Scanning Mechanism of the FY-3 Microwave Humidity Sounder

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Abstract

Astrium GmbH Germany, developed the scanning equipment for the instrument package of the Micro-Wave Humidity Sounder (MWHS) flying on the FY-3 meteorological satellite (FY means Feng Yun, Wind and Cloud) in a sun-synchronized orbit of 850-km altitude and at an inclination of 98.8°. The scanning mechanism rotates at variable velocity comprising several acceleration / deceleration phases during each revolution.

The Scanning Mechanism contains two output shafts, each rotating a parabolic offset Antenna Reflector. The mechanism is operated in closed loop by means of redundant control electronics.

Introduction

MWHS is a sounding radiometer for measurement of global atmospheric water vapour profiles. An Engineering Qualification Model was developed and qualified and a first Flight Model was launched early 2008. The system is now working for more than two years successful in orbit.

A second Flight Model of the Antenna Scanning Mechanism and of its associated control electronics was built and delivered to the customer for application on the follow-on spacecraft that will be launched by the end of 2010.

Instrument Description

The operating frequencies of MWHS include both the atmospheric transparent window at 150 GHz and the water vapor absorbing lines around 183.31 GHz. The 150-GHz radiometer has two polarizations (V and H) and the 183.31 radiometer has three channels (from ±1 to ±7 GHz around 183.31 GHz).

The instrument comprises four major functional units, namely the Antenna Scanning Mechanism (ASM) with Antenna Reflectors and Feed Horns, the Motor Control Drive Electronics (MCDE), the Front-end Receiver with Receiver Electronics and the Instrument Electronics Unit. An Instrument block diagram is shown in Figure 1.

The scanning equipment (shown in the center of Fig. 1) includes the Scanning Mechanism, the Antenna Reflectors and the Feed Horns, all mounted to a base-plate on top of the instrument.

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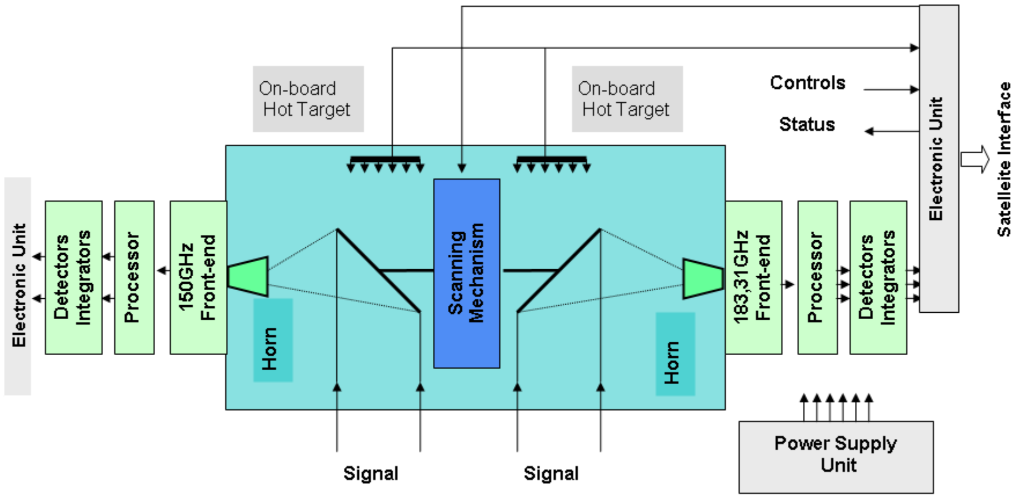

Figure 1. Instrument Block Diagram

The arrangement of the MWHS instrument on the spacecraft is shown in Figure 2. The Scanning Unit is mounted on top of the instrument electronics compartment (shown in Figure 2 on the right side). Figure 3 depicts a typical picture taken by MWHS, showing the global brightness temperature.

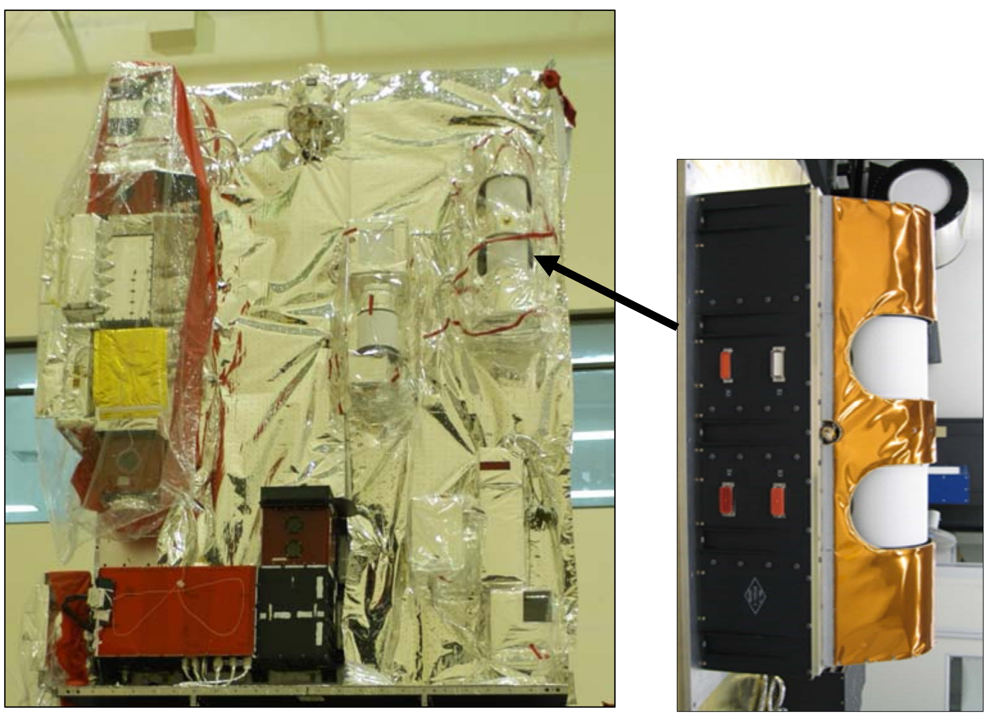

Figure 2. MWHS Instrument Configuration on FY-3 Spacecraft

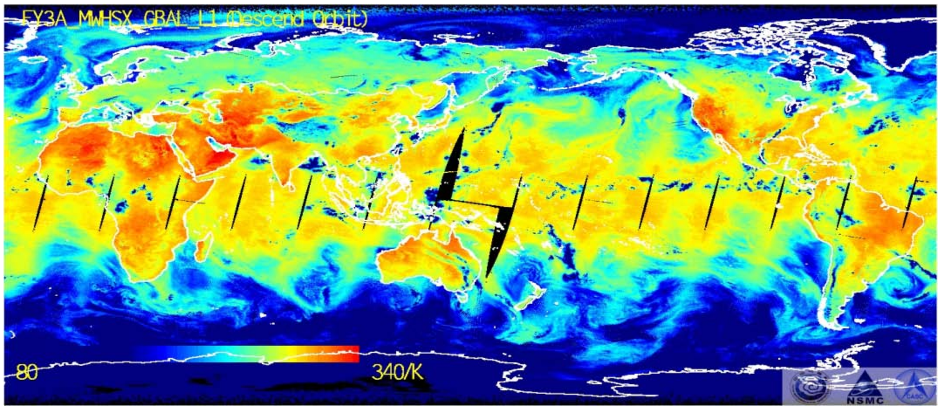

Figure 3. Global Brightness Temperature taken by MWHS

Key Requirements

Major mechanism functional performance characteristics are the scan velocity constancy, the scanning time accuracy, the pointing accuracy (calibration), and the capability to accelerate/decelerate the Antenna Reflectors within a minimum time in order to maximize the observation time during each scan period.

Switch-over capability between three different scanning modes is provided. There is the nominal scan mode with its variable speed, a constant velocity mode without hot/cold calibration, and the possibility to stop the scan at each arbitrary position. The equipment orbit life requirement of 3 years leads to about 36 million mechanism revolutions at nominal operation.

A summary of the key requirements is shown in Table 1.

Table 1. Key Requirements

Requirement	Value
Orbit Altitude	836 km
Swath Width	2700 km
Spatial resolution (Nadir)	15 km
Power consumption	< 18W
Power Supply	DC: 27V, ±12V, +5V
Mass	15 kg (overall, incl Base Plate and thermal H/W)
Environmental temperature	-30° ~ +55°C
Life	>Three Years
Viewing Angle (Earth Scan)	+/-53.35°
Scanning speed error (during earth scan)	1 %
Pointing Accuracy	<0.1 deg
Scanning Period	2.667 s ± 50 ms
Scan profile	Scheme 1: Nominal Scan profile Scheme 2: constant speed in 2.667 s period Scheme 3: stop at any position
Operation Frequency	150 and 183 GHz

The nominal operational instrument rotation speed is variable (hot calibration, cold calibration, earth scan and motion between these three angular ranges). The earth scan takes 1.71 s for 106.7 deg. of scan angle.

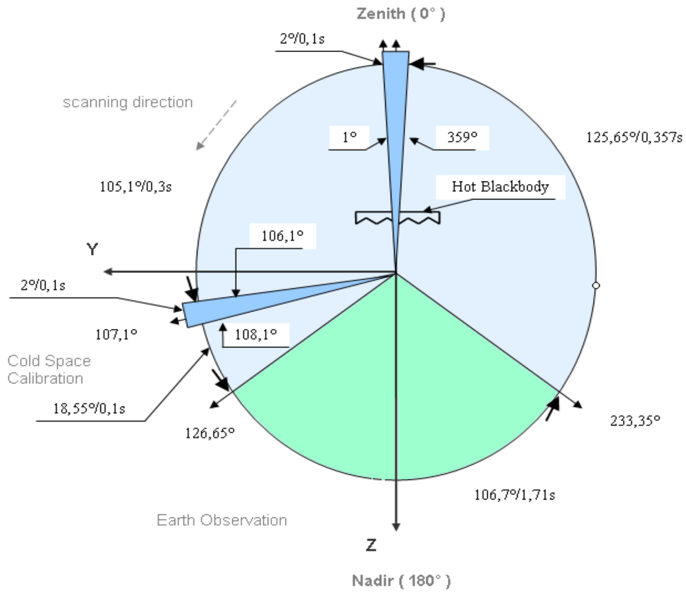

Figure 4. Scan Profile

Scan Mechanism Overview and Configuration

The Antenna Scan Mechanism uses a Base Plate on top of which the Scan Drive Unit is mounted. The Scan Drive Unit comprises a brushless DC Motor with redundant stators and a redundant 17-bit optical encoder for closed loop velocity, respectively position control. The controller is FPGA based and included into the Motor Control Drive Electronics (MCDE). The motor carries two output shafts. One Antenna Reflector is mounted to each of the output shafts in order to allow simultaneous and synchronous rotation of both reflectors. The incoming signal is focused via the two reflectors to the focal planes of the overall three Feed Horns mounted to support structures on either end of the Base Plate.

Some important design features are:

- The mechanism is equipped with two pairs of pre-loaded ball bearings in face to face arrangement. In combination with the direct drive, the output motion is free of backlash and hysteresis.
- A very good scan speed performance (low speed error) is achieved by the controller using sine commutation and by mechanical optimization of the motors for low detent torque.
- The mechanism is designed for high dynamic performance (high reflector acceleration) and energy efficiency. This implies minimization of the moment of inertia of the rotating masses.
- The flexible control electronics interface allows fine definition and rotational adjustment of the reflector mechanical zero position even on the spacecraft level.

The rotating mass' moment of inertia (<0.007 kg-m^2) was minimized, not only to avoid a momentum compensation drive in the mechanism which would have increased the mechanism complexity, but also to minimize for power consumption and to provide maximum reflector acceleration capability, leading to a maximum of useful earth observation time. This goal was achieved by designing light weight antenna reflectors from aluminium with an attached lightweight thermal shield ("barrel"), rotating together with the reflectors.

Since the Drive Unit carries the rotating Antenna Reflectors, it has to be aligned with high accuracy with respect to the Feed Horns (Front Ends) mounted to both sides of the Drive Unit. Due to the fact that the base plate thickness was limited to 20 mm maximum, special attention had to be paid to limit the mechanical and thermal deflection of the Base Plate especially in combination with the attachment interface on instrument side. After specifying the interface planarity on Instrument side, the Al base plate was designed as a milled structure with stiffening ribs, closed by a thin Al cover plate attached to its bottom by means of screws and dowel pins in order to achieve a box-type structure providing good bending but also adequate torsion stiffness at low sensitivity against thermal gradients.

Figure 5 shows the arrangement of the Scan Drive Unit and Antenna Reflectors on the Base Plate. The Front Ends with Antenna Horns are mounted to each end of the Base Plate.

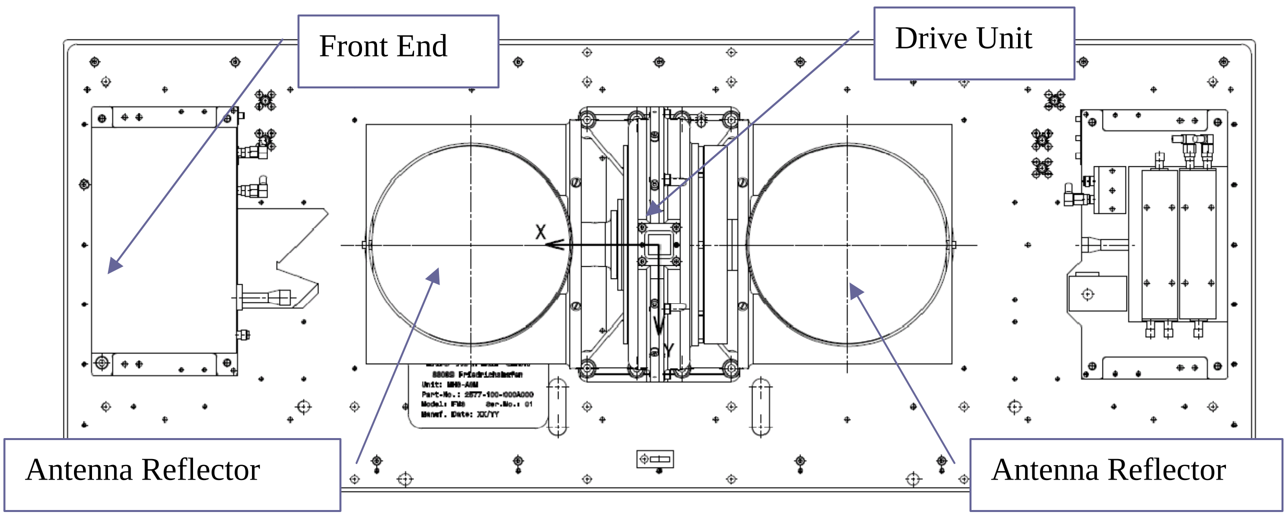

Figure 5. Top View of Antenna Scan Mechanism (ASM)

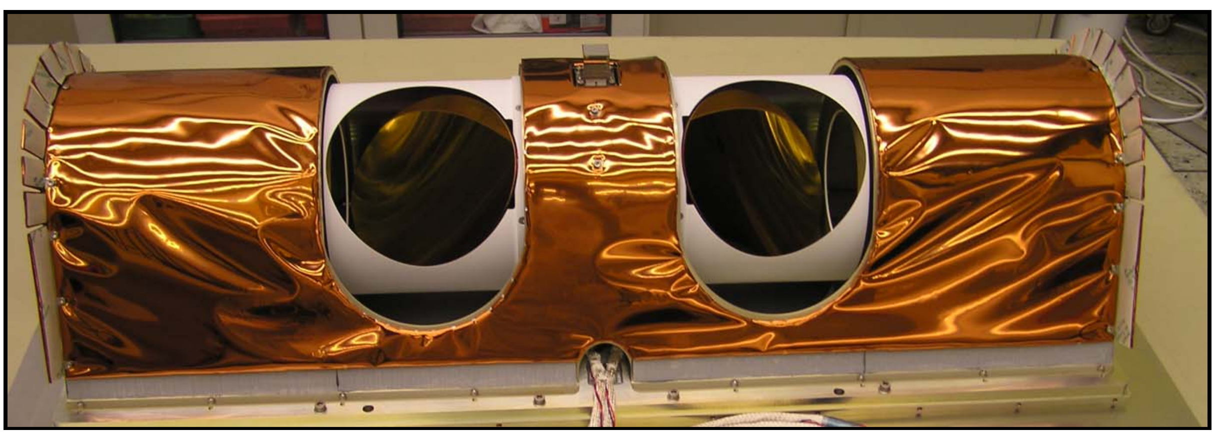

Figure 6. Scan Drive Mechanism Complete (ASM).

Drive Unit

The Drive Unit is built up with a titanium Housing and a steel Shaft interfacing the two Antenna Reflectors. The material combination was chosen to optimize for minimum mass and good thermal match at temperature extremes. The Optical Encoder for motor commutation and position feedback is mounted to one side of the Drive Unit Housing. The Drive Unit is mounted via its footprint to the structural Base Plate.

Two pairs of preloaded thin ring angular contact ball bearings with a contact angle of 20° in face to face arrangement are used in the ASM. The outer bearing diameter is about 50 mm. The number of balls is 24 per bearing and the ball diameter is 3.175 mm. Bearing material is stainless steel 440 C equipped with phenolic resin cages, lubricated with Fomblin Z 25. The bearing preload is 650 N.

The brushless DC motor is designed for a maximum output torque of 2.3 Nm at 27 V. The motor has independent stators so to provide redundancy and to allow adjustment of the two stators in rotational direction with respect to each other. This feature was included in order to further optimize the system in view of the high required velocity constancy. By rotational adjustment of the redundant stator with respect to the main stator, an additional minimization of the overall detent torque could be realized.

Motor commutation and position feedback to the controller is provided by an optical 17-bit encoder in redundant configuration.

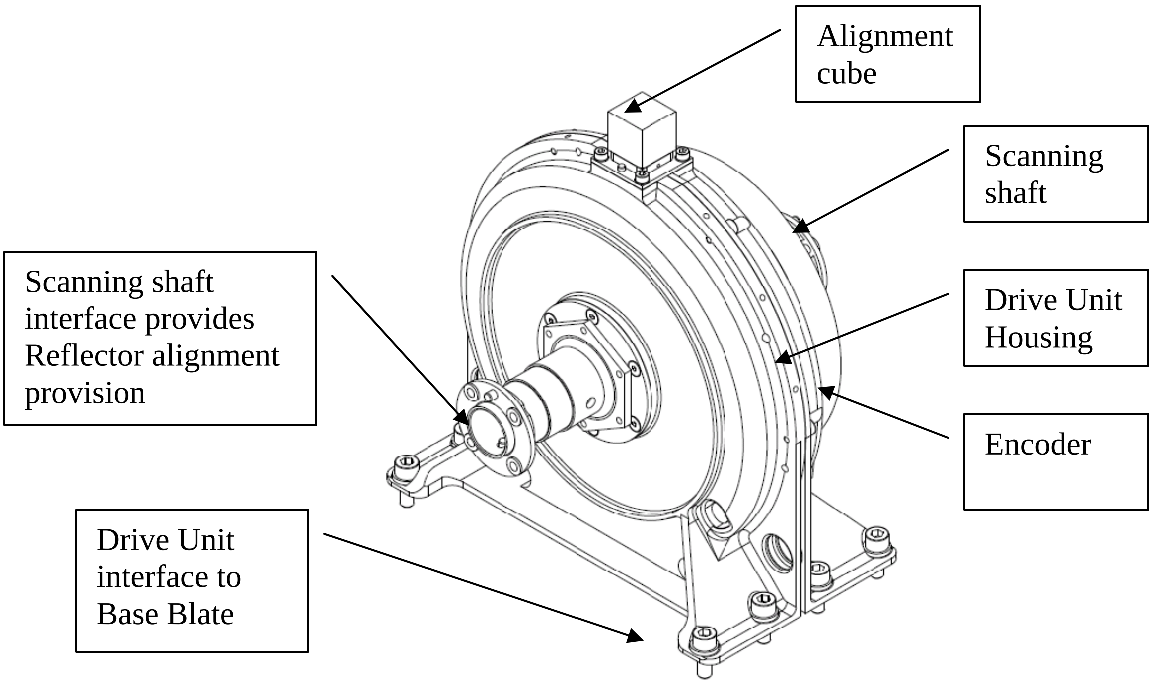

Figure 7. Drive Unit (Drive Module)

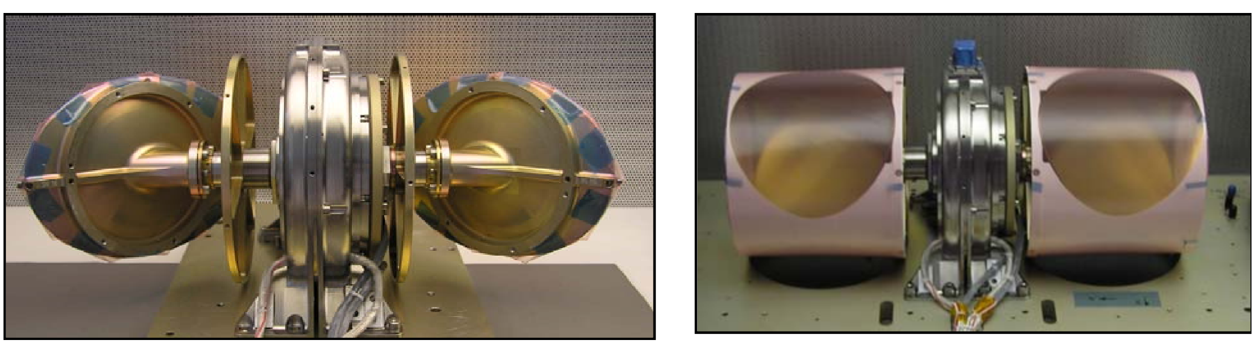

Figure 8. Drive Unit with Reflectors and Thermal Baffle (AIT protection mounted)

Antenna Reflectors

The two Antenna Reflectors are designed from aluminium. The required rms value is 5 µm minimum. This value was exceeded by splitting the manufacturing process into several individual sub tasks at different specialized suppliers. The coordination of the related tasks was followed and closely supported in order to minimize the technical and subsequent programmatic risks. The major working steps were:

- Coarse manufacturing of the Reflectors (at leaving additional material on the Reflector surface for later fine turning)
- Heat treatment of the pre-shaped Reflectors
- Intermediate fine surface manufacturing
- Inspection of Quality including surface accuracy measurement
- Cleaning process
- Final surface shaping with diamond tool
- Inspection of quality including surface accuracy measurement
- Cleaning process
- Pre- and post surface treatment by applying gold coating

Motor Control Electronics

The Motor Control Electronics (MCDE) is designed as a completely cold redundant unit, each part acting to the main respectively redundant motor stator and receiving feedback from the redundant high resolution encoders. The controller is implemented into the FPGA.

The MCDE is a two-channel, 3-phase, brushless DC motor controller, which has been especially adapted to MWHS. It has linear power stages for extremely accurate, wide-bandwidth and high precision tracking control. It incorporates redundancy both in the power stage and the encoder input. It employs extensive use of FPGA logic, which have been adapted to support serial interface protocols, sequencing, digital velocity and position control, profile generation, redundancy management etc.

The power stages are linear (non-switching) and are designed to operate at 27V and at a peak current of up to 2A. These power stages possess two current sensors in the output phases to support full sine-wave commutation, which ensures optimum torque and velocity control characteristics. The use of linear power control and precise control of the operational current guarantees an excellent performance at low drift, high bandwidth and high linearity.

Control of the MCDE is by means of a serial bus interface, which also feeds status information back to the host. In addition there are two enable and status signals for each of the redundant power stages and encoder feedback channels.

Specific Development and Test Issues

Mass and Inertia Minimization of Welded Baffle

In order to achieve the required scan performance (minimum time between the operational points which are earth scan, cold and hot calibration), the system had to be designed for maximum acceleration capability. Since the available torque is limited by the available motor power, the moment of inertia of the rotating part of the mechanism had to be minimized.

This was achieved firstly by designing light weight Reflectors. However, for thermal reasons a cylindrical thermal baffle ("barrel") surrounding the Reflectors was needed in order to keep the Reflector temperature as stable as possible. The thermal baffles (two of them) provide significant contribution to the overall moment of inertia and its mass and radius had therefore to be minimized. Consequently the baffle was designed as a very thin walled structural cylinder (1-mm wall thickness) manufactured out of a bent aluminium plate and stiffened up by means of a radial ring at its one end (close to the Front Ends). The cylinder and stiffening ring were manufactured and connected by electron beam welding in order to simplify the manufacturing process. The other end of the baffle was attached via screws to a circular plate attached between Drive Unit and Antenna Reflectors (see Figure 8).

During vibration testing, a failure of the electron weld seam was identified, so that a re-design of the thermal baffle was necessary. In order to solve the issue, it was decided to manufacture the Baffle structure in a sophisticated manufacturing process from one piece of aluminium so to avoid any welding seams and the critical welding process (Figure 9). The subsequently repeated vibration test was successfully passed without any problem.

Figure 9. Thermal Baffles Manufactured as Monolithic Structure (Originally Welded)

Minimization of Motor Detent Torque

According to the requirement, a maximum scan speed error of 1% shall realized. In order to achieve this value, the motor Control Electronic commands the Brushless DC motor in sine control. However, due to the fact that the motor detent torque plays also an important role in achieving good velocity stability, additional measures to reduce the detent torque were identified. The mechanism contains two independent motor stators for redundancy reasons. An overall detent torque of up to ±25 Nmm was expected on basis of analysis for the two stators. It was found that by rotation of one of the two stators by half a stator slot pitch (corresponding to 2.5 deg rotation), the detent torque could be significantly reduced to a maximum of ±15 Nmm. This design feature was consequently included into the design to further optimize for minimum velocity disturbances.

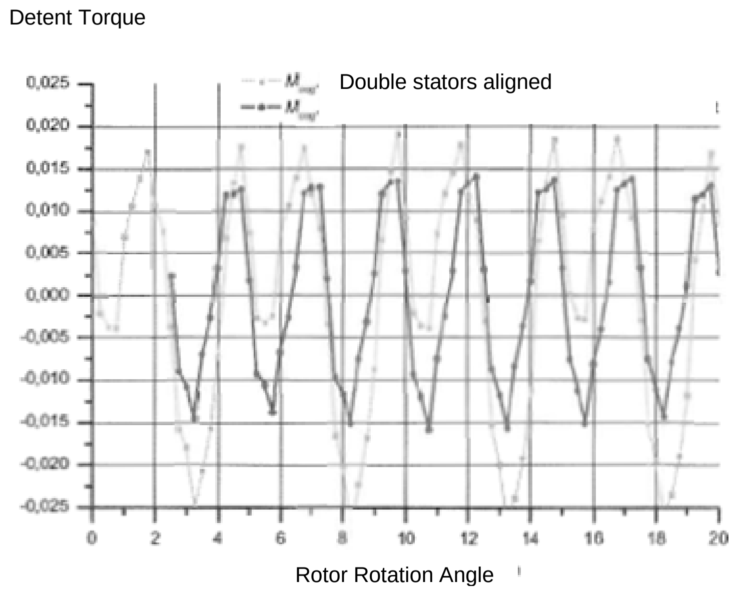

Figure 10. Minimization of Motor Detent Torque

Alignment Concept

Based on the existing tolerance chain between Drive Unit and Base Plate, Drive Shafts and Reflector and between Base Plate and Feed Horn (Mounting Brackets), the implementation of a suitable alignment concept was mandatory in order to fulfil the pointing and performance requirements.

In order to cope with the schedule constraints during the integration and test phase, it would have been favorable to avoid as far as possible a time intensive alignment concept. For example, concepts using in situ shimming and adjustment of the individual components during the integration and test process are time and effort intensive.

Therefore, two alignment alternatives were discussed in this context: one was to manufacture the relevant mating parts with sufficiently high accuracy in order to avoid shims wherever possible. This alternative was found not to be adequate, since the involved tolerance chains did not allow to manufacture the individual parts with sufficiently high precision without high additional effort.

The second alternative was to provide active adjustment and alignment provisions already by design, so to allow alignment by means of suitable adjustment screws after integration. This alternative was skipped due to the fact that it added high design complexity, imposed stiffness and load capability limitations and would have increased mass and moment of inertia. Therefore it was decided to go for a conventional shimming approach and to adjust first the Reflectors about two axis in the interface between Drive shaft and Reflector and then to shim the feed horn support structures with respect to the Reflectors.

The correct Reflector alignment with respect to the feed horn was supported by using Reflector best fit analysis data as an input for the 3D measuring machine during the reflector alignment process.

A zero referencing possibility in rotational direction was additionally implemented in the electronics command interface in order to allow for compensation of rotational misalignment of the Reflectors between the S/C mechanical and electrical zero.

Encoder Supply Voltage

During the last environmental test which was the common TV test of ASM (Mechanism) and MCDE (Electronics), an error was observed in the main path of the equipment. The observed phenomenon was a randomly occurring incorrect start command execution of the scanning function after switching from the redundant to the main path.

The error was observed at first during cold TV condition in the main equipment path however it could later be reproduced also on the redundant path and also after cross-strapping between main electronics and redundant mechanism. Therefore, it was concluded that a systematic random error had to be considered.

After detailed check of the electronics function and also of the mechanism integrity, the detailed root cause investigation led to the suspicion that the error must be produced by the power supply used during equipment test. It was proven by test, that the probability to reproduce the random error was depending on the actually used power supply unit.

Therefore the power supply characteristics were investigated in detail and it was found that the encoder supply voltage (5 V) provided to the encoder had a rise time of >20 ms. Detailed discussion with the encoder supplier led to the conclusion that this fact could cause a starting issue in the encoder ASIC. The RC part of the ASIC has time constant of <10 ms so that the encoder start-up could not always be executed in a reliable manner.

As a consequence a switch box was integrated into the output line of the power supply so to allow switching the encoder voltage by a separate command after switching on the power supply in order to guarantee a voltage rise time of < 5 ms. By including the additional switch box, the scanner start up issue was solved and the TV test was successfully repeated.

Scan Performance during Ground Test

The key functional performance requirements of the Antenna Scan Mechanism are its high velocity constancy during the earth scan period and the requested minimum time consumption for the motion time between two earth scans (hot/cold calibration and movement between these positions) in order to maximize the useful observation time. This was achieved by optimizing the motor dimension and its output torque and dynamics in combination with a minimized moment of inertia of the rotating masses.

The achieved measured velocity and acceleration profile of two subsequent scan periods is shown in Figure 11. The maximum angular velocity ω is about 9 rad/s, the maximum achieved acceleration is about 150 rad/s^2 while the maximum deceleration is up to 180 rad/s^2 (deceleration is supported by bearing friction torque).

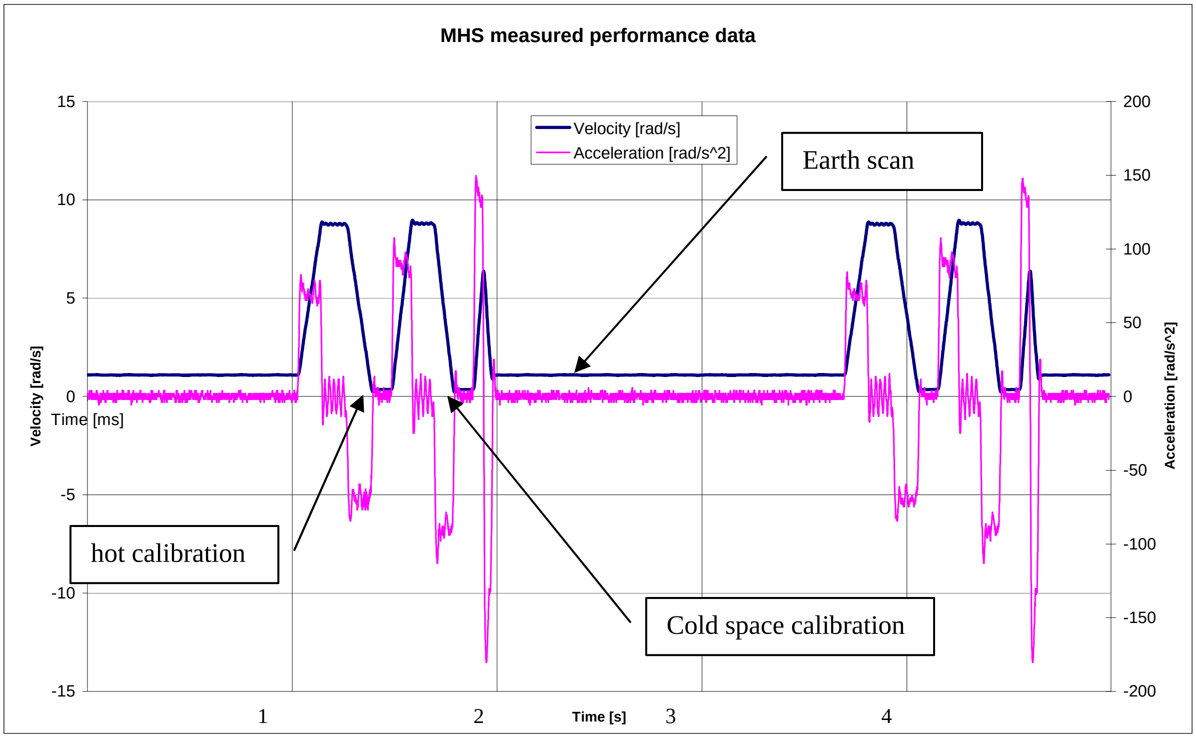

Figure 11. Measured Performance Data (Velocity and Acceleration)

Orbit Performance

The temperature variation of the mechanism over the orbit was analyzed during the development phase. The housekeeping data obtained during the mission show good correlation to the analysis. An active thermal heater concept for the instrument is not needed due to a trimming radiator. The available orbit data of the mechanism demonstrate that the 183 GHz Front-end remains at a very stable temperature of 12°C over one orbit while the 150 GHz Front-end temperature varies between 20 and 22°C.

In Figure 12, the average current needed to drive the scan mechanism is plotted over time. Since the current needed to drive the system is a good indicator of the mechanism health status and especially of its bearings, such data are extremely helpful to gain information for similar flight designs requesting non-uniform bearing rotation.

As can be seen, the current is at about 0.37 A during a first orbital run-in phase lasting for about 3 months. After this time, the current decreases to about 0.35 A and finally to an average value of about 0.34 A after a time of about 9 months. The overall number of scans performed within the time frame shown in Figure 12 amounts to about 16.5 million revs (almost half of the nominal operational life).

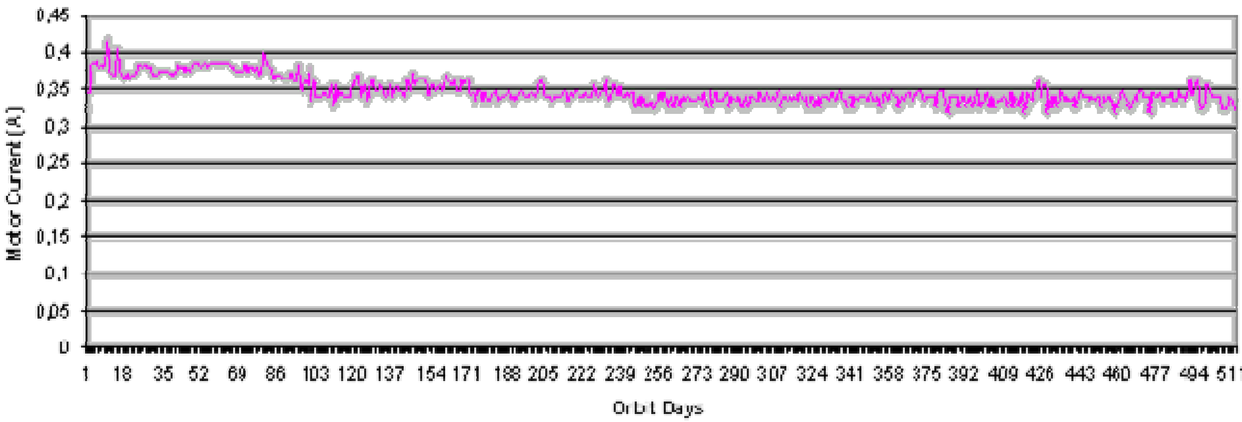

Figure 12. Motor Current Curve from June 2008 to Nov 2009.

Conclusions and Lessons Learned

Electron beam welded connections (electron beam) were found to be not adequate for the application and should be carefully investigated in view of their load capability and durability under the given vibration loads. If possible, alternative solutions should be considered.

Alignment concepts using accurately manufactured parts provide schedule advantage over alignment concepts using shimming methods, however depending on tolerance chains they are often hard to be realized. Actively adjustable shimming provisions, e.g., alignment screws, etc., suffer from mass and stiffness constraints and add design complexity. Therefore, the conventional in situ shimming method using shim washers during integration and test process was found to be the most effective one.

The detent torque of the motor using two independent motor stators could be reduced by turning one of the redundant motor stators by half a stator slot pitch with respect to the other in order to smoothen the overall detent torque amplitude.

The output characteristics (voltage rise time) of power supplies might be important for the correct operation of sensitive equipment (e.g., optical encoders). The voltage rise time of power supplies and potential requirements from equipment side should be carefully cross checked before using standard power supplies on sensitive equipment.

The drive concept using liquid lubrication and two pairs of thin ring ball bearings in face-to-face arrangement provides good life performance at continuous extreme acceleration / deceleration conditions as in the presented application. Based on the available current housekeeping data, the current is very stable over time and no bearing degradation which would result in a higher torque /current level is observed after 2 years of continuous scanning operation (24 million revs).