Qualification of a High Accuracy Dual-Axis Antenna Deployment and Trimming Mechanism

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Abstract

The Antenna Deployment and Trimming Mechanism Mark 2 (ADTM Mk2) has been developed to answer today's need for a generic antenna deployment and high accuracy pointing mechanism, allowing RF sensing applications and easier dual deployments configurations.

This paper presents the design and evolution from its predecessor, the experience of the design team from kick off to qualification and batch manufacture, as well as some lessons learned from ramping up "mass-production" capabilities while implementing customer driven changes.

Introduction

Astrium has manufactured and flown ADTM units for the past 20 years, from an initial deployment-only mechanism developed for the Orion program to today's Eurostar E3000 ADTM family. The Antenna ADTM Mk2 is an evolution of the original ADTM Mk1. Although it uses Mk1 building blocks to minimize risks associated with the development of a new product, it incorporates major evolutions and is the new baseline for Astrium latest generation of Eurostar E3000 telecom satellites.

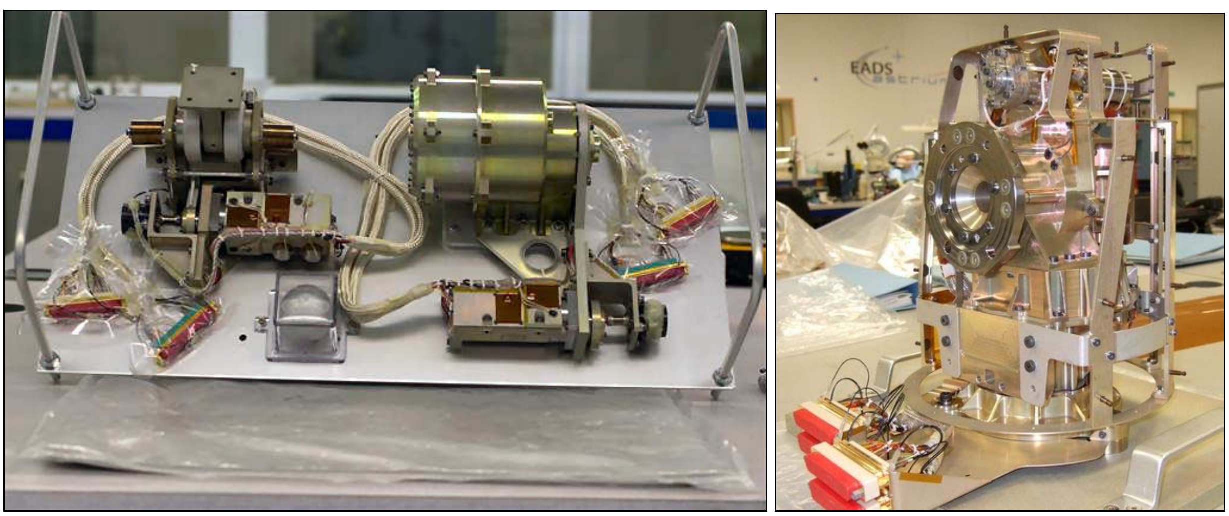

Figure 1: Left = ADTM Mk1 (one-axis), Right = ADTM Mk2 (two-axes) (without MLI fitted)

The ADTM Mk1 is used to deploy large antenna reflectors that are stowed on the spacecraft walls during launch. It is composed of an active trunnion (motive source for pitch deployment and trimming) and a passive trunnion (passive pitch deployment follower and motive source for roll trimming). Deployment is ensured by a passive spring-loaded motor, while each trimming axis is powered by a stepper motor gearbox (SMG).

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The new ADTM Mk2 is made of two identical one-axis Rotary Actuators (RAs) mounted together (each powered by a CDA Intercorp stepper motor gearbox), with added antenna and spacecraft interfaces as well as MLI enclosure. It has been developed to fulfil the following requirements difficult to achieve with the previous Mk1 version:

- ✓ Compatible with large 2.6+ m diameter antenna reflectors;
- ✓ Compatible with sequenced deployments (complete control of both deployment axes movements), allowing dual antenna deployments. The Mk1 version was single-axis using a passive spring motor for deployment, only capable of a one-off deployment to a mechanical stop;
- ✓ High resolution of 0.0025 °/step over the full range of motion, continuous trimming / re-pointing over the lifetime of the spacecraft, thus compatible with RF sensing applications and/or mission reconfiguration, allowing steering the antenna beam on different Earth locations as requested by the mission management (related to the operators needs);
- ✓ Manufacturing process and number of parts are minimized.

At the time of writing this paper, the ADTM Mk2 Qualification Model has been manufactured and has completed a significant portion of its planned qualification testing.

Table 1: ADTM Mk2 Main Characteristics

Weight:	7.7 kg (includes 2 RAs, spacecraft interface, antenna interface, harness + connectors, MLI)
Size:	240 x 240 x 290 mm (without connectors)
Axes:	* 2 perpendicular RAs, used for deployment and trimming / pointing functions * 120° movement range on each RA * 0.0025 °/step on the whole angular range
Operating temperatures:	* Bulk temperatures: Operational: -25°C to +105°C, Survival: -55°C to +125°C * Antenna interface thermally decoupled from antenna due to a custom thermal washer. Eurostar E3000 typical operational temperature ranges are -95°C to +115°C for antenna side and -10°C to +70°C for spacecraft side.
Power consumption:	<15 W including thermal control (one axis command)
Available Output Torque:	At least 20 N-m (including 200% margin, or 60 N-m without margin) across the whole operating temperature range.
Backlash:	None up to a minimum of 7 N-m
Load Capacity (Min):	see below
Stiffness:	>10,000 Nm/rad around deployment X and Y axes, >40,000 Nm/rad around remaining Z axis

Load Capacity (Min):

	Axial	Torque	Shear	Bending
Structure Interface	1600 N	100 Nm	1800 N	240 Nm
Reflector Interface	1600 N	100 Nm	1800 N	120 Nm

Design

General Description

The Roll RA controls the deployment and trimming functions of the ADTM Mk2 in the spacecraft antenna roll direction; the rotation axis is perpendicular to the spacecraft wall.

The Pitch RA controls the deployment and trimming functions of the ADTM Mk2 in the spacecraft antenna pitch direction; the rotation axis is parallel to the spacecraft wall and adjusting the antenna pitch. This axis is not fixed with regards to the spacecraft coordinate system but rotates during roll motion.

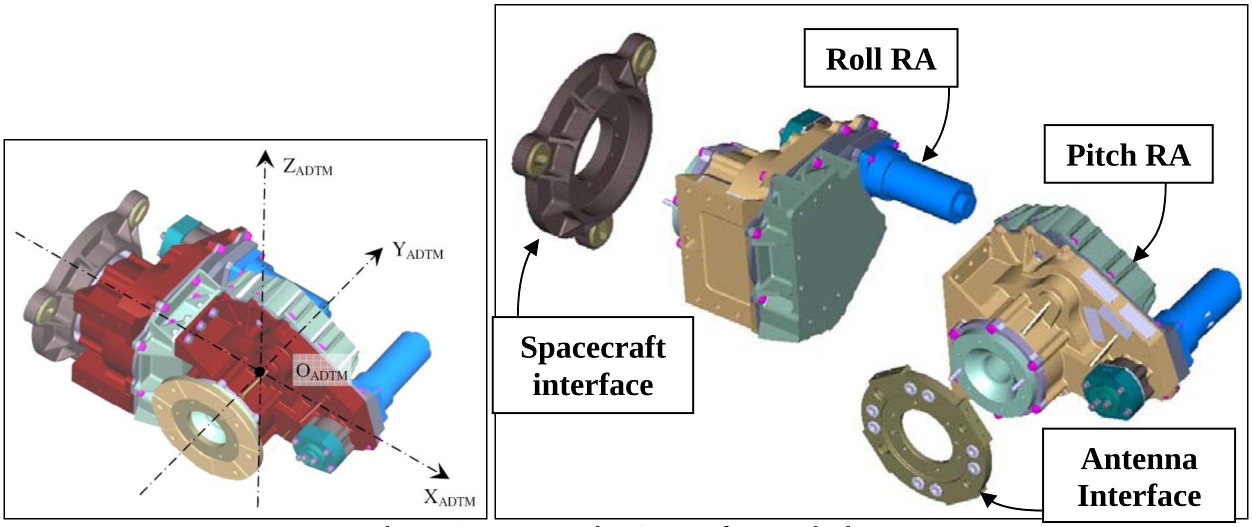

Figure 2: ADTM Mk2 General Description

<u>Key Elements</u>

- Each RA is composed of building blocks from the ADTM Mk1, but re-arranged and providing different functions:
  - ✓ a stepper motor gearbox (SMG) from CDA Intercorp (Florida, USA) providing the active motion for both deployment and trimming functions on Mk2, was used for trimming function only on Mk1,
  - ✓ a spring motor used as an anti-backlash device on Mk2, was performing the main deployment function on Mk1,
  - ✓ a potentiometer monitoring the SMG output shaft (no direct measurement of the RA output shaft)
- spacecraft interface,
- antenna interface, insulating the ADTM Mk2 from the antenna thermally (low thermal distortion)
- thermal control

<u>Anti-backlash</u>

Figure 3: Anti-backlash Spring Motor

The spring motor design here is one where springs are attached to a central torque drum with screws and naturally wound around the storage drums due to their curling treatment. When the torque drum is rotated away from its rest position, an almost constant torque is applied on the torque drum axis throughout the motion range.

In the ADTM Mk2, the spring motor acts as an anti-backlash device, mounted such that it will act in a counter-clockwise direction. Backlash can so only occur when the RA is subjected to a clockwise torque exceeding the spring motor constant preload torque. The size of this spring motor is the limiting factor for the travel range; 120° range is enough for today's deployment and trimming requirements, and this range can easily be extended by increasing the number of torque drum allowable rotations.

<u>Harness</u>

The harness on the ADTM Mk2 has been designed to accommodate all ADTM Mk2 movements within the space allocated, so that the harness on the satellite side is fixed. This has been accommodated by creating a relaxation loop as shown in Figure 4, allowing ±60° rotation around the RA1 roll axis (vertical axis in Fig. 4).

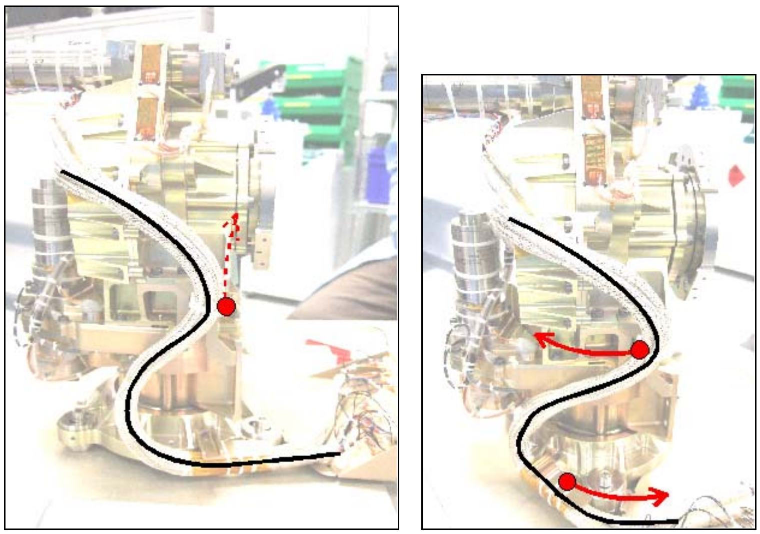

Figure 4: Harness Relaxation Loop,
Left = Roll at reference position,   Right = Roll at -60° position

As seen in Figure 4, there are two fixing points, the harness being formed in a loop allowing the RA1 roll rotations. The top mounting point is a pivot point, minimizing harness stress within the whole movement range. The lower bracket is a fixed line contact bracket, guiding the harness loop in the restricted available space.

- ✓ Reference position (left picture on Figure 4): the harness is in its most relaxed position as set during manufacture, and as shown on the left picture the harness is lightly stressing the RA1 roll actuator vertically. This load is easily handled by the RA1 roll output shaft mounted on a duplex pair bearing.
- ✓ 0 to +60° (not shown on Figure 4): the harness loop deploys but the loop itself is remaining similar (similar radius all the way), the top pivot point following the harness thus minimizing torsional stress. The harness is acting similarly as in the reference position, without added torsional stress.
- ✓ 0 to -60° (right picture on Figure 4): although the harness loop is following the movement and the top pivot point minimizes stress, the bottom fixed line contact bracket is forcing the loop to stay in the same location, which decreases the loop radius and therefore increases the torsion stress on the RA1 roll output shaft (spacecraft interface), acting clockwise.

Tests have been carried out using a rapid prototyped ADTM Mk2 with a proper harness routing but with sliding surfaces instead of a duplex pair bearing, and the worst-case torque measured was less than 0.3 N-m, which is not adding significant loads compared to the anti-backlash spring motor and load requirements.

Design Board: The Key Ideas leading to Higher Stiffness

Achievement of high stiffness has been a key target set in the ADTM Mk2 design specification.

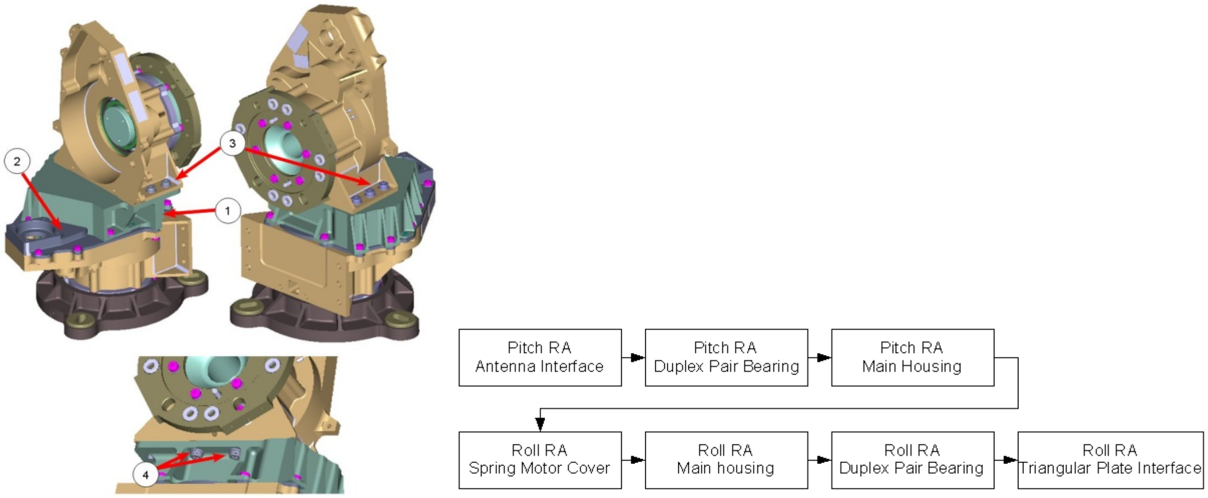

Figure 5: Load Path

Every intermediate part in the load path is another flexibility introduced in the system, so the number of parts used in the load path is minimized to achieve a high global stiffness goal:

- ✓ At position 1 in Figure 5, the preliminary design of the ADTM Mk2 used an additional inter-RA bracket, necessary because of the geometry of the RA and the required relative positions of the roll and pitch RAs (perpendicular crossing axes). It has been determined by stress analysis that growing the roll spring motor cover achieved the same position function but with a higher stiffness.
- ✓ Position 2 in Figure 5 designates the intermediate plate used as the SMG and spring motor mounting bracket. The preliminary design was using a smaller spring motor cover, bolted to this plate, itself bolted to the main housing. Due to the required high loads going through the load path, this roll RA intermediate plate was acting as a flexible membrane, reducing the global stiffness. To avoid this limitation, the spring motor cover has been extended to the main housing border, and bolts are all directly screwed from the spring motor cover, through the intermediate plate, to the main housing. This resulted in much improved stiffness response, with an acceptable mass increase.

Specified stiffness was also achieved during design phase by further structural improvements:

- ✓ Webs have been strategically placed to improve reinforcement of the structure in relatively high load areas. Similarly, thicknesses have also been increased in the higher stress areas.
- ✓ Position 3 in Figure 5 highlights the "legs" of the RAs main housing, used to mount the pitch RA onto the roll RA. These are very similar to the ADTM Mk1 active trunnion design. They are fairly far apart to ensure good moment stiffness results around the pitch Y axis; the right stiffness around the other axes is achieved by adding two screws at position 4 in Figure 5, better linking the pitch RA to the stiff roll RA spring motor cover. This solution was much better in terms of manufacturing, mass and volume than for example having additional brackets between the two actuators.
- ✓ The preliminary design of the triangular plate interface with the spacecraft was flat, and with only 3 attachment points (to allow better accommodation on the spacecraft), it was acting as a membrane. It has been reinforced as much as possible within the ADTM Mk2 volume and movements constraints by adding a thick cylinder plus webs all around. It is now a very stiff bracket (see Table 1) comparing favorably with the duplex pair bearing stiffness.

"Mass Production"

Gearing towards Mass Production

The ADTM Mk2 has been developed to better answer dual deployment requirements, which is now becoming the standard. This means that instead of one large antenna per East/West spacecraft wall, two large antennas are to be deployed on each wall. A few spacecraft were equipped with ADTM mk1 for dual deployments but as it is a single deployment axis mechanism, heavy and voluminous support structures were needed to have the right orientation of the mounting plane of the mechanisms.

Once qualified, the ADTM mk2 is intended to become the baseline deployment mechanism for E3000 spacecraft. It has to cope with any mission, meaning it has to have a fine angular resolution of 0.0025° on the whole angular range, be compatible with the top floor antenna environment (earth-facing wall), and fulfil the most severe missions like RF-sensing missions requiring in-orbit daily trimming operations over the whole lifetime of 15 years.

Therefore, the number of ADTMs required per spacecraft has at least doubled compared to Mk1, and production of this equipment needed to be scaled up to cope with the demand. The design and development phase of the ADTM mk2 was done taking into account the expectations of the first customers. Today (18 months later), we have successfully passed all major reviews and are close to the end of qualification. The first batch of 20 units is in manufacturing and delivery and another half from the next batch2 production has been sold. This has been a fast-paced development, only possible thanks to the dedication of the team and the close co-engineering we developed with our internal and external customers.

Electrical Ground Support Equipment (EGSE)

The ADTM mk1 is a “passive” mechanism for deployment which is driven by springs; only the trimming function is done using electrical actuations. The ADTM mk2 requires electrical actuations whatever the operation: deployment or trimming, and this on a wider angular range. Although the number of ADTM per spacecraft has increased, the specification requires a lot more data about performance of the units and family data comparison than in the past with the Mk1. It has been very challenging to conceive, manufacture and validate a new EGSE within the short time between kick-off and the first tests.

To cope with the increased amount of tests, data and analyses now required, three identical EGSE have been developed in parallel to the ADTM Mk2, each capable of testing up to four ADTMs in parallel (consistent with most dual deployments spacecraft where four antennas are to be deployed), enabling the automation of most of the functional tests performed on the ADTM Mk2, recording all data and pass / fail status in a spreadsheet.

The EGSE units programmed under Labview environment produce extremely useful data. The amount of data collected today is large (~0.5 GB per functional test per unit) but is currently necessary to clearly understand and characterize the behavior of the ADTM. It is planned to make a data reduction exercise in the future once we have a clear understanding of what parameters are important to monitor.

Design Lessons Learned

Load through the output shaft

A duplex pair bearing supports the RA output shaft. It is designed to survive the specification worst case design loads. These have continuously increased throughout the project, exceeding the initial allowable design loads. This led to modifications of the preliminary design of some of the screwed joints within the RA.

These screws are used to preload the RA output shaft duplex pair bearing and retain a gear onto this shaft. Due to increased torsional loads requirements, these were not strong enough to eliminate sliding between the gear and the output shaft during spacecraft launch; up to 2.5 degrees shift can occur. The solution implemented during detailed design phase was to add shear pins and corresponding hole / slot at the gear / output shaft interface, as well as to increase the size of the screws allowing higher preload, and therefore increasing the sliding threshold. The lesson here is to always allow enough contingency overall to cope with likely increased requirements and to recognize the benefit of shear pins which are less dependent on the bolted joint to prevent sliding.

<u>Harness Routing</u>
The overall azimuth movement range is 120°. This movement is composed of long strokes at beginning of life (deployments during ground tests, then in-space deployment after up to 6 years ground storage), and then subsequent small movements over the lifetime (15 years in-orbit). These small movements are daily continuous for Radio Frequencies (RF) sensing applications.

The harness design has been chosen mainly due to the volume constraints requirements, and include a relaxation loop (left picture of Figure 4). Design of the relaxation loop has been greatly accelerated and proven to be a good concept due to the use of rapid prototyping early in the project. However, both RAs being identical, they have the same harness length, leading to different connectors positions. A tooling bracket is used at ADTM Mk2 level to ensure each RA harness achieves the same positions consistently. Integration at ADTM Mk2 level of two RAs proved difficult to consistently achieve these positions, due to small variations of the cabling inside the harness. Harness bending / routing reflects these variations, and influences significantly the end position of the connectors. A solution for this was to implement longer wires with temporary connectors at RA level for tests, and cut to length at ADTM Mk2 level then wire the final flight connectors.

Qualification

<u>Qualification Status</u>
At the time of writing this document, initial functional and post mechanical (i.e. vibration & shock) tests have been performed on the qualification model and some flight models (FMs). Functional tests consist of RA torsional stiffness measurements (including backlash threshold verification), resistances + insulation + grounding measurements, axes perpendicularity and coning measurements, full sweep motion over the complete angular range of both RAs (for step size accuracy and repeatability), minimum start-up voltage (for torque margin analysis) and hysteresis performance across the operating range.

Thermal Balance has been performed on the qualification model and thermal model correlation performed. Thermal Vacuum tests have been performed on both qualification model and the first four FMs. The qualification model will continue to final functional tests and life test sequence.

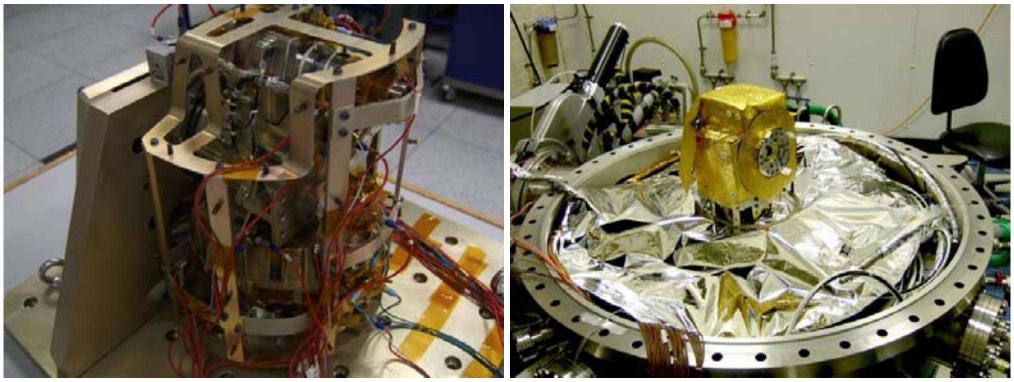

Figure 6: ADTM Mk2, Left = Vibrations and Shocks Setup, Right = Thermal Balance Preparation

<u>Coning and Stiffness results</u>
The requirements for coning and stiffness measurements have been met; Figure 7 shows a few pictures representative of the performance achieved.

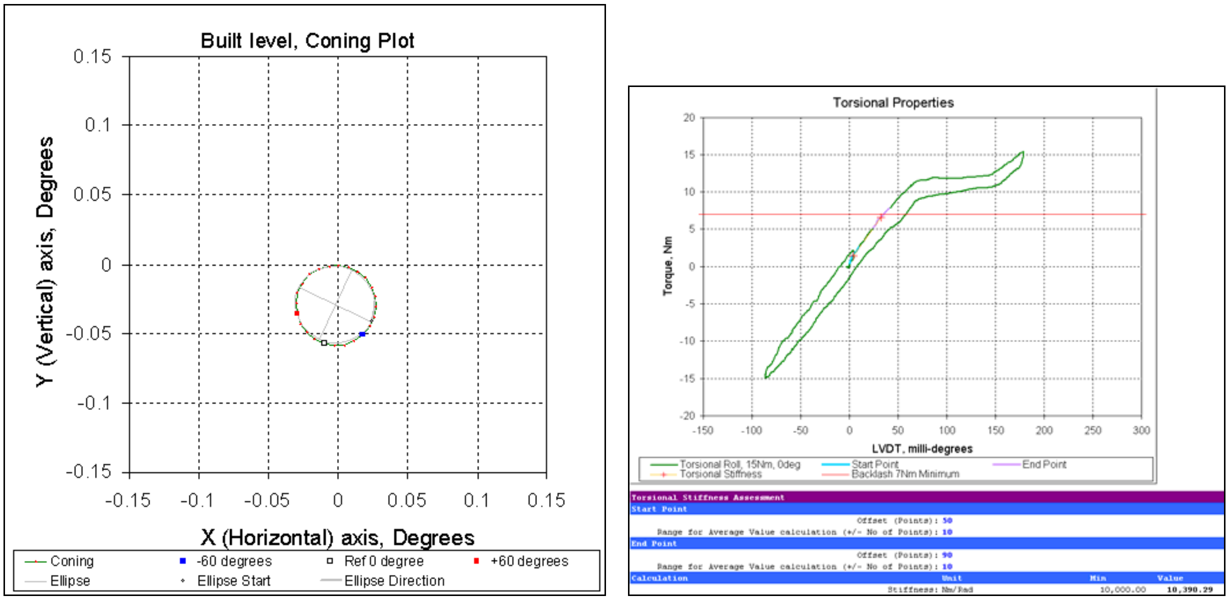

Figure 7: Left = Coning measurement, Right = Stiffness + Backlash measurements

Tests Lessons Learned

<u>Step size Accuracy</u>

The step size accuracy is one of the key functional parameters of the ADTM Mk2 when used for RF sensing missions. The performance of the closed control loop system is indeed improved when the dispersion of the step size is low. The knowledge of the step size accuracy is therefore fundamental and has to be characterized during qualification and acceptance tests.

To measure all the steps sizes (which are nominally 0.0025° /step) with the required resolution, a 22-bit encoder (resolving down to 360°/2^22 ≈ 0.000086°, which is 3.4% of the nominal step size) mounted on the output shaft of the monitored axis was selected. Measurements are made during a full sweep cycle of the 120° angular range in functional tests, an example is shown below in Figure 8.

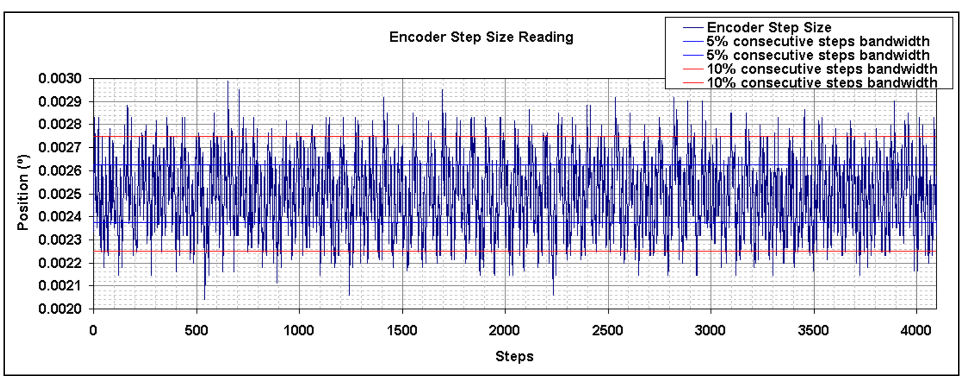

Figure 8: Encoder Step Size Reading during Motion

Zooming on Figure 8, some repeatable frequencies seem to occur, as seen in Figure 9.

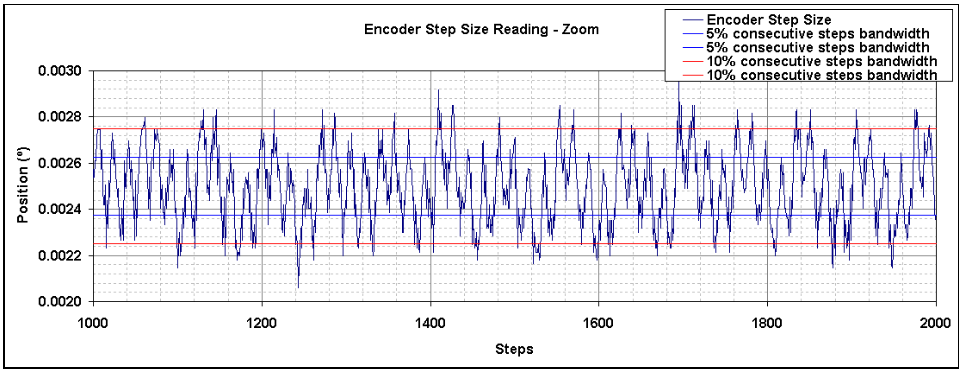

Figure 9: Encoder Step Size Reading during Motion, Zoomed In

Further investigating this in an Excel spreadsheet and using the discrete Fourier Transform by FFT on the encoder and ADTM Mk2 potentiometer readings, the plots shown in Figure 10 were produced.

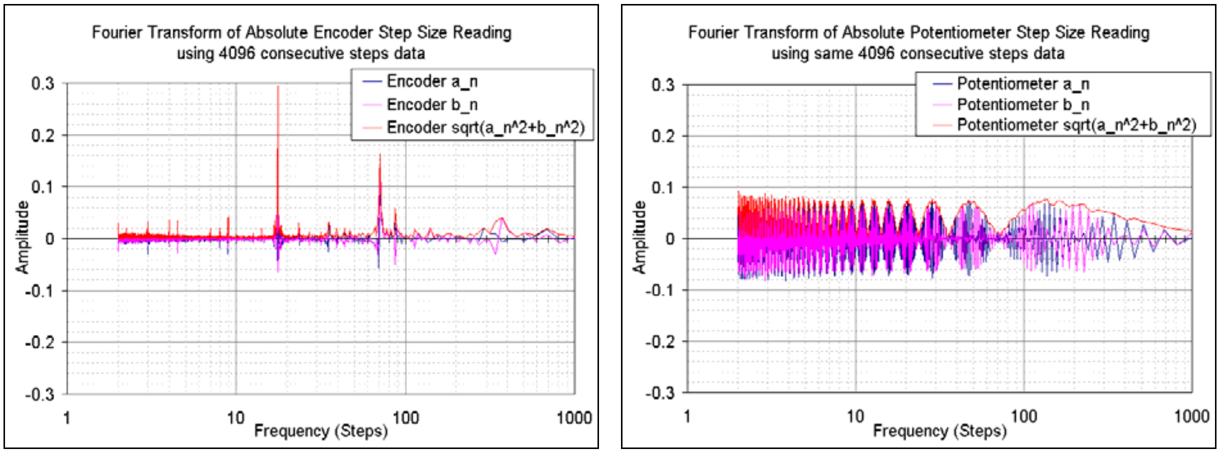

Figure 10: Fourier Transform of step size over 4096 consecutive steps,
left = Encoder Fourier transform, right = Potentiometer Fourier transform

The Fourier transform on potentiometer data does not yield exploitable results (aberration from the FFT algorithm, no frequency detected in the noise of the potentiometer reading), but the FFT on the encoder data does make the frequencies very easy to read.

Further thoughts on the root cause lead to calculate all the ADTM gearboxes tooth to tooth frequencies, which converted back to output step size are the following: 1.125, 8.889, 54, 360, 2400steps.

The FFT analysis tool in MS Excel is limited by the maximum of 4096 samples. This leads to a frequency analysis only possible in the range 2 to 2048 steps (if taking 4096 consecutive steps), with a very rough resolution in the higher steps frequencies and a good resolution in the lower steps frequencies. So in the identified frequencies above, the 1.125 and 2400 steps one won't be visible. Note: to increase resolution on higher steps frequencies, it is possible to analyze 16384 steps modulo 4 (i.e., 4096 samples), but this method cannot be extended indefinitely as we will then hit the maximum mechanical range of the ADTM Mk2.

In the left plot of Figure 10, only 8.889 and 360 can be identified, 54 does not appear.

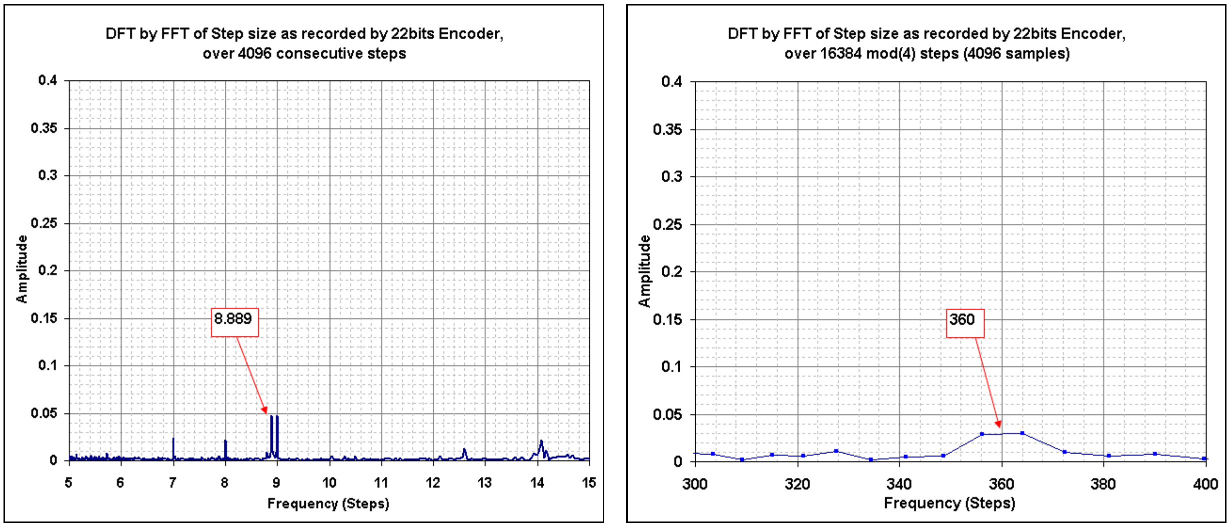

Figure 11: Fourier Transform, Zoom-In

However, this does not explain the much higher amplitude frequencies found in the left plot of Figure 10. Looking now at the encoder itself, it returns a 22-bit position with normal binary numbers. Calculating the relationship between bits number and the equivalent steps length, the frequencies shown in Table 2 appear.

Table 2: Relationship between Encoder bits and Steps Frequency

Encoder Bit	Bit Changes over 360°	Angle per Bit Change	Steps per Bit Change
22	4194304	8.58307E-05	0.034332275
21	2097152	0.000171661	0.068664551
20	1048576	0.000343323	0.137329102
19	524288	0.000686646	0.274658203
18	262144	0.001373291	0.549316406
17	131072	0.002746582	1.098632813
16	65536	0.005493164	2.197265625
15	32768	0.010986328	4.39453125
14	16384	0.021972656	8.7890625
13	8192	0.043945313	17.578125
12	4096	0.087890625	35.15625
11	2048	0.17578125	70.3125
10	1024	0.3515625	140.625
9	512	0.703125	281.25
8	256	1.40625	562.5
7	128	2.8125	1125
6	64	5.625	2250
5	32	11.25	4500
4	16	22.5	9000
3	8	45	18000
2	4	90	36000
1	2	180	72000

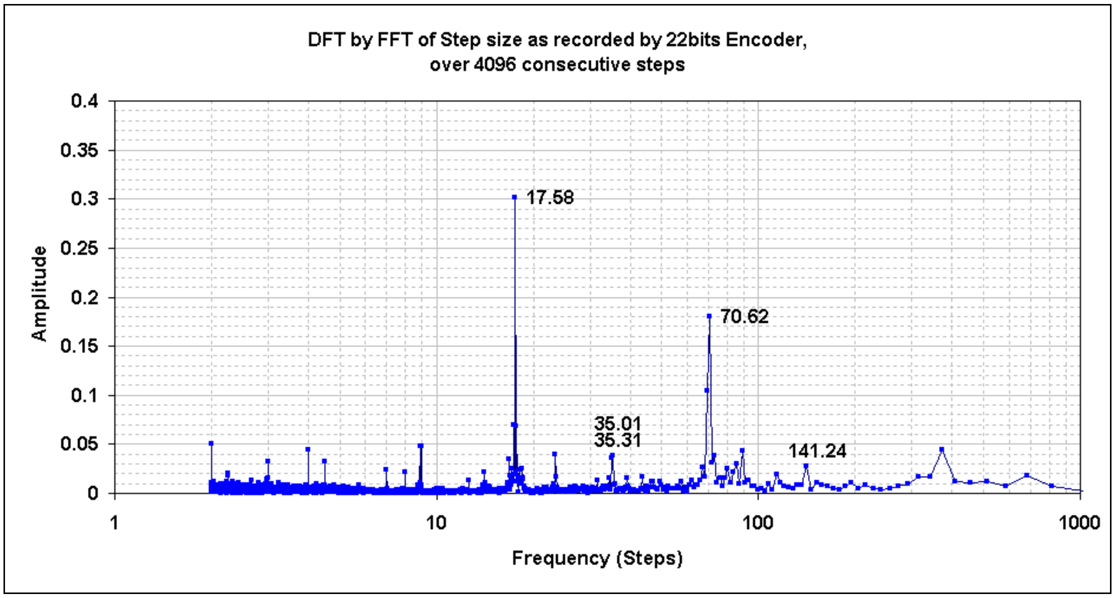

Figure 12: Fourier Transform, Zoom-In bis

Looking back to Figure 10, some of these frequencies do appear in the readings. In particular, in Figure 12, the amplitude seen at the positions corresponding to the 11th bit (70.31 steps) and 13th bit (17.58) are the major contributors to the error recorded by the encoder. Thus it seems that most of the error recorded by the encoder during functional tests is actually generated by the encoder itself. Looking in detail at the encoder technology used, it appears that only the first 11 bits are real mechanical bits, and the rest of the bits are interpolated using sine / cosine signals in the encoder. Therefore, it would appear that the interpolation algorithm used has some edges effects that are very significant compared to the data read resolution.

There is a lesson learned here: we should not select high precision measuring equipment only based on claimed accuracy by the supplier, but should also qualify such equipment beforehand. In this case, the supplier claimed a much finer absolute accuracy than what we are actually seeing using the FFT function, and this is repeatable on all the encoders we have bought for mass production tests. At the time of writing this document, alternative measurement equipments are being investigated, but we now have a better understanding of our current test equipment and may be able to correct data after calibration, although this is an on-going activity as well.

Despite the disturbances of the step size accuracy introduced by the test encoder, the ADTM mk2 performances have been proven to be compliant with the targeted flight applications.

Thermal Vacuum (TVAC) Tests with an Inertia

When testing the qualification model in a TVAC configuration (after thermal balance), it was initially planned to attach the pitch output shaft to a rigid inertia to simulate the worst case antenna load. To achieve this, a 90 kg-m^2 inertia was to be used outside the chamber, with a shaft linking it to the ADTM unit via a feed-through on the top of the TVAC chamber. The main interest for this inertia was to be able to measure hysteresis, and preliminary tests proved that the pass-though seal had too large an influence on the results to be of any use, as shown in Figure 13.

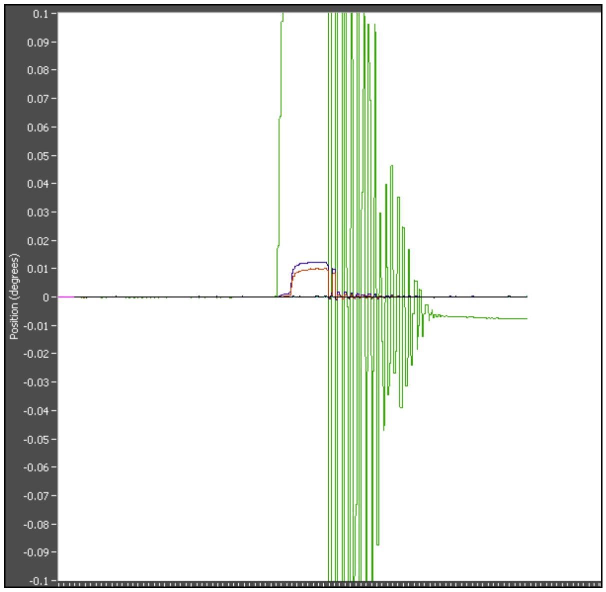

Figure 13: Inertia Test

On the Figure 13, the inertia was loaded to apply ~25-Nm load on the ADTM shaft, and then released free, the idea being to make a quick verification of the frequency response of the setup. The green line is the inertia movement read by the encoder, and the other lines are the prime and redundant potentiometer monitoring the SMG movements. This test enables us to measure a few things:

- ✓ First the backlash measured on the potentiometers when loading the inertia corresponds to the SMG backlash, which is apparent when the applied load on the RA output shaft is compensating the spring motor anti-backlash device (>7 Nm). The backlash measured on the SMG here is ~0.01°, or 4 steps.
- ✓ The other interesting information from this plot is the hysteresis of the inertia: after the test, it settled about 4 steps away (according to the encoder) from its start position. So here again, the lesson learned is that to measure sensible data on very small movement, it is necessary to really think through all the possible causes of friction that would influence significantly the results (here: passing through a TVAC chamber seal).
- ✓ And finally, zooming in the data it is possible to extract the length of a cycle of the inertia during motion, which corresponds to the natural frequency of the system. Here it was measured to be at ~1.15 Hz.

Conclusion

The ADTM Mk2 has been a challenging program. New mass production test equipment has been developed and is still being improved to cope with the higher demand (more than double from Mk1 versions). Qualification and flight productions have been and still are running in parallel successfully, thanks to the good cooperation between the prime customer and the ADTM team.

First qualification test results were as expected and demonstrated the robustness of ADTM mk2 design. Some lessons have been learned along the way, such as design improvement rationale and also test equipment selection and calibration, such as encoder accuracies. Combination of analyses and units tests results are being collected to allow family data to be built up and presented (as is being requested more and more by our customers). Production is on its way!

Even if today the ADTM Mk2 fulfils the most stringent requirements for the current flight missions, the anticipated evolution of these missions continues to require better performances like a smaller step size or increase of the angular range. The lessons learned during the development of the ADTM Mk2 will be invaluable to complete the development on time and on cost of a mechanism with higher performances.

Figure 14: ADTM Mk2 Project Team