EXTREMELY COMPACT TWO-AXIS X-BAND ANTENNA ASSEMBLY

Manfred Schmid [1], Dr. Sang Soon Yong[2]; Sang Gyu Lee[2]

ABSTRACT

The X-Band Antenna Equipment is dedicated to data downlink on LEO Satellites and Astrium GmbH developed for application on the Kompsat3 program under the Contract with KARI. The equipment comprises an extremely compact two-Axis Antenna Pointing Mechanism (APM) with integrated Hold-down and Release Mechanism (HRM), a dual channel circular polarized corrugated Horn Antenna with Septum Polarizer and a fully cold redundant Antenna Pointing Driver (APD) control electronics.

In this paper, we present design and development approach of the extremely compact XAA as well as some lessons learnt during the development.

1. INTRODUCTION

The goal of XAA is to secure the earth exploration data downlink between KOMPSAT-3 satellite and ground station, by means of precisely positioning the X-band RF Antenna at minimum induced mechanical disturbance. In the KOMPSAT-3 application, as shown in Fig. 1, the mechanical parts of the XAA (APM, HRM and Antenna) are completely redundant i.e. the main electronics of APD controls one APM while the redundant electronics controls the other. In the contingency, simultaneous operation of both APM units are also possible to transmit orthogonally polarized two independent signals from each Antenna held by the APMs.

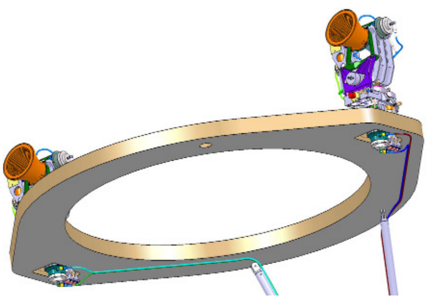

Fig. 1 Redundant APMs on S/C Platform

In this section, firstly, we briefly summarize the function of each unit comprising the XAA.

The XAA provides hemispheric antenna coverage and allows a two channel RF Power Transfer via Rotary Joints mounted into each of the rotation axes (azimuth and elevation).

A slipring unit is included in the azimuth axis in order to allow provision of electrical power and signals to the elevation stage. This concept allows continuous rotation of the azimuth axis without restrictions.

The elevation axis provides a working range of 130 deg and ranges from about 15 deg to about 145 deg. The elevation range is limited by hard end stops respectively by high precision end switches powering the motor off before reaching the mechanical stop.

The Antenna Pointing Driver Electronics (APD) controls the APM stepper motors in open loop and in micro-stepping mode for minimum induced jitter.

From now on, we discuss design and development philosophy of the XAA.

2. KEY DESIGN AND PERFORMANCE REQUIREMENTS

In LEO satellite systems, the task of the antenna is to maintain the communication coverage to the Ground Station independently from the ground track of the satellite in order to secure communication link between satellite and ground station. This is achieved by adopting an omni-directional antenna, gimballed pointing antenna or similar system.

In the case, where high speed downlink is required, gimballed antennas are used in general to secure the link performance. In earth exploration satellite systems, the mechanical interference of both, induced disturbance and jitter which are caused by gimballed antennas might significantly affect the satellite imagery. Therefore specific attention was paid during the development to achieve minimum Antenna Inertia at minimum induced Jitter in order not to affect the S/C operation by the operation of the XAA.

A short overview on the XAA APM requirements is listed below:

Astrium GmbH [1], KARI[2]

Proc. '13th European Space Mechanisms and Tribology Symposium – ESMATS 2009', Vienna, Austria 23–25 September 2009 (ESA SP-670, July 2009)

Requirement	Value	Comment
Envelope	Diameter 290 mm	Cylindrical rotational envelope
Rotation velocity nominal	<10 deg /s	max
Temperature range	-50 to 80 deg C	
Vibration levels	20 g sine 20.2 grms random	
Mass	7.0 kg achieved	per APM
Life	4 year	
No. of nominal operation cycles	20,000	Full range
RF Frequency Range	8.05 to 8.4 GHz	
Antenna gain	13 dB	at beam edge of +/- 15 deg
RF power max	15 W	
Insertion Loss	1.5 dB	overall
VSWR	2.5:1	

Tab. 1 Requirements Overview

Design driving Requirements are:

- Dynamic envelope
- Motion range
- Mass
- RF requirements
- Induced Jitter
- Need for a HRM device

3. EARLY SPECIFIC DESIGN ISSUES

The XAA design has been optimised on basis of an extremely stringent envelope requirement with an allowable Antenna rotation radius of only 145 mm, while achieving all functional and performance requirements.

By principle, the performance of individual sub-units is also influenced by their dimensions. Typical examples are the Rotary Joint (RF Characteristics), the hollow shaft Slipring (defined by the number of tracks and the inner bore needed for RJ feed-through), the bearing units (load carrying capability), the Antenna (RF Performance) and the Stepper Actuators (torque, power consumption and rotation velocity).

Since these components provide specific characteristics only at a certain dimension, they have strong influence on the overall unit envelope, which can only be further minimised by varying the arrangement of the components within the unit.

The Mechanical Unit comprises the following main subassemblies:

APM Azimuth Stage

- Azimuth Bearing Unit
- Azimuth Actuator (Stepper Motor, Harmonic Drive, Spur Gear)
- Slipring Unit
- Dual Channel RF Rotary Joint
- HRM Unit

APM Elevation Stage

- Yoke Structure
- Elevation Bearing Unit
- Elevation Actuator (Stepper Motor, Harmonic Drive, Bevel Gear)
- Dual Channel RF Rotary Joint
- Antenna Horn with Septum Polarizer

After clarification of the achievable component performance characteristics in close cooperation with the suppliers and harmonisation of the procurement specifications, the system could be detailed and optimised before design freeze. In the following, the design evolution and optimisation is explained.

Since the XAA specification requires an azimuth rotation angle of 540 deg, a first design approach was established using an electrical power/signal Cable Wrap instead of a slipring unit on the azimuth axis.

In this first approach the use of only one Rotary Joint in the azimuth axis was considered while for the elevation axis a coilable harness concept formed the baseline.

During the preliminary design phase it turned out that the Cable Wrap became quite heavy and bulky if realised for the requested rotation angle and that the required end-stop configuration overriding the full revolution by +/- 90 deg would have been indeed feasible, however with significant concessions w.r.t. geometry, mass, complexity and development effort. In addition, a full rotation capability of the Azimuth Axis was preferable since it increases significantly the system versatility.

Based on the outcome of this analysis it was decided to go for a slipring unit and to avoid the Cable Wrap in the Azimuth Atage.

A specific issue came up during the early life test of the elevation coaxial harness at low temperatures. The test showed that the torque needed to bend the RF harness in the foreseen configuration (two coaxial cables arranged in parallel in a 180 deg loop) at low temperature was quite high and not reproducible over the number of cycles.

In addition it turned out that the RF harness was also not compatible to the life requirement. The harness failed well within the nominal number of expected orbit cycles of about 20,000.

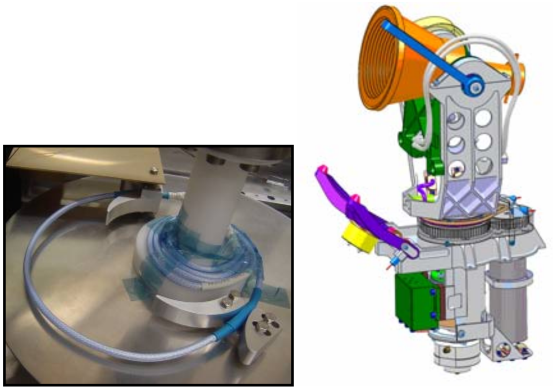

Fig. 2 Co-axial RF Harness Life Test Configuration 180 deg Loop

As a consequence the elevation harness routing was changed in the design and an additional loop was added to relieve stress peaks by using a 540 deg loop (1.5 harness turns). In this configuration the harness survived the low temperature life tests but the geometry and design of the necessary RF harness guidance structure became bulky and a well defined configuration was hard to achieve over all environmental test and operational conditions.

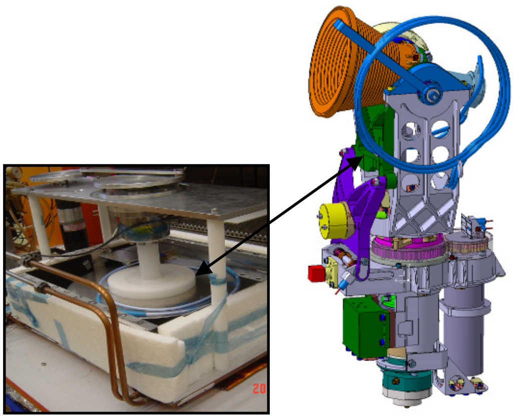

Fig. 3 Co-axial RF Harness, 540 deg Loop Life Test Configuration

Due to the cumulated overall length of the RF harness in this configuration, the RF losses were out of spec, so that a decision was made to go for an additional Rotary Joint also on the XAA elevation axis. This led to a simple and clean final design approach and to the XAA configuration as built.

An additional observation made, was that the co-axial harness torque was not reproducible over temperature and was strongly depending on number of cycles performed. Therefore a reliable torque budget calculation for the actuator was not possible.

4. APM DESIGN OVERVIEW

The final XAA design of the mechanical unit is shown hereunder. Azimuth and elevation actuators are both arranged in parallel and in off-axis configuration. While in the Azimuth Axis a spur gear is accommodated, the elevation axis makes use of a bevel gear for torque transfer. This off axis drive concept allows the arrangement of the two-axis Azimuth RJ inside the slipring rotor.

While the Azimuth Stage is contained inside the thermally controlled part of the S/C structure, the Elevation Stage is directly exposed to space thermal environment. Therefore a thermally insulating Ti I/F between azimuth and elevation stage is included so to avoid heat flux from the warmer S/C compartment to the Elevation Stage. The Base Bracket forms the central load carrying part of the APM Unit and provides the attachment I/F to the S/C. The base bracket contains the Azimuth Bearing and supports the Actuator, the Slipring and the Rotary Joint as well as the Spur Gear acting to the Azimuth Axis.

The Azimuth Axis interfaces the Yoke which forms the load carrying structure of the Elevation Axis. Azimuth and Elevation Axes are thermally de-coupled from each other via the a.m. Titanium I/F.
The Yoke accommodates the elevation motor, the bevel gear, the elevation bearings, the elevation Rotary Joint and finally the Antenna.

The HRM unit is attached to the azimuth stage via journal bearings and if closed, the HRM prevents the azimuth and elevation axis from rotation and supports lateral loads.

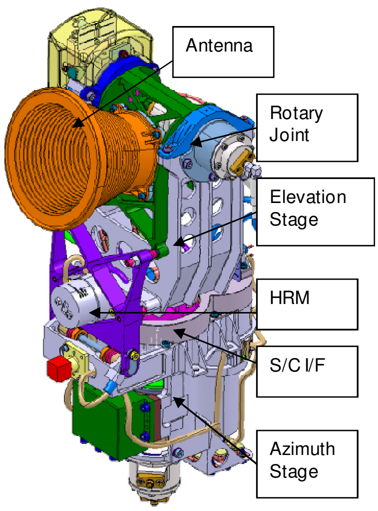

Fig. 4 Final XAA Configuration

Fig. 5 XAA Unit,Elevation Stage

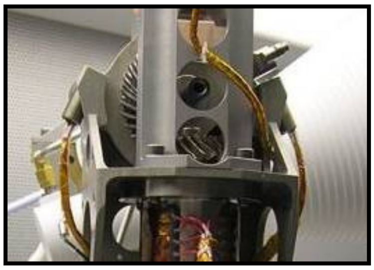

Fig. 8 Elevation Gear Stage

4.1. Actuator

Each of the two identical actuators consists of a stepper motor, connected to a harmonic drive unit size 11. The output of the Harmonic Drive acts to a precision spur gear on the azimuth and to a bevel gear on the elevation axis. The overall ratio on both axes is 1:80. Depending on the step frequency the motor provides a running torque of about 140 Nmm. The harmonic drive is wet lubricated with Maplub PF 101-a. The housing of motor and gear is manufactured from Titanium for mass saving.

A life test was performed on actuator level and in thermal vacuum conditions in order to prove early the compatibility of the motor and Harmonic Drive to the XAA life requirements.

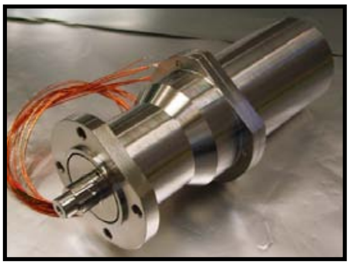

Fig. 6 Actuator

4.2. Spur Gears/ Bevel Gears

The gears are lubricated with Map-lube, the spur gear is split and spring-loaded for 0 backlash, the elevation bevel bear is adjusted for minimum backlash by shimming the elevation actuator axially.

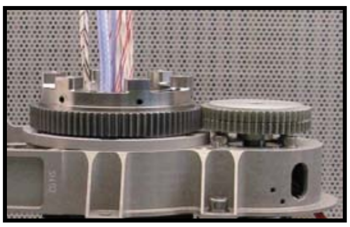

Fig. 7 Azimuth Gear Stage

4.3. Azimuth Bearings

The Azimuth Bearing comprises a pair of pre-loaded inclined ball bearings in back to back arrangement manufactured out of X 30 steel and equipped with ceramic balls.

4.4. Rotary Joints

The two axis Rotary Joints are electrically identical, the outer I/F to the XAA is however different for design reasons. The RJs were electrically optimised to the performance needed and optimisation was performed to achieve similar electrical performance data for both channels. The RJs do not contain own internal bearings to avoid alignment- and thermal issues. The RJs are supported by the XAA azimuth respectively elevation bearings.

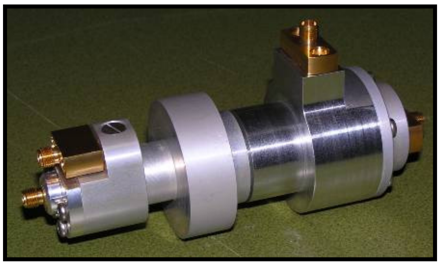

Fig. 9 Bearing-less Two Channel Rotary Joint

The performance of the Rotary Joints was measured over the temperature (dotted lines +55 deg C, bold line 20 deg C, interrupted line -50 deg C). The results are well in spec for all temperature conditions.

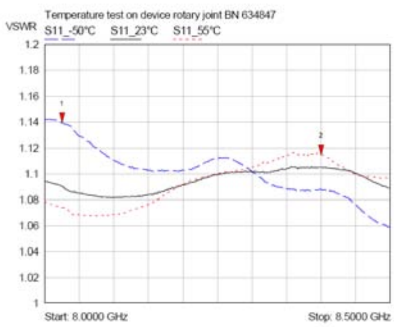

Fig. 10 RJ VSWR over Frequency

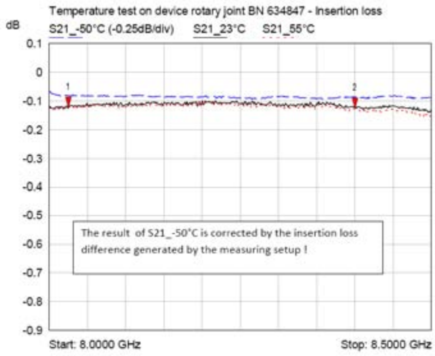

Fig. 11 Insertion Loss over Frequency

4.5. Slipring

The Slipring Unit in the Azimuth Stage is equipped with a hollow shaft in order to allow accommodation of the Rotary Joint inside the slipring rotor. The slipring is equipped with 15 power and signal tracks and provides a bore in the rotor of 40 mm inner diameter, in order to allow accommodation of the Azimuth RJ.

4.6. Precision Reference Switches

Mechanic Precision switches (normally closed) are used to reference the Azimuth and Elevation axis. The switching accuracy of the switches is in the µm range. The switches were specifically modified for space application and were flown in different applications. Extensive qualification tests and life tests were performed on switch level prior to including it into the XAA. Since the switches in their basic configuration are only compatible to axial contact forces, a special spring blade was designed, allowing transfer of the lateral motion of the switch contact interface into an axial motion on the switch pin. For this purpose a copper beryllium blade of 0.2 mm thickness providing a chamfer in its centre is used. The chamfer is laterally contacted by a miniature ball bearing on the moveable side so that the switch is activated in axial direction if the roller runs over the chamfer.

Fig. 12 High Precision Micro- Switch

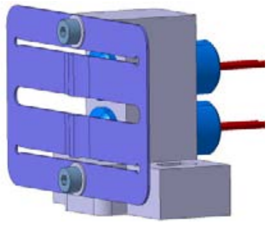

Fig. 13 Switch Mechanism

4.7. Antenna

The Antenna comprises a corrugated Antenna Horn and a Septum Polarizer. This design was chosen since it provides the required antenna performance at minimum dimension and mass.
The Antenna is dual circular polarized and is specifically designed for the application. The I/F to the RF harness (co-axial harness) is of the SMA type.

Fig. 14 Antenna (Corrugated Horn with Septum Polarizer)

The antenna directivity requirement is 13 db at the +/- 15 deg beam edge. The requirements were verified by test. The test result is shown in the next figure. The measured insertion loss of the antenna is 0.18 dB.

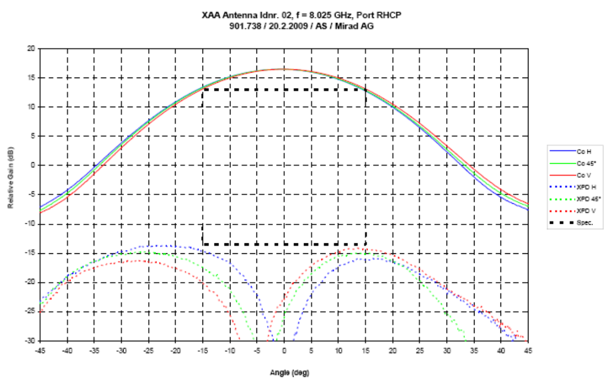

Fig. 15 Antenna Directivity Pattern 8.025 GHz

The overall insertion loss of antenna including Rotary Joints and Co-axial harness is about 1 dB, the overall VSWR is in the range of 1.7:1

4.8. Co-axial Harness

For RF signal transfer from the antenna to the elevation Rotary Joint, semi-rigid RF connections are used. From there to the Azimuth Rotary Joint, flexible co-axial cables are mounted in order to allow easy accommodation inside the Azimuth stage.

4.9. HRM

A specific design issue was defined by the need for a HRM to be included in the XAA APM within the requested launch and operation envelope. An integrated HRM unit was developed fixing both, the Azimuth and Elevation Axis at the same time with one single release device.

The HRM is composed of a stiff HRM Bracket which is movable about a rotation axis attached to the base bracket. After HRM release, the HRM bracket is tilted to its released position via a pair of redundant leg springs.

In the latched configuration, the loads induced into the base bracket are supported by two journal bearings. The journal bearings are preloaded in this configuration by the release bolt fixed between the Release Nut and the Yoke structure. The release nut itself is mounted into the HRM bracket.

In locked configuration the upper part of the HRM bracket is engaged to the Yoke Structure by means of two adjustable cup/ cone interfaces, preloaded by the NEA non-explosive release device, so to prevent rotational and lateral motion of the Yoke. The elevation degree of freedom of the antenna is constrained by another set of two adjustable interface pads preloading the antenna elevation bracket at a defined, adjustable pre-load. In the elevation I/F area cup cones are only used between HRM Bracket and Antenna Bracket, but not between Antenna Bracket and Yoke. In the next figure the load path and load distribution is explained.

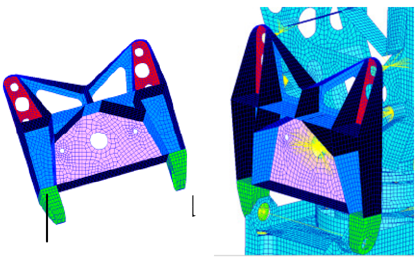

Fig. 16 FE Model of HRM

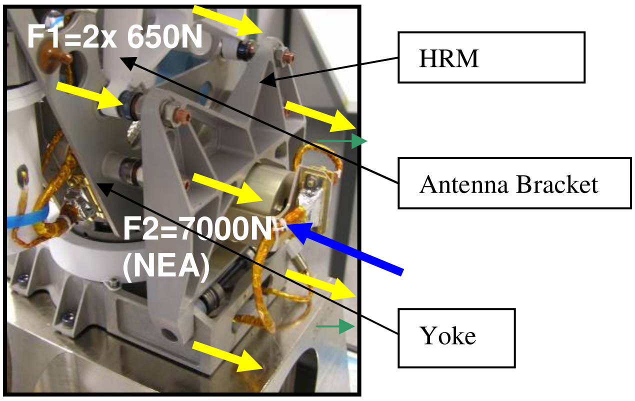

Fig. 17 Force Distribution on HRM H/W

The nominally adjusted preload on the NEA Release nut is 7,000 N. This leads to a force distribution of about 1,500 N per I/F point on the lower cup/cone I/Fes and of about 15,00 N at each of the journal bearings of the HRM bracket rotation axis. The upper cup cone I/F respectively the plan I/F pad between Antenna Bracket and Yoke structure are loaded with 650 N each.

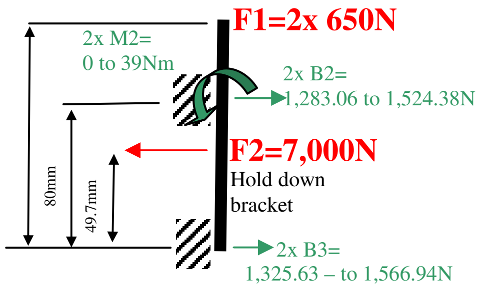

Fig. 18 Force Distribution on HRM

The next figure shows the HRM in released condition after vibration test. The release bolt is retracted by means of a spring loaded bolt catcher implemented in the Yoke structure and the HRM bracket is tilted out of the mechanism working area by means of the leg springs mounted into the axis of the journal bearings.

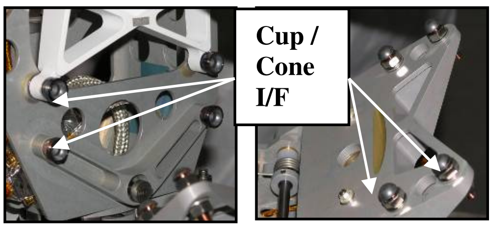

Fig. 19 HRM Released

A detailed FE model of the HRM bracket and Yoke was established and included into the overall XAA model.

The calculated first eigenfrequency of the XAA in locked condition is at 102.5 Hz. This value was confirmed by the vibration test.

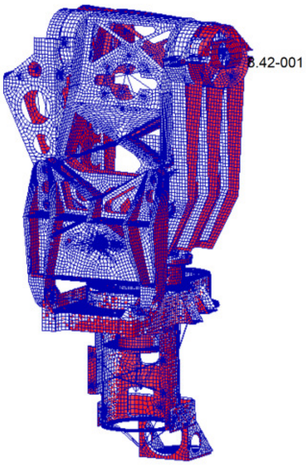

Fig. 20 FE Model of XAA

5. CONTROL ELECTRONICS

The XAA APM is driven by open loop stepper motor control electronics in micro-stepping mode at a maximum designed velocity of 10 deg/s. For minimization of disturbance torque and torque jitter influences to the satellite, the APD software is adjustable to limit both, operational velocities and acceleration to the actually needed operational value, which is lower than the maximum as designed velocity.

In the case the commanded Antenna speed should exceed the internally fixed velocity limit for a certain time the APD will eliminate the accumulation of the resulting pointing error by catching up the position as soon as the velocity falls below the internal speed limit.

The electronics act the motors in a current controlled mode using micro-stepping technology and thus provides constant torque level at minimum induced jitter independent from mechanism temperature. The signals of precision switches mounted on the Azimuth and Elevation Axes are used together with a dedicated hysteresis elimination procedure to reference the 0 position of the APM with maximum accuracy (reproducibility in the mdeg range).

The APD is a µ-Controller based system providing a MIL-Bus interface for command/telemetry and providing the capability to precisely follow a tracking-profile for Azimuth- and Elevation.

The tracking profiles are uploaded to the APD for each orbit and contain the tracking information in polynomial form. An exemplary tracking profile is shown in the following chart with Azimuth- and Elevation angular pointing over time.

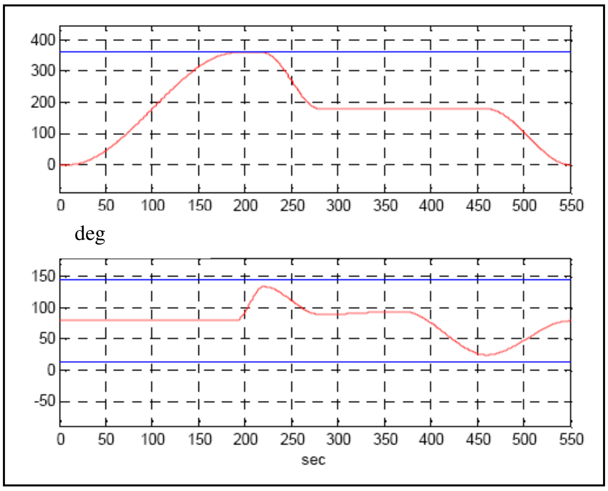

Fig. 21 Typical 2 Axes Tracking Profile

6. JITTER PERFORMANCE

The torques and forced induced into the S/C by residual disturbances produced by the XAA stepper motor and by the actuation chain as such, were minimised during the design phase. A Harmonic Drive was included into the design instead of a planetary gear which showed higher noise level during an early confidence test. In addition focus was laid on the surface quality and precision of the spur gears respectively bevel gears. On the motor side micro-stepping was used to keep the induced disturbances low and in addition the motor control current shape was optimised to reduce residual disturbances.

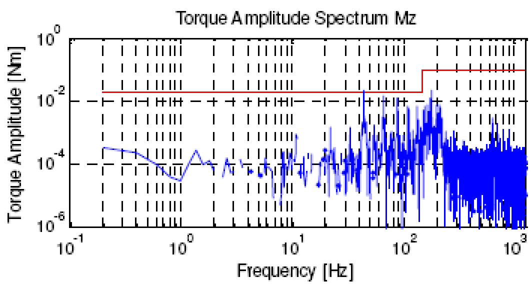

Fig. 22 Induced Torque Spectrum about Motor Rotation Axis

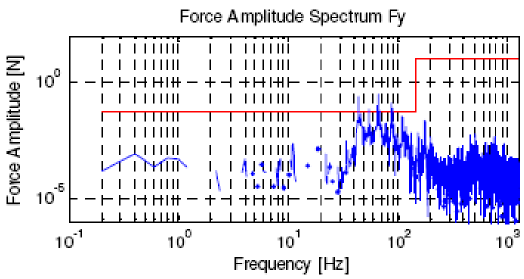

Fig. 23 Induced Lateral Force Spectrum

The Jitter data were collected by using a Kistler micro-vibration table allowing measurement of all six Degrees of Freedom of induced disturbances in stiff I/F condition. From the time domain the data were transferred to the frequency domain by performing fast Fourier Transformation.

7. QUALIFICATION SUMMARY

The test program performed on the XAA equipment consisted of component level tests for Rotary Joint, Co-axial Harness and Antenna and of equipment level Qualification Tests.

These were Functional Performance Tests, Micro Jitter and Vibration Test followed by a TV test with HRM release under TV conditions and by an end to end RF Test.

8. LESSONS LEARNT

The harness wrap had no significant advantage over the Slipring concept. Especially in combination with a necessary override of the end stop (>540 deg rotation requirement) the system would have been very complex compared to a slipring concept providing the advantage of unlimited rotation range.

The use of flexible co-axial cables is in-adequate to cover the required elevation range and lifetime requirements. This was confirmed by test. Either the test was survived by using long, weak harness loops, then the RF performance was found to be limited, or alternatively a short harness was selected, what led to good RF performance but to in-adequate life performance. Furthermore the stiffness of the Co-axial harness under cold conditions was very high and not really predictable. This caused also an issue for the calculation of motor torque margins.

If no specifically critical requirements are identified for the application and in order to fit to a short development schedule, the use of industrially available high precision bearings lubricated and equipped with a suitable cage material is preferable in view of cost and schedule constraints, compared to specifically designed space bearings which are normally identified as long lead items.

In order to gain design and procurement synergy within the schedule constraints, building blocks modified for space application and adapted to the specific space requirements were successfully and extensively used (Motors, Gears, Bearings, Slipring Unit, Rotary Joints, Co-axial Harness Micro-switches).