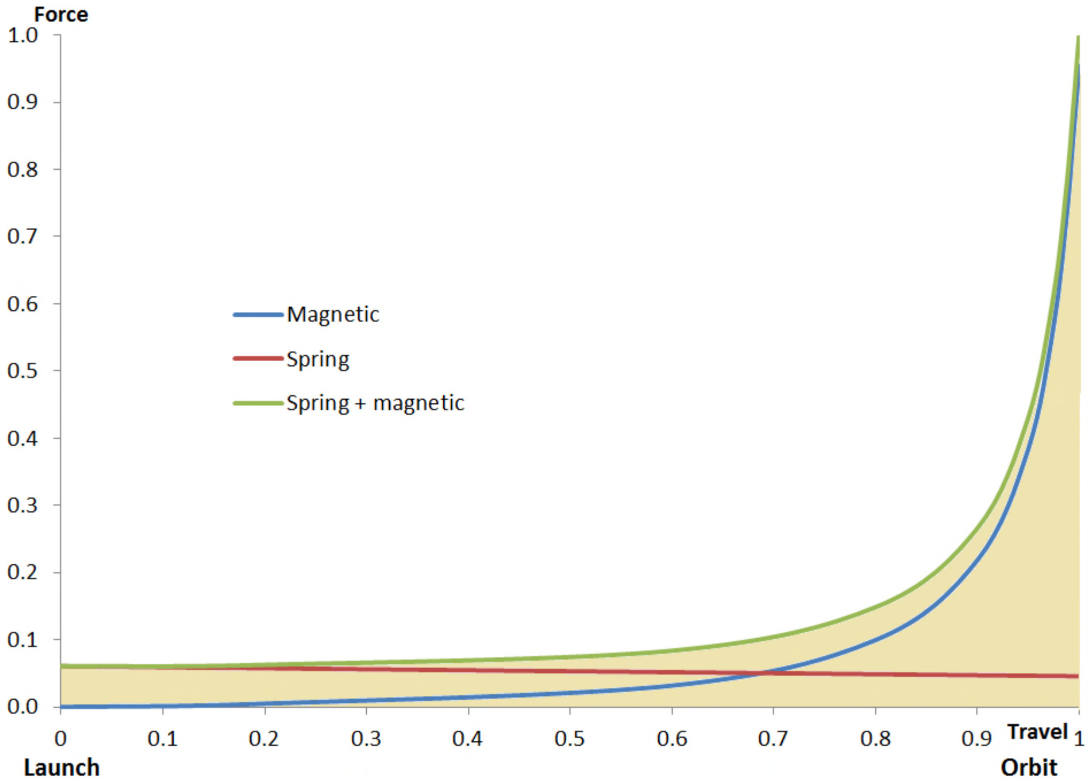

Figure 8: The energy released for the actuation is the area under the green curve (presented values are adimensional).

Reconciliation “c” is challenging because the low stiffness in the contact regions leads to considerable local deformations under cutting loads during machining. These deformations make it almost impossible to achieve well defined dimensions and geometries. The expectation is this reconciliation with a correct tuning of stiffness and machining parameters.

<u>LOD Dynamic analysis</u>

Dynamic simulations were made to predict the configuration change. The main parameters modeled were:

- Masses and inertias of: S/C non rotating part; SCM rotor; Instrument rotating part.
- Most relevant stiffnesses: cones coupling; bearing membranes …
- Actuating forces: spring; magnetic,
- Friction on contacts
- Damping; bearings, material.

Some results are presented in Figures 9 and 10.

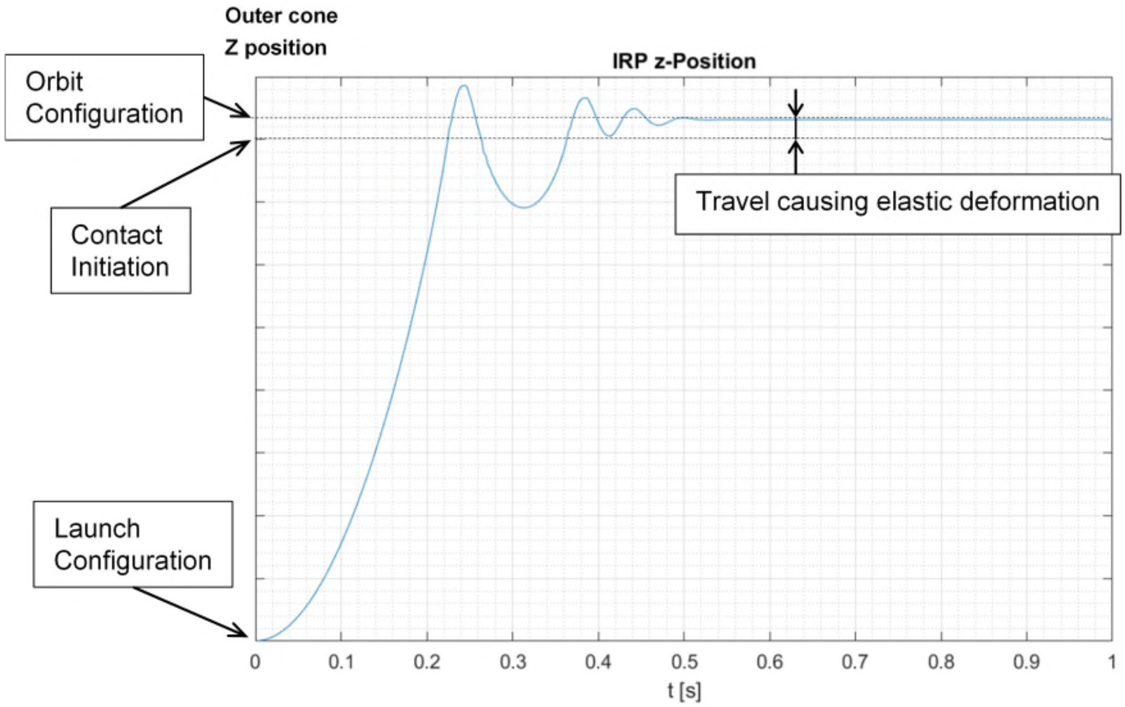

Figure 9: Configuration change travel (axial direction).

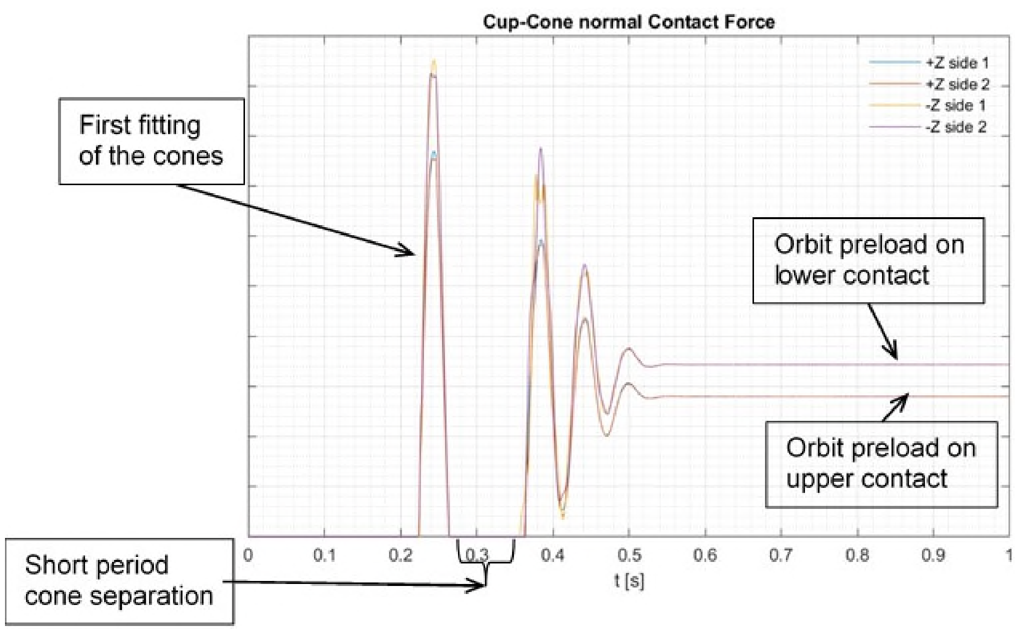

Figure 10: Contacts normal force during configuration change.

It is curious to see that the cones separate during a short period, after the first fitting. This is explained by the low friction in the contacts, relatively high fitting angle, and the considerable amount of energy bounced back by the bearing membranes.

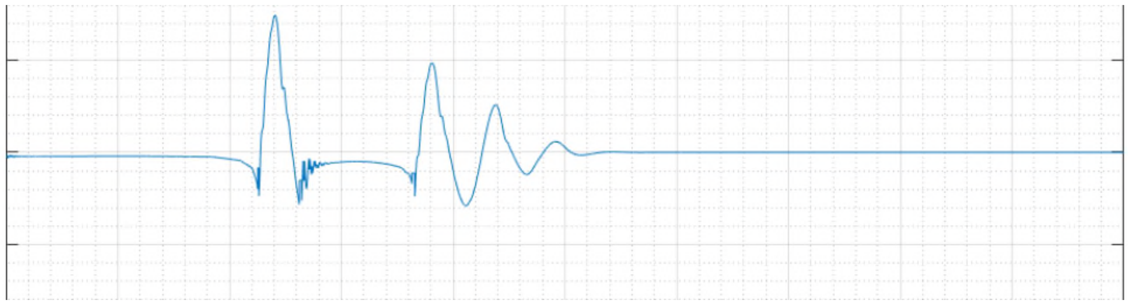

Figure 11: Axial force on bearings.

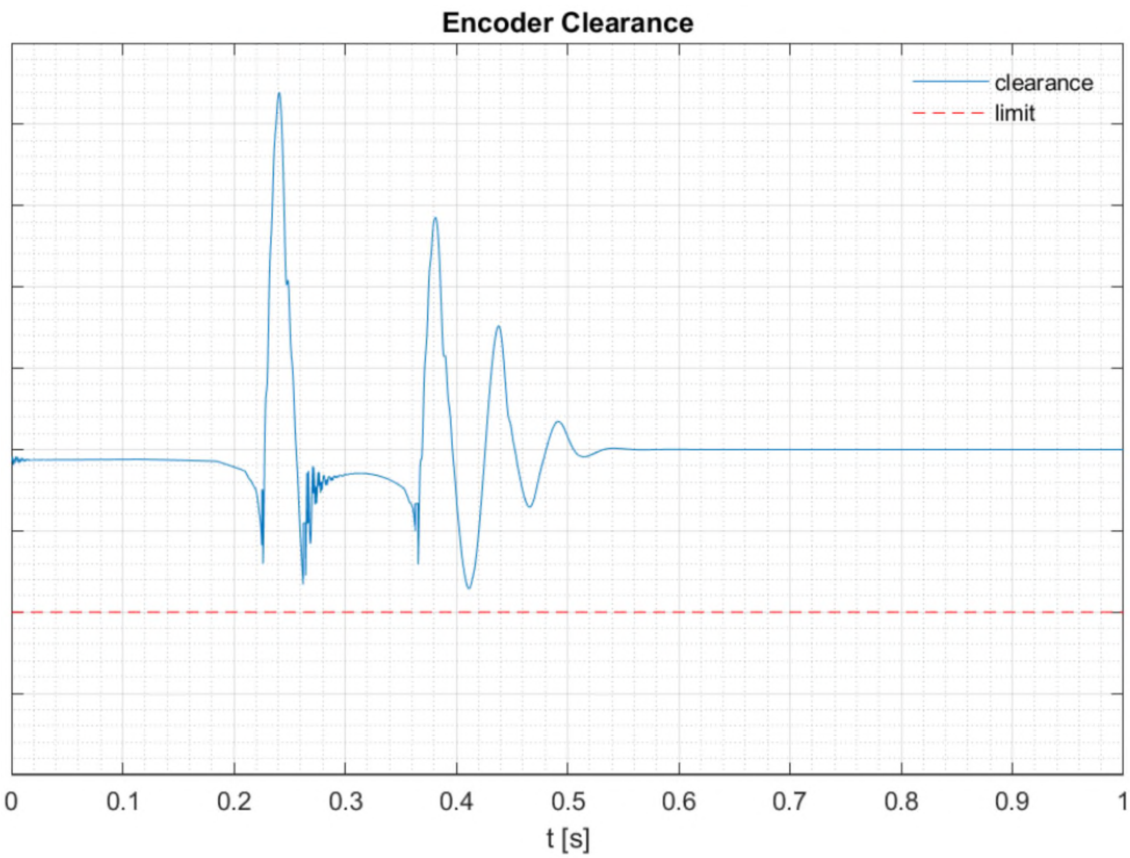

Figure 12: Encoder clearance during configuration change.

To be noticed the following relations of the graphics:

- Sliding on the cones contacts <-> Variation of contact normal force <-> Z force on the bearings (Sliding on the cones causes deformation of the contact regions and force changes on the contact due to stiffness, Z bearing force and inertial forces push and pull the contacts)
- Z force on the bearings <-> Encoder clearance (due to bearing membrane elastic deformation)

LOD Breadboard (BB)

Multiple requirements apply to this device i.e., high load transfer, high stiffness and high pointing repeatability. Many effects are contributing to the performance of the LOD, being that some of them are rather difficult to predict. Therefore, a Breadboard test program is the most efficient way to determine / verify / reduce uncertainty of several parameters. Table 1 presents the main effects to be studied during a BB test campaign, as well as the main requirements affected by these parameters.

Table 1: Breadboard goals

Parameter / effects	**Goal at BB level**	**Source requirement**	**Uncertainty preventing determination by analysis**
LOD position and orientation repeatability	To be measured	Pointing performance;	Manufacturing tolerances, Friction
LOD angular stiffness	To be measured	On orbit stiffness	contact on the cones (with low preloaded when compared to bolted interfaces)
Cones fitting force	To be measured	Reliable cone fitting	Manufacturing tolerances, Friction
Kinetic energy transferred to the bearing membranes	To be indirectly measured	Survivability encoder disc	Friction, other damping sources
Magnetic force along transition travel	To be measured (reduce margins)	Pointing performance; On orbit stiffness;	Material properties; Model verification;

The test setup concepts for two tests are presented in Figures 13 and 14.

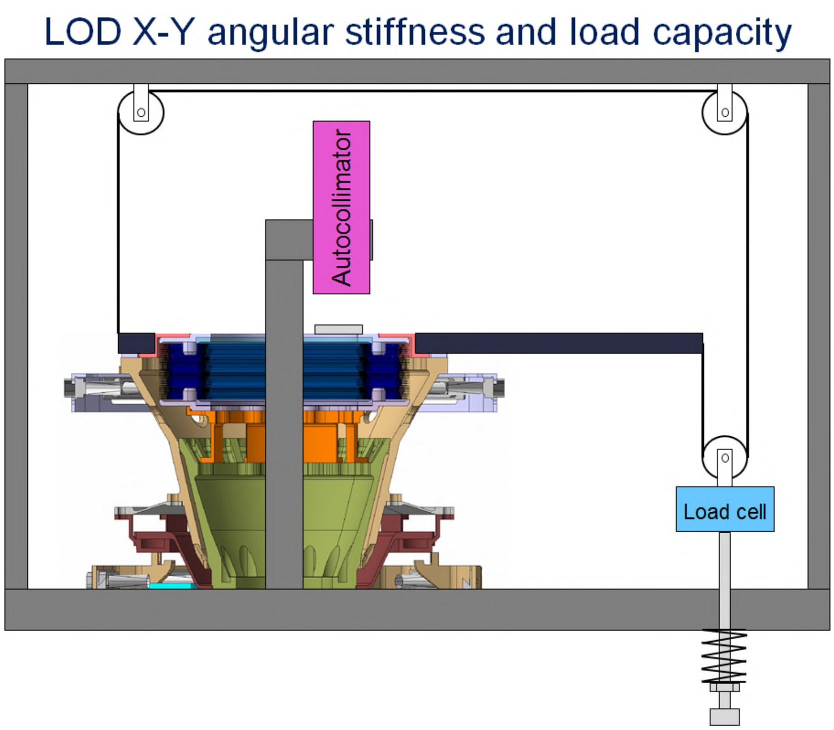

Figure 13: X-Y LOD angular stiffness, static measurement.

The concept is direct, to apply a torque and measure the angular displacement. Complementarily a dynamic test will be done in the shaker to measure the first Eigen frequency.

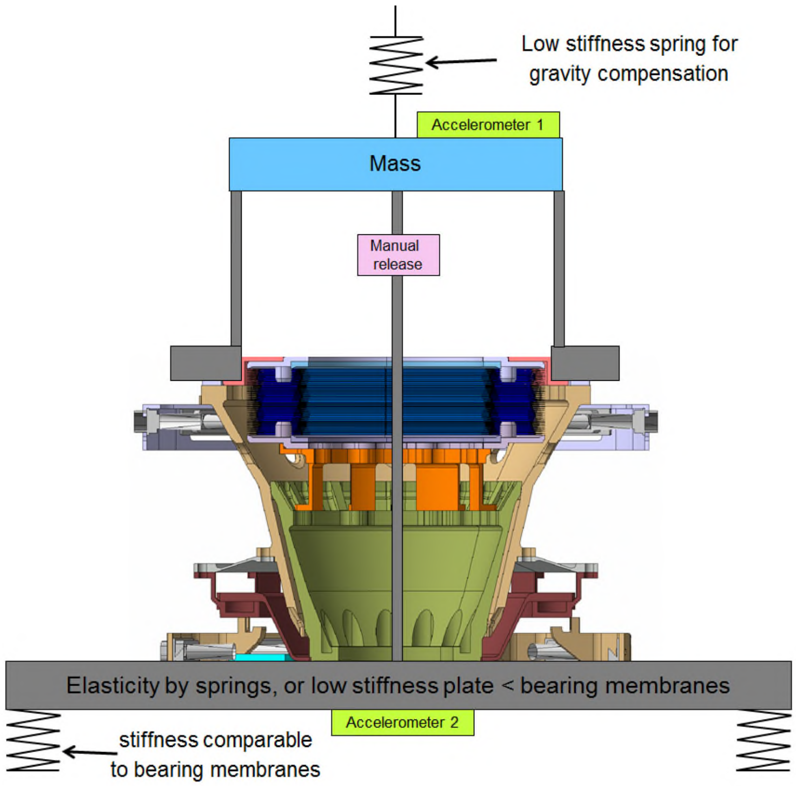

Figure 14: Kinetic energy transferred to the bearing membranes during configuration change.

The concept is to execute the configuration change with gravity compensation in order for the test to be energy representative. The stiffness of the support will be measured during the test measuring the first Eigen frequency and using the previously measured oscillating mass. With the stiffness of the support and amplitude measured by accelerometer 2, the energy can be calculated and compared with the predicted in the dynamic simulations.

Life Test

Scan Mechanisms usually operating during the entire mission. The required life revolutions depend on mission time and speed and can be usually several hundred million revolutions. Therefore, the lifetime qualification needs specific attention and a good preparation since the test validation takes a long duration even in accelerated condition and introduces a notable risk to the project with respect to schedule and effort in case of failure.

A usual approach is (if representative) to perform a life test in accelerated condition to have the test validation available prior FM manufacturing. However, the orbit condition representativeness cannot be easily demonstrated, as some parameters are different like speed, lubrication regime, heat dissipation, temperature gradients, motion etc.

On the previous MetOP SG project, the life test has shown an issue with some Roll-Ring channels which haven't performed in the expected way. A detailed investigation has been performed. A Build Fixture, which was used for the Roll-Ring assembly was not sufficiently accurate, causing a malfunction that allowed the Coupler to move outside of the ring. Furthermore, an investigation was performed to predict if such an error can be due to an accelerated speed of over 225 rpm, which is a factor of 5 times faster than the orbit speed. No reliable calculation method was found for a clear relation between speed factor and degradation factor, but negative effects couldn`t be excluded.

As with any electrical rotating interface, circuit resistance performance is degraded somewhat due to moisture effects and the test setup requires at least two parallel circuits to be measured together which makes it difficult to isolate areas of concern.

Complicating the situation, an Instrument Unit was designed with a very sensitive under voltage protection, supplied by power via the roll-ring. Therefore, the concern was raised about the resistance peaks within millisecond range.

These challenges led to a specific resistance measurement and measuring equipment with the following characteristics:

- Continuous resistance recording of all roll-ring channels at the same time
- Continuous current transfer of the power lines during lifetime
- Resistance sampling rate of 25 kHz of all channels (well above industry standard)
- EGSE noise level < 0.0005 ohm (well above industry standard)
- Resistance recording during entire life test sampled for trend analysis
- Resistance recording with high data rate at a specific event (versus a threshold value)

This specific ground support equipment was manufactured and is under operation to perform monitoring of the Roll-Ring under real environmental conditions.

The Roll-Ring technology demonstrates inherent low dynamic resistance noise levels over extended periods of time. Humidity can impact the noise level which is usually higher after long term storage (under clean room conditions) but quickly improves with nitrogen purging or in a vacuum condition. The dynamic resistance noise level also varies in relation to the shaft speed. Figure 15 shows the Roll-Ring dynamic resistance noise measurement with a sampling rate of 25 kHz. No filter is applied to the measurement data, and this sampling rate is well above industry standard, but used here for our purposes. The resistance measurement was performed in ambient condition.

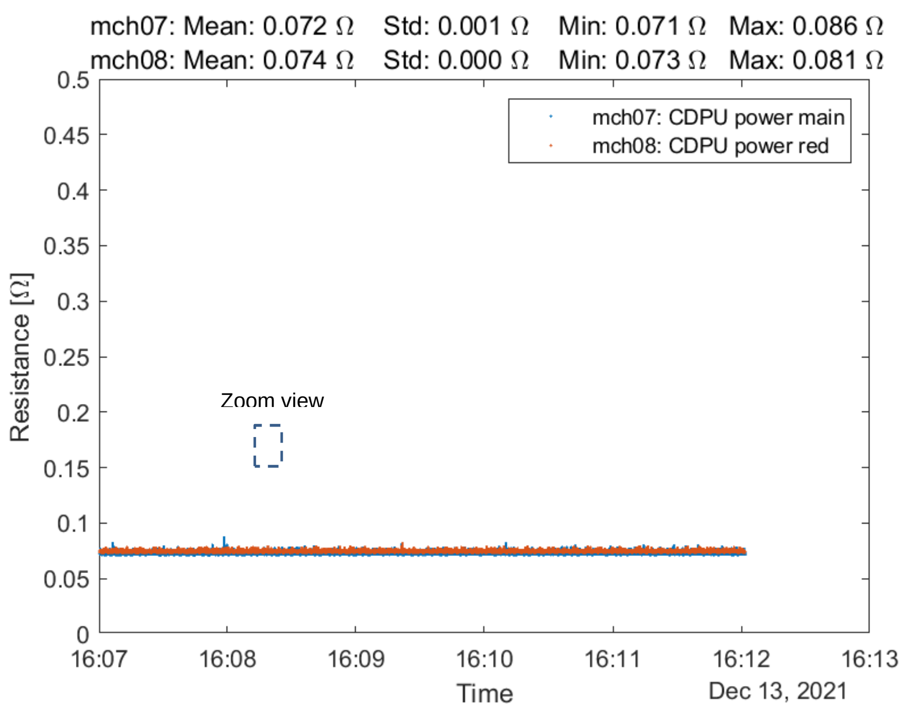

Figure 15: PDTD Resistance noise with 25 kHz sampling rate

Figure 16 is a zoom view of Figure 15 with short resistance peaks in a millisecond range. There are many possible reasons for this, to include moisture effects, contamination, or irregularity in contact surface.

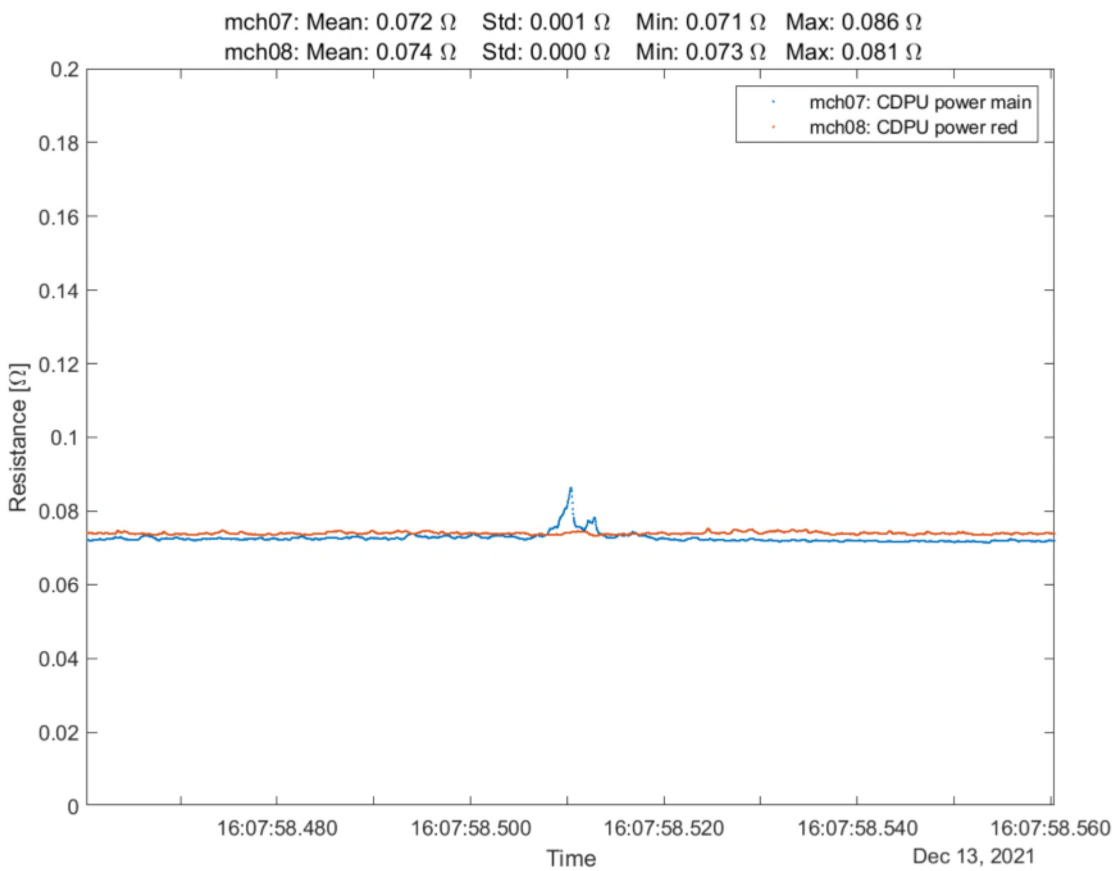

Figure 16 Zoom view

Figure 17 shows the nomenclature of the Roll-Ring items. Electrical contacts are between the inner Ring and Coupler and between the Coupler and the outer Ring.

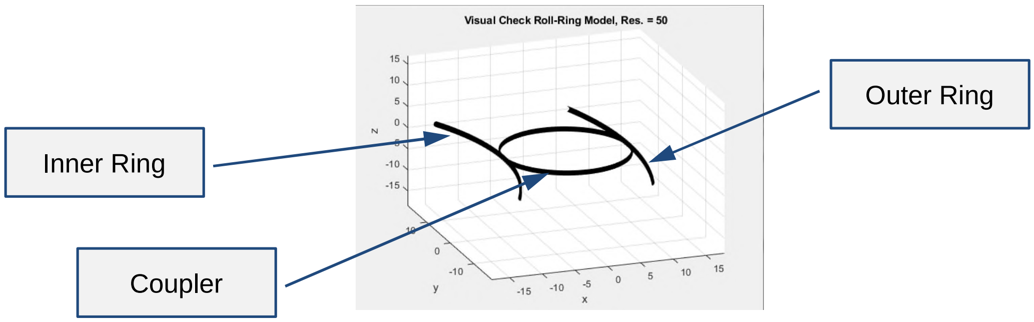

Figure 17: Roll-Ring® nomenclature

Figure 18 shows the Roll-Ring characteristics which were helpful for failure detection. The plot represents the measured 4 Channels with two in series at a sampling rate of 25 kHz, again without any filter. The plot shows the measured value in the frequency domain. There are typical peaks at specific frequencies which are clearly linked to the three contact surfaces for Inner Race, Outer Race and Coupler.

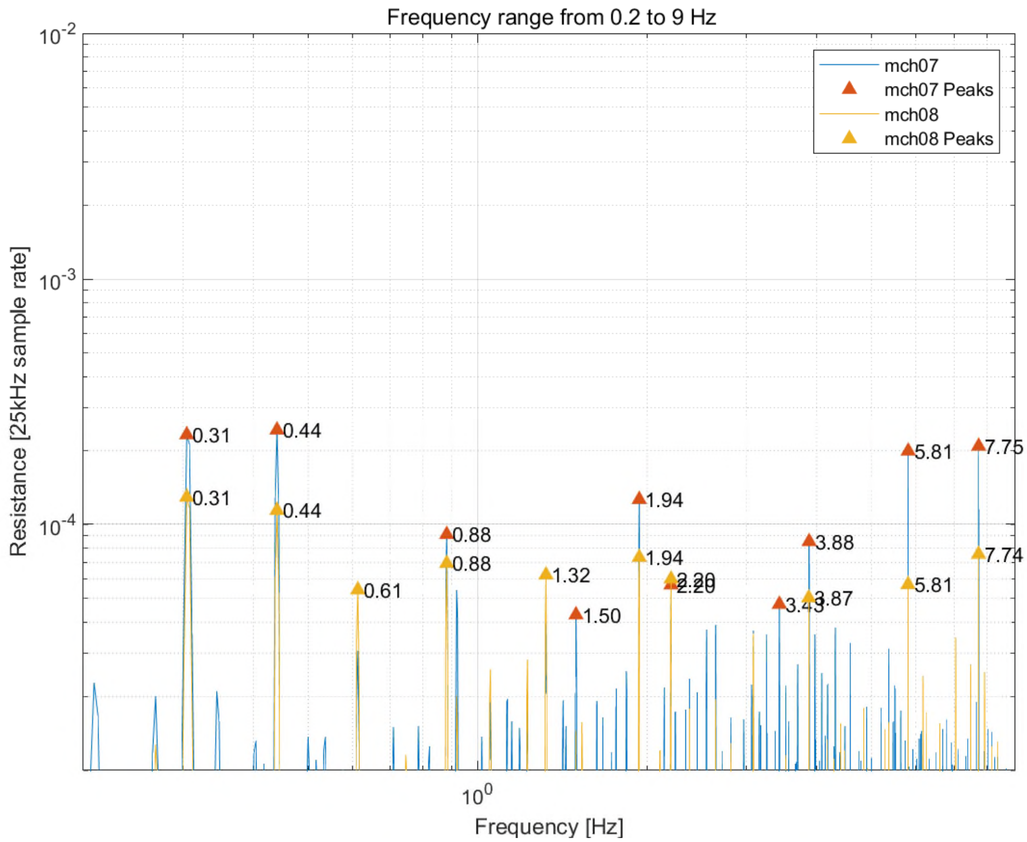

Figure 18 Fast Fourier Transformed resistance data

The Roll-Ring supplier has made improvements to ensure a robust solution that will operate with a misaligned build fixture and at accelerated speed with sufficient margin. With all the experience of the previous life test, the Roll-Ring supplier has implemented the knowledge gained to all design and manufacturing standards.

Therefore, the following are key lessons learned

Customer levels:

- The envelope should be defined by means of feasible design concepts with sufficient margin.
- Best practice selection process does not allow envelope iteration with the bidders. Therefore, the envelope should be defined as a goal and not as a hard requirement to make different design concepts possible for best selection.
- Electrical dynamic contacts cause resistance noise. Power regulation and under voltage protection must be adapted accordingly.
- Adequate planning with successful life testing is warranted.

Supplier level:

- Accuracy of the build fixture must be verified by test, preferably with and without the installed device.
- Be aware that an envelope change becomes more difficult as the project progresses.
- Design must be sufficiently robust against manufacture tolerances and accelerated life test speed.

The robustness of the CIMR PDTD design is significantly improved against manufacture and alignment tolerances compared with the previous design. Early confidence test verification has been implemented to verify the assumptions prior to SCM Life test with the following aim:

- Margin verification with respect to accelerated speed
- Margin verification with respect to manufacture tolerances
- Margin verification with respect to rated and de-rated current transfer
- Confidence life test at PDTD level prior to SCM life test

In summary, the issues experienced have led to advanced understanding and robustness improvements. The Roll-Ring provides excellent resistance noise levels over extended time periods and is therefore considered the best choice in high performance data and power transfer for long life applications.

Acknowledgement

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