In-Orbit Performance of the MWRI Scanning Mechanisms

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Abstract

Scanning Equipment supporting the Millimeter Wave Radiometer Instrument (MWRI) are flying in a sun-synchronized orbit of 850-km altitude with an inclination of 98.8° on the FY-3 meteorological satellite (FY = Feng Yun, Wind and Cloud). MWRI is a linearly polarized, ten-channel passive Radiometer; it measures precipitation and water clouds, sea ice, snow/water equivalent, drought and flood index, land temperature and soil moisture.

Following the FY3-A, the FY3-B Satellite was launched in autumn 2010. Since that time, the Scanning Equipment was continuously operated. During the last three and a half years in orbit, the Scanning Mechanism has executed about 65 million revolutions, while the Scan Compensation Mechanism (SCM) - used for momentum compensation - has already successfully executed more than one billion revolutions.

During the commissioning phase of the instrument and during the first operation phase, random torque spikes, which manifested themselves as a motor current increase, were observed in the Scan Drive Mechanism, whereas the Scan Compensation drive operated nominally from the beginning.

The result of the root cause investigations performed in order to isolate the issue, and the consequences for the follow-on MWRI equipment which was successfully launched by end of September 2013 (now flying on the FY 3-C Spacecraft), are discussed.

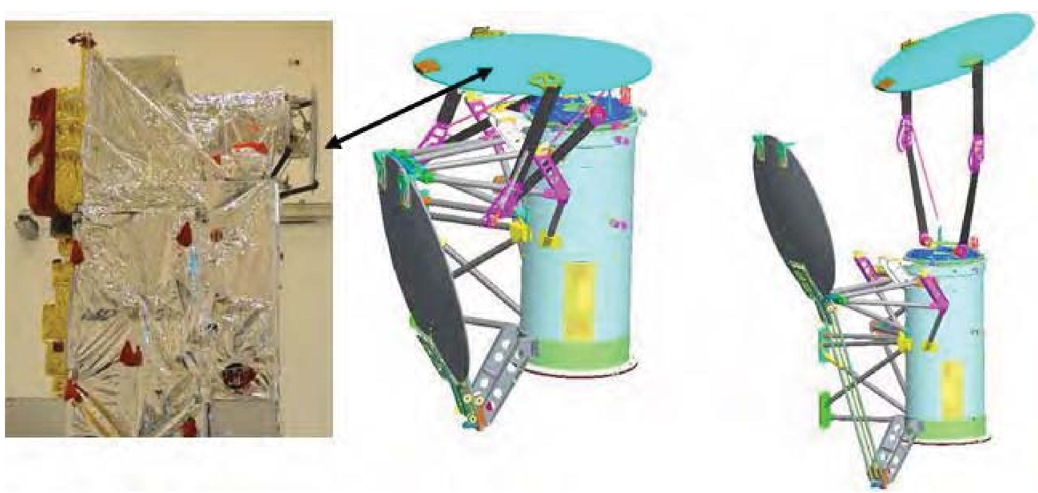

Figure 1. FY3 Spacecraft and Instrument Configuration

Introduction

The scanning equipment consists of the Scan Drive Mechanism (SDM), a physically independent Scan Compensation Mechanism (SCM), and the Scan Drive Electronics (SDE). The conically scanning MWRI instrument with a mass of 60 kg is continuously operated by the Scan Drive Mechanism (SDM). The

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velocity of the Scan Compensation Mechanism (SCM) is electronically coupled by a fixed factor to the closed-loop-controlled Scan Drive Mechanism (SDM) in order to achieve momentum compensation during the instrument acceleration and deceleration and during normal operation phases.

The Scan Drive Electronics (SDE) controls and synchronizes the two mechanisms. The spin rate stability of the SDM is 0.3 ms. The spin stability is achieved by a closed-loop control scheme applied to the BDC motors and by a 16-bit encoder feedback device included in the SDM.

The nominal but adjustable spin rate of the SDM is 1.7 s/rev. The rotation speed of the counter-rotating Momentum Compensation Stage is coupled by a fixed factor to the SDM speed and is in the range of 560 revs/min.

During launch, the SDM mechanism bearings are off-loaded by a launch offload device attached to the SDM in the interface between mechanism and instrument. The instrument is supported during launch by instrument-provided holddown release mechanisms (HRMs) fixing the instrument to the S/C. By this design, parasitic loads introduced during launch by the heavy instrument into the SDM bearings are avoided.

After HRM release, the launch offload device - realized by a pre-loaded cup-cone element - provides a precise rotational axis for the Instrument and avoids potential run-out of the instrument CoG from the SDM rotation axis, what would lead to a cyclic excitation of the S/C.

The Flywheel of the Scan Compensation Mechanism with a mass of about 4 kg does not use a HRM. During launch, the flywheel is supported by the SCM bearings only.

Instrument Description

Figure 2 shows the MWRI Instrument block diagram. After launch and HRM release, the antenna dish is deployed to its final configuration by means of a deployable support structure.

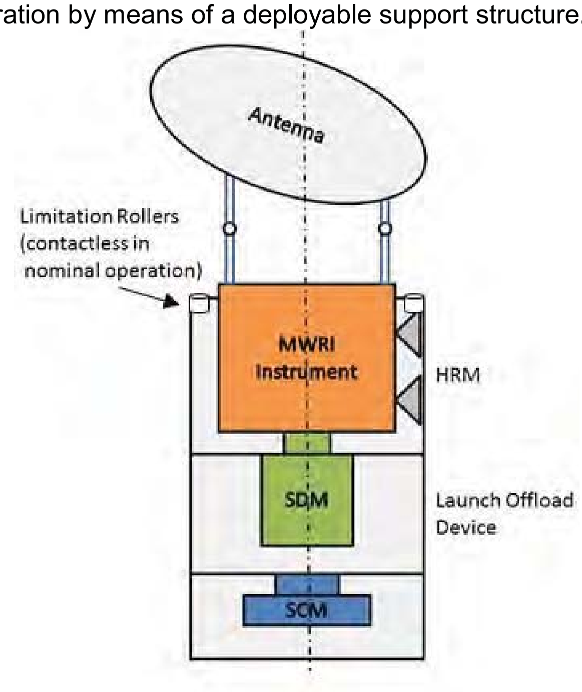

Figure 2. MWRI Instrument Block Diagram

The MWRI Instrument is rotated together with the antenna by means of the SDM in order to allow conical ground scanning. The SCM is used for momentum compensation during normal operation (scan rate changes) and during start-up and potential deceleration phases which take 180 s each, performed in a synchronized and controlled mode. MWRI receives data in 10 frequency channels from 10 GHz up to 89 GHz with a ground resolution of 0.25~1 km. A typical output is depicted in Figure 3.

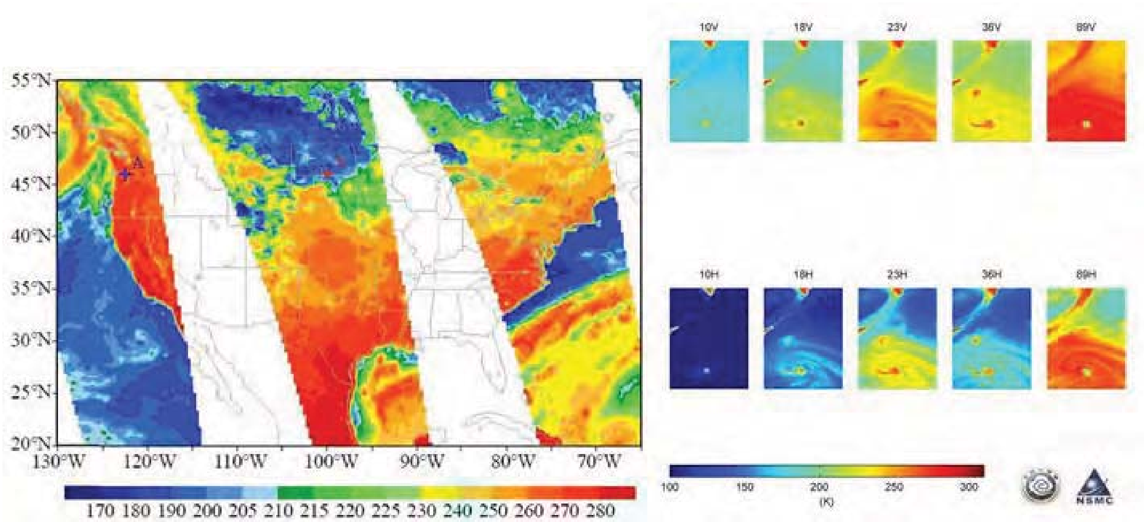

Figure 3. Spatial Distribution of Brightness Temperature and Tropical Storm over the Pacific

Scan Equipment Definition

The MWRI Scan Equipment consists of a Scan Drive Mechanism (SDM) including a Launch Offload Device, of a Scan Compensation Mechanism (SCM) and of a closed loop Scan Control Electronics (SCE).

Figure 4. SDM (with Instrument MoI/Mass Simulator) and SCM

Scan Drive Mechanism Design (SDM)

The SDM consists of a drive module using two hard preloaded pairs of ball bearings, a redundant brushless DC motor and a redundant optical encoder for closed-loop velocity control. On the rear end of the drive module, a slip ring unit for power and signal transfer from / to the rotating Radiometer Instrument Package is attached. The Harness is guided through the hollow drive shaft to the slip ring rotor.

The I/F to the rotating instrument mounted on top of the SDM is formed by a launch off-load device. The launch off-load device consists of axially pre-loaded flexible metallic bellows and an accurately shaped conical Interface. The combination of both elements also provides high instrument alignment accuracy and torsional stiffness about the rotation axis during the mission. During launch, the conical I/F is lifted off from the mechanism I/F, so to de-couple the instrument load path from the mechanism. After release of the Instrument HRMs, the instrument is pulled back into its conical I/F and torque transfer from the SDM to the instrument is allowed.

The SDM rotor shaft is mounted via 2 pairs of hard preloaded angular contact ball bearings in face-to-face arrangement into the SDM housing (preload 400N). The bearings are manufactured from Stainless Steel 440C, the cages are manufactured from Phenolic Resin, vacuum impregnated and lubricated with Fomblin Z 25 (changed in the FY3C mission to Nye Oil/ Maplub for commonality reasons with the SCM).

The motor is a brushless DC type with completely cold redundant independent stators. The redundant optical Encoders provide position data with 16-bit resolution.

The slip ring for power and signal transfer to the instrument is composed of 19 solid gold tracks and redundant gold alloy brushes to achieve the expected orbit life of 3 years (3.5 years already achieved, corresponding to 60 million revs, 5 years goal).

The SDM mechanism design as used on the FY3-B Spacecraft is shown in Figure 5.

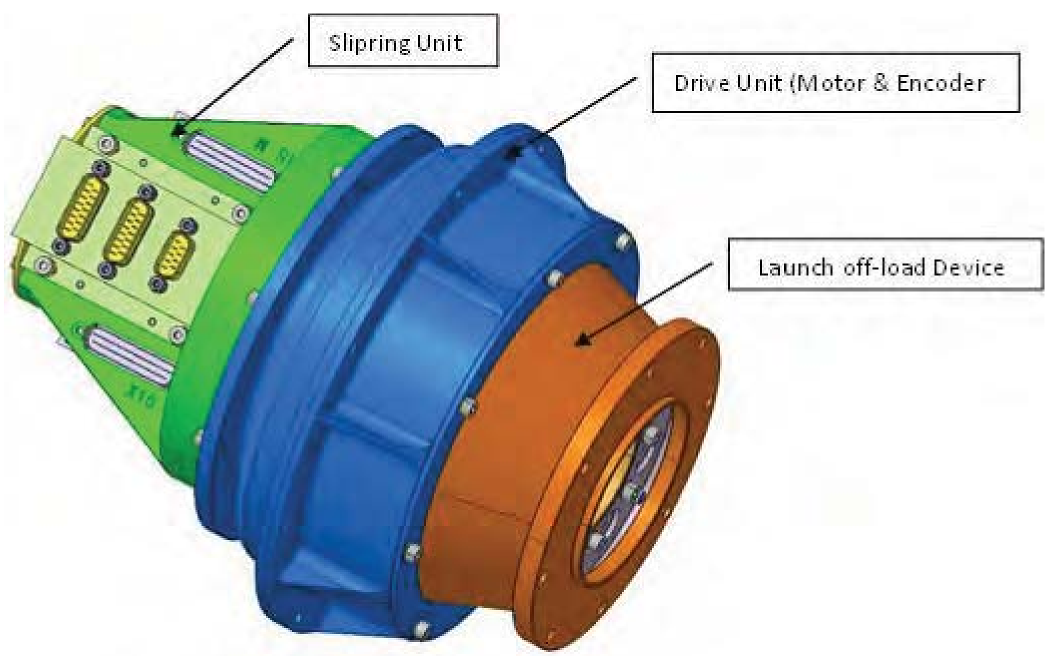

Figure 4. SDM Design as flown on FY3-B

Scan Compensation Mechanism (SCM) Design

The SCM consists of a drive module using a brushless DC motor with redundant motor stators. The SCM motor is similar to the SDM motor, but optimized for the higher operation speed.

For rotation speed feedback, 3 Hall Sensors are included in each motor stator. A flywheel with trim masses is attached to the motor output shaft.

The SCM is lubricated with Nye Synthetic Oil 2001A and Maplub Grease SH051A. The bearings are identical to the SDM bearings. However, in the SCM only one pair of bearings is used in back-to-back arrangement. The bearing preload is set to 400 N.

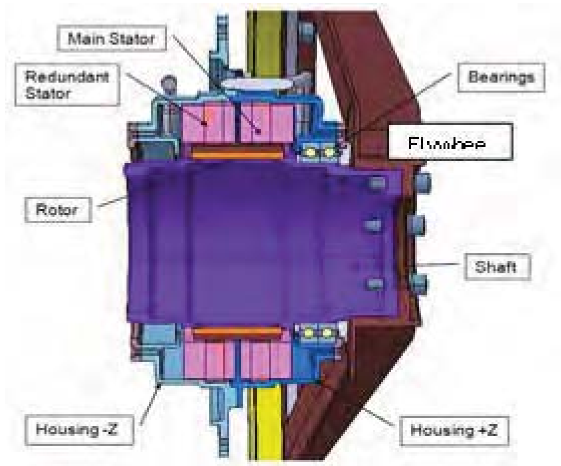

Figure 6. SCM Design

Orbit Performance and Start-up Issue

During the instrument's in-orbit commissioning phase it was observed that the SDM current was not stable, but it was randomly varying over time. Nominally the current should have been in the range of slightly above 0.2 A, however, in reality current spikes up to the 1 A range were randomly observed along with long term current variations. From this behavior, the conclusion had to be drawn that the torque needed to operate the SDM together with its MWRI instrument module was varying over time.

It can be seen that after about 16 months of operation, the motor current stabilized back to the expected nominal current values of about 0.2 A and also the scan rate performance improved to nominal values.

In Figure 7, the SCM current is plotted for the observed mission time frame and we see that the motor current and consequently the mechanism friction looks very stable over all mission phases and it is well within the expected nominal range from the beginning.

From the telemetry data (current, temperature and scan rate stability), it was not clear which effect could have caused the friction variation in the SDM, leading to the controller current spikes and current variations as observed. In order to understand the issue better, an in-depth root cause investigation was performed.

In Figure 8, we see the typical current variation as received via Telemetry during the instrument start-up and first operation phase. A direct correlation between the motor current variation and the scan rate stability was observed, and the current variation leads also to a reduced controller performance.

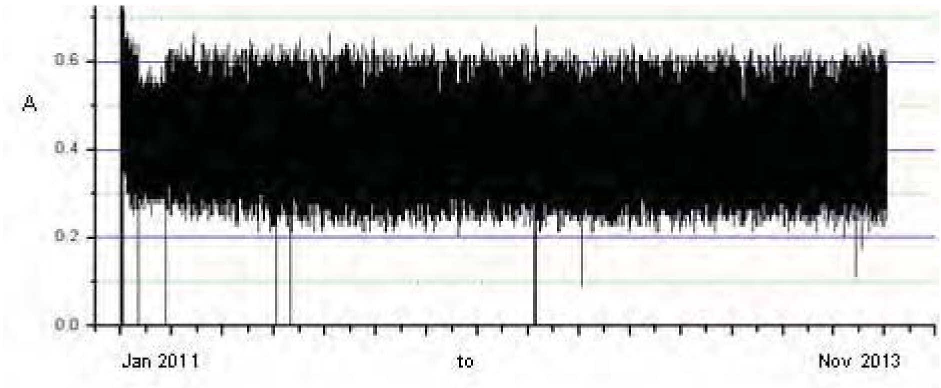

Figure 7. Typical SCM Current over 34 Months

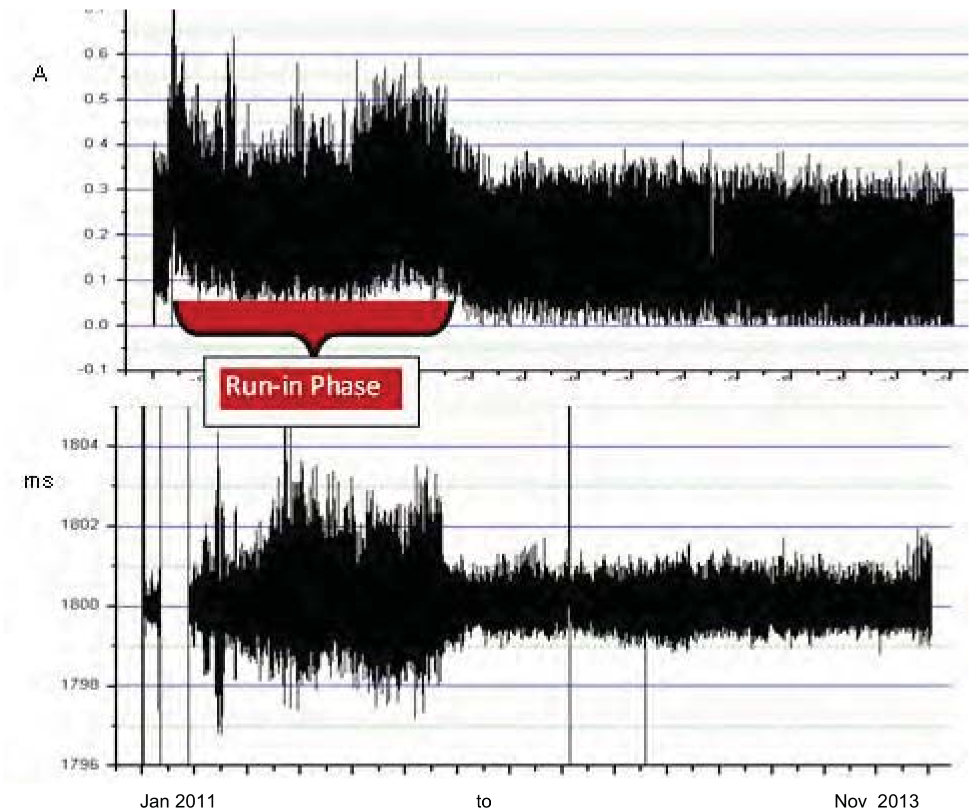

Figure 8. SDM Motor Current Spikes and associated Scan Rate Stability over 34 Months

Root Cause Investigation

In order to identify the root cause for the current /friction anomaly observed, all potential disturbance sources were identified and investigated in detail. For initial identification of all potential root causes of the observed anomaly, a fish-bone diagram was used (Figure 9).

Identification of Potential Error Sources
Some of the potential root causes could be excluded very soon. These were:

- Transfer of wrong telemetry data --> eliminated due to the fact that all other data was transferred correctly; no anomalies
- Degraded slip rings --> slip rings are new in the first mission phase and no anomaly was observed during the limited number of ground test cycles.
- Bearing degradation --> bearings are new in the first mission phase and no anomaly was observed during any phase of ground testing or after environmental test.
- Bearing contamination by particles--> The probability of parasitic particles or contamination of the mechanism bearings could of course only be judged on the basis of the available documentation and photos and on the basis of discussions with the integration personnel. According to these investigations, and due to the fact that during all integration and test steps from equipment to system level a clean environment was provided, and due to the low probability that external particles could enter into the mechanism during any higher level integration stage, this option was also judged to be very unlikely.

Three different potential root causes could be isolated which might have caused the current issue.

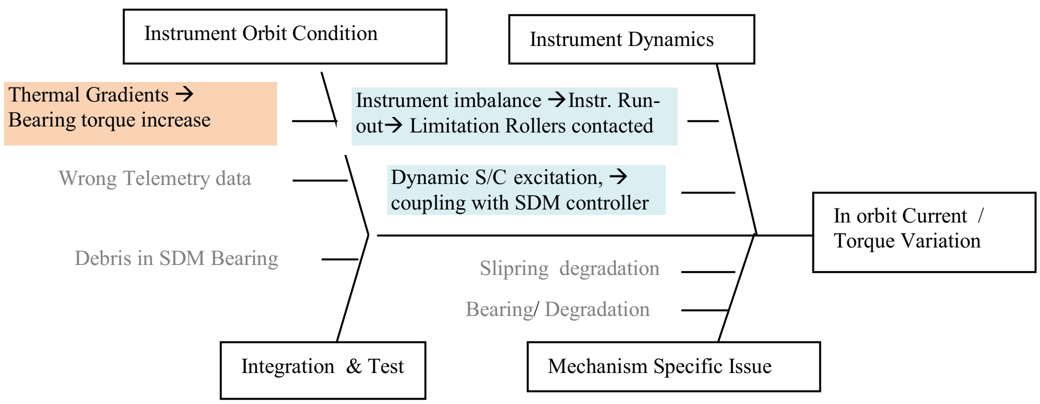

Figure 9. Fishbone Diagram for Root Cause Investigation

Instrument Imbalance

A more likely scenario was seen in a potential misalignment of the rotating instrument axis with respect to the Scan Drive Mechanism, which could cause a lateral run-out and imbalance of the instrument compartment. Such a lateral run-out would lead to a contact of the (nominally contact-less) limitation rollers attached to the top of the instrument compartment with its rotating part. The friction of these rollers would influence the controller behavior and consequently also the current consumption of the mechanism. However, after checking all tolerances and after a proper check of the instrument center of gravity (CoG) and the subsequent calculation of the residual eccentric forces that would act on the off-load device of the mechanism, this possibility could also be excluded.

As a consequence, two remaining root causes were identified:

- Potential dynamic excitation of the quite large antenna on top of the instrument could have caused disturbances to the control loop due to the fact that the real orbit condition of the deployed antenna could not be simulated on ground (1 g condition).
- Thermal gradients in the mechanism that were not specified and not tested on ground.

Dynamic Excitation of Deployable Antenna Appendage

Since quite a large appendage composed of the antenna dish and of a deployable antenna support structure is mounted on top of the instrument compartment, the possibility of a dynamic coupling between the appendage and the SDM controller was seen as a potential root cause for the observed current increase. By nature, all on-ground tests on system level had been performed under 1 g conditions, so that influences on the dynamic behavior under 0 g condition could not be excluded.

Therefore the available engineering model (EM) Scan Mechanism was used to support a dynamic test with the goal to quantify potential influences of the antenna and its support structure on the mechanism performance. For this purpose, a test setup was built, simulating the instrument inertia and the mass and stiffness of the antenna deployment structure.

For this purpose the eigen-frequency results from the instrument analysis were used as reference and a spring blade test setup was designed and adjusted to the system reference eigen-frequency by means of a dedicated finite element model (Figure 10). The first rotational system frequency is at about 9 Hz, whereas the first lateral one is at about 5 Hz.

In this configuration, a dynamic test was carried out on the EM Scan Drive Mechanism, with the finding that the influence of the antenna and of its large deployable structure on the mechanism controller, and subsequently on the power consumption, was negligible.

In Figure 11, the H/W of the test setup as derived from the analytical model is depicted. The two masses on the both sides simulate the instrument inertia while the mass on top and the spring blades in between represent the antenna mass and the torsional stiffness of the antenna support structure.

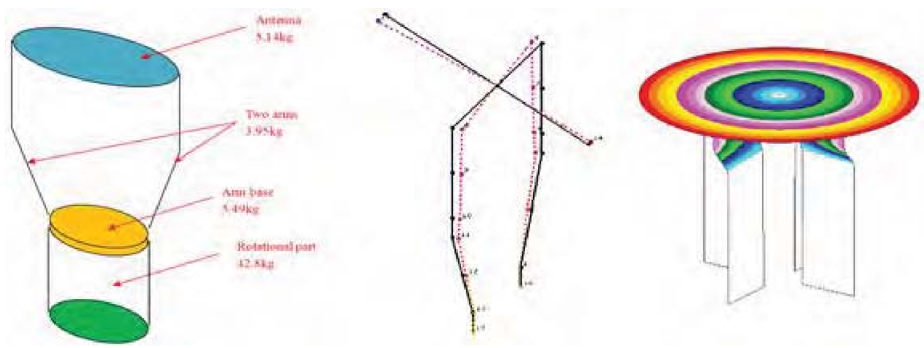

Figure 10. FE Model of the Antenna Deployment Structure and Analogous Model for Test Setup

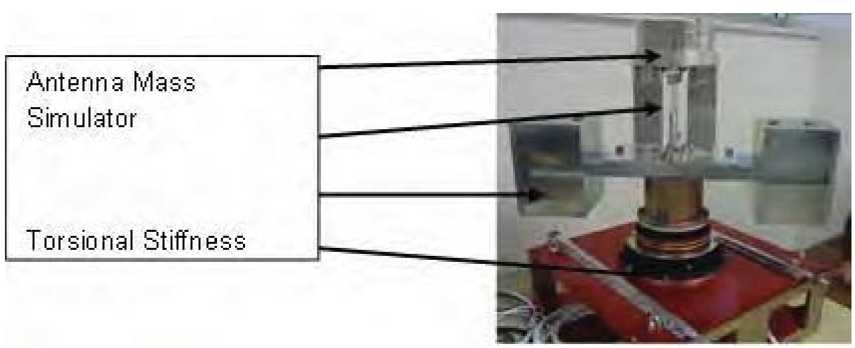

Figure 11. Torsional Stiffness Test Setup

<u>Thermal Gradients as Root Cause</u>

The MWRI Instrument is mounted on one side of the Spacecraft. This means that one side is exposed to space, while the other one is oriented towards the S/C structure. As a consequence, temperature gradients might act on the instrument structure, leading to a planarity change of the mechanism mounting I/F and of the mechanism housing itself.

The temperature range in the area of the Thermistors 149 and 150 is in the range of -6 to 0°C (Figure 12). The mechanism temperature (TMP 141/144) and SCM housing temperatures (TMP 132) are also at about 0 deg during operation, with only minor variation. However, the instrument I/F (attached to the mechanism rotor) has a temperature of about 23°C. Therefore, we see a lateral gradient acting through the mechanism mounting I/F to the structure, and also an axial gradient between the Instrument mounting I/F (rotor I/F) and the mechanism bearings.

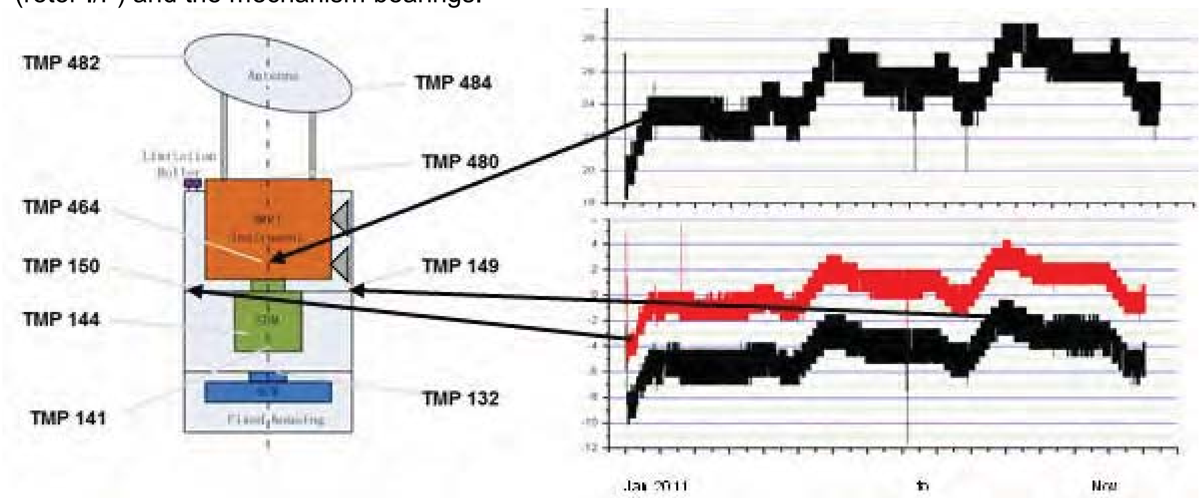

Figure 52. Relevant Temperature Data (deg C°) of FY3-B over 34 months

Based on the available orbit temperature data, a thermal deflection analysis was established in order to identify the maximum possible deviation of the mechanism I/F due to thermal gradients in its mounting structure (Figure 13). The analytical result was that the relative displacement of the mounting I/F flange along the mechanism rotation axis due to the gradient influence of the mounting flange is about 65 µm.

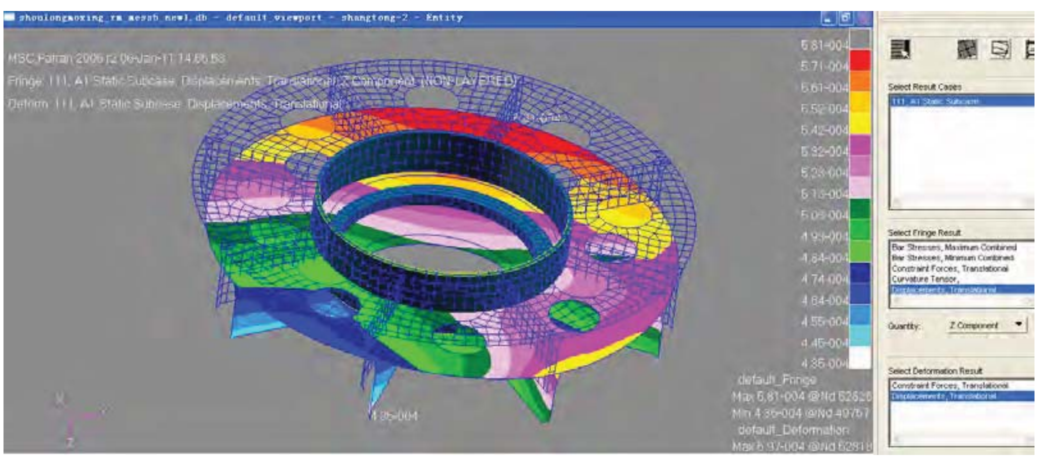

Figure 13. Thermal Deflection Model Mechanism I/F to S/C

Based on this result, and based on the fact that an additional axial temperature gradient from the warm instrument to the colder mechanism is observed, the assumption that the orbit current increase was resulting from such gradients which were not tested on equipment level during the qualification and acceptance test campaign, was valid.

In order to verify the findings, the available EM Scan Drive Equipment was submitted to a TV test campaign with the goal to apply realistic gradients as seen in orbit to the system and to prove the influence of such gradients to the motor current and control performance.

In this test, the baseplate (S/C I/F simulator) was cooled by means of cooling loops to the required low temperature, while the mechanism rotor was controlled to the Instrument I/F temperature (Figure 14). At the start of the test, the mechanism rotor I/F was heated to the orbit I/F temperature, while the S/C I/F temperature was at ambient. During continuous rotation of the mechanism, the S/C I/F temperature was decreased while maintaining the rotor I/F at the warm level. During the test, the rotation rate stability was also measured.

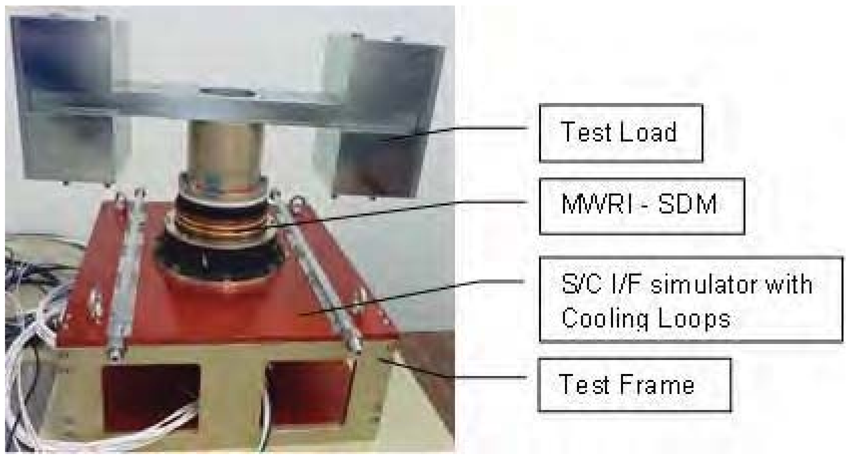

Figure 14. TV Test Setup for Gradient Test

A test result overview is depicted in Figure 15. One can clearly see the influence of the thermal gradients acting between the warm mechanism rotor and the cold S/C I/F flange on the motor current.

According to Figure 16, we can also confirm the influence of the thermal gradients to the scan rate stability. If the motor current rises due to thermal gradients in the system, the control performance of the scan rate decreases.

The effect can be explained by the fact that the SDM housing as flown on FY3B was manufactured from aluminium whereas the rotor shaft was manufactured from steel. Therefore the gradient between rotor and stator leads to a decrease in diameter of the outer rings of the thin ring bearings, while the inner ring stays stable. In addition, the deflection of the mechanism housing due to the lateral gradient over the SDM mounting I/F, as shown by the finite element model, will influence the bearing configuration.

The above findings explain well the mechanism behavior during the first mission phase and the associated current increase. The fact that the current and scan performance went back to nominal values after some months of operation can be explained by a run-in effect observed in the new (deflected) bearing configuration which established due to the thermal gradient effects. After a run-in phase of the bearings in the new slightly different configuration, the bearing friction adjusted back to nominal values.

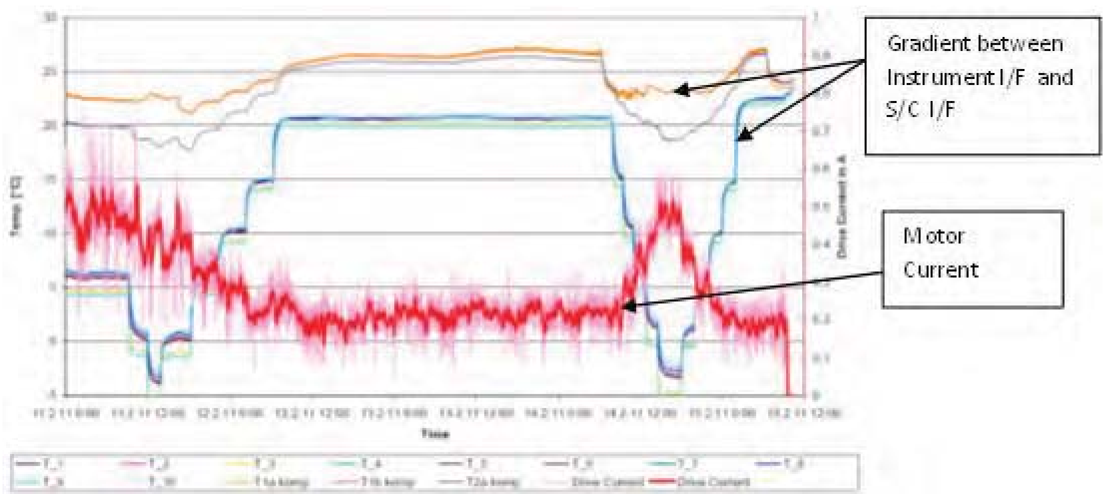

Figure 15. Influence of the Thermal Gradient to the motor current

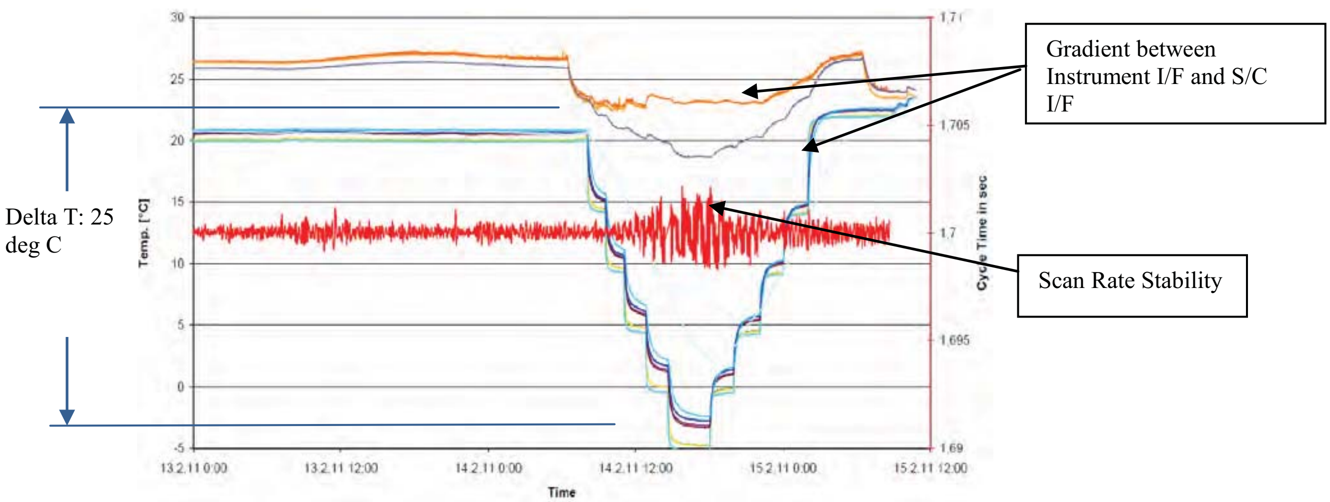

Figure 16. Influence of the Thermal Gradient to the scan rate stability

Optimized Design of FY3-C Equipment

As a consequence of the root cause investigation that confirmed and correlated well with the observed orbit behavior, the relevant findings were transferred into a design modification on the FY3C flight equipment in order to avoid issues as observed on FY3B in the future (see also Figure 17).

- Change the SDM housing material from aluminium to titanium and add additional stiffening ribs:
  - improves insensitivity towards external stresses
  - reduces thermal mismatch due to gradients
- Modify conical I/F of the launch offload device (LOD) to steeper angle (general risk mitigation and improvement of design robustness):
  - improves capability to handle potential instrument CoG shift
  - improves mechanism rotation axis accuracy
- Set bearing preload to 400 N
- Add isolating Ti washer in the I/F to the instrument
  - reduction of thermal gradients in the mechanism

- Add mechanism cover (general risk mitigation and design robustness improvement):
    - dust /contamination protection cover

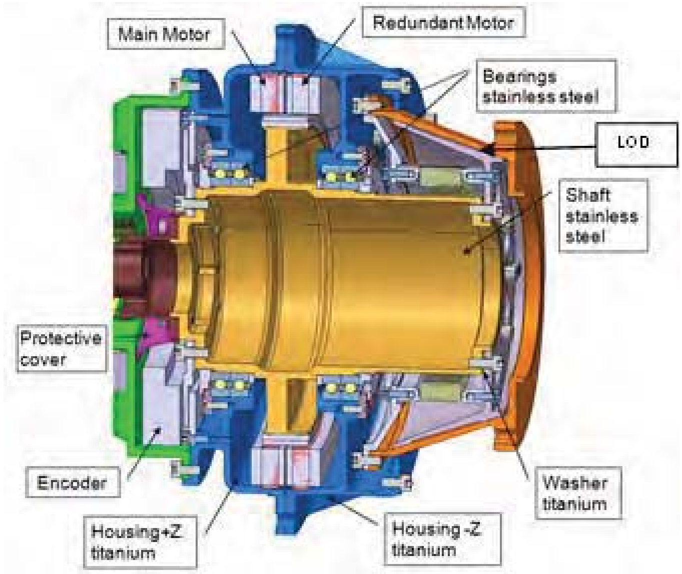

Figure 17. Optimized FY3-C Design

Ground Test Results with Optimized Design

A summary of the TV ground test results after FY3C flight mechanism modification is depicted in Figure 18. It can be seen that the insensitivity of the Scan Drive Mechanism against thermal gradients has significantly improved and that the current only increases only marginally with the temperature gradient. Also the cycle time deviation stays well within the requirement. Due to the fact that the tested flight mechanism is new and un-used, we can expect an additional run-in effect which will decrease the motor current again over time and further improve the scan rate stability.

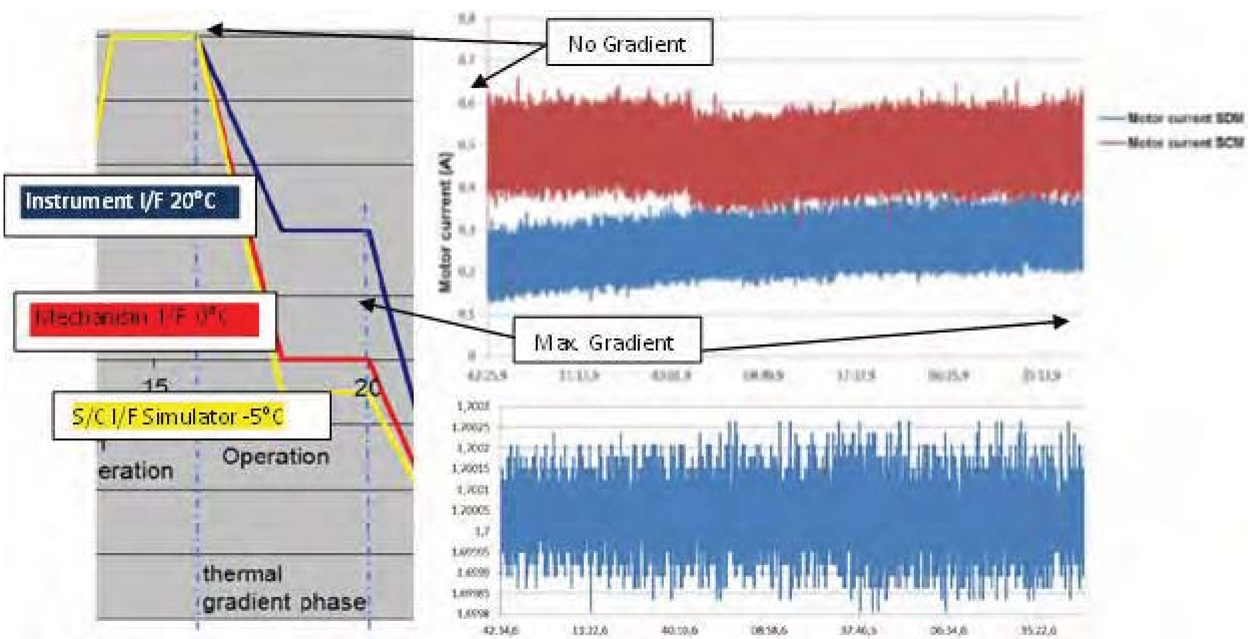

Figure 18. TV Gradient Test results

SDM Orbit Performance with Optimized Design

The FY3C S/C was successfully launched at the end of September 1013 and the MWRI instrument went operational some days later. The first telemetry current and performance data achieved over a time frame of one week fully confirm the validity and efficiency of the chosen design modifications (Figure 19 and Figure 20).

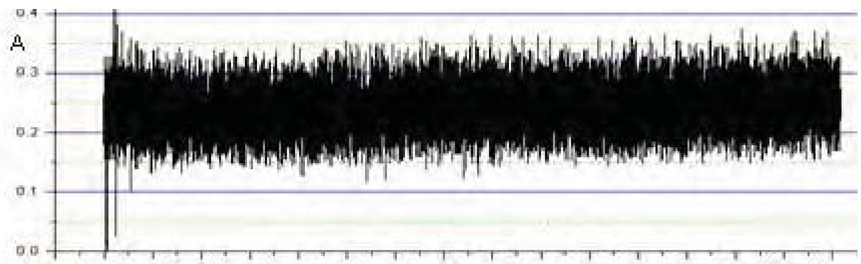

Figure 19. SDM current (A) of FY3-C over the first two Months of Mission Time

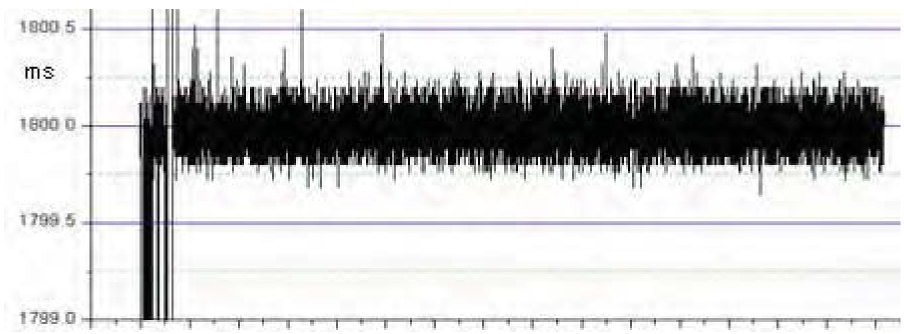

Figure 20. Scan Rate stability (s) of FY3-C over the first two Months of Mission Time

Conclusions and Lessons Learned

- Check for sensitivity of mechanisms with respect to thermal gradients, even if gradients are not specified.
- In mechanisms with limited torque budgets or highly sensitive control loops such gradients might be critical.
- Limit by design the potential influence of thermal gradients
- Design the I/F to the S/C to be as stiff as possible in order to avoid planarity changes in the S/C I/F due to temperature changes and consequent setting effects influence the performance.
- If slight misalignment effects occur due to (more or less constant) gradients, a "healing effect" of the bearings over time may be observed due to run-in effects on a new ball track.