Development of a High Resolution Rotary Actuator for an Antenna Trimming Mechanism

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Abstract

The High Resolution Rotary Actuator (HR²A) product is one of the main components of the Antenna Trimming System (ATS) developed for a commercial satellite. The mechanism needs to deploy and point the reflector around two axes and is composed of two HR²A in a gimballed configuration. It operates in a closed loop system using an RF beacon on the ground. This assembly is called MADPM, Multimedia Antenna Deployment and Pointing Mechanism. These mechanisms are located between the spacecraft structure and the reflector. The positions and orientations of these mechanisms on the spacecraft result from an architecture layout analysis, dealing with deployment and pointing objectives. The HR²A mechanism is developed to be able to steer a large reflector along a wide deployment angle (up to 180° with steps of 0.02°), to point it with a small output resolution (0.002° each step) and to perform a large number of micro cycles. The mechanism is qualified and 6 flight models have been built in parallel of the qualification and are now assembled on the spacecraft.

Introduction

Initially, system engineers required that the mechanism shall be able to perform a high and not well defined number and type of cycles. The first choices of technology were therefore based on this main requirement. This requirement disqualifies automatically all the links with tribological contact. After more work with system engineers and in order to be able to qualify this type of product, the number and types of cycle were determined for the generic Thales Alenia Space platform. It appeared that the need still required a technology and design with no risk with regard to the life time. Moreover, the mechanism will have to be able to deploy the reflectors up to 180° of motion. Aiming at reducing the number of actuators, we decided to use the same actuator for deployment and for pointing. The background of Thales Alenia Space mechanism product line with very large number of cycles led us to use the heritage of the Scan Drive Unit Actuator. The Scan Drive Unit actuator is a part of the SEVIRI instrument of METEOSAT Second Generation spacecraft and has been fully developed by Thales Alenia Space. This mechanism is a linear actuator constituted mainly by a stepper motor, a spindle, ball bearings and potentiometer. The peculiarity of this mechanism is to be fully sealed and filled with oil. As a rotational movement is required to deploy a reflector, it was necessary to have another mechanism able to transform a linear movement into a rotational movement without risk with regards to life time. It is in this framework that the HR²A has been successfully developed by Thales Alenia Space.

Mechanism Description

The High Resolution Rotary Actuators is made of different components based on several innovative ideas.

- A high life time capability linear drive unit.
- A high life time capability reducer, that realizes, with the same linear kinematic input, a large amplitude rotating movement (deployment), following by a small amplitude rotational movement, with a high accuracy (fine pointing).
- A specific guiding (and crossing) system, with flexible blades, that provides stiffness and loads capabilities.

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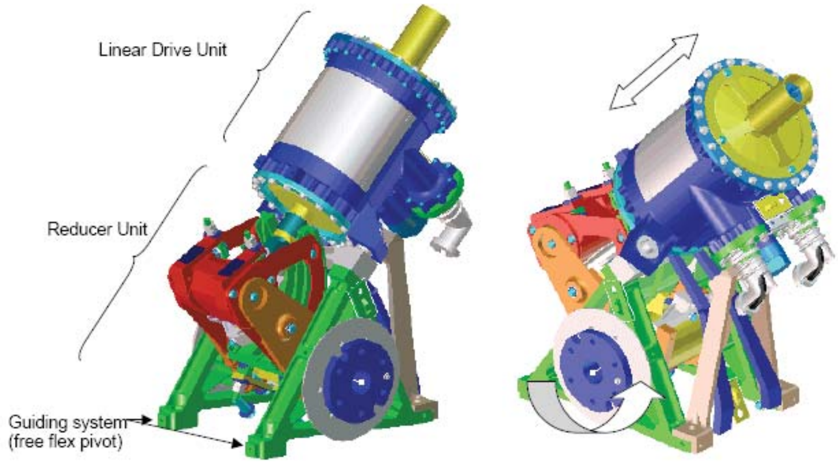


Figure 1. High Resolution Rotary Actuator

The linear drive unit is composed of:
- a redundant two-phase permanent magnet stepper motor
- a redundant rotational potentiometer (fine)
- two linear potentiometers (nominal and redundant) (coarse)
- a roller screw
- ball bearings
- metallic bellows
- ring metallic joints
- oil
- hard stop

The reducing unit is composed of:
- metallic strap
- free flex bearing
- ball bearings
- hard stop
- two outputs

Three patents are filed for this product.

- 1st innovative idea: the reducer : (Patent: Folio 652805)
- 2nd innovative idea: combined guiding: (Patent: Folio 652667)
- 3rd innovative idea: The specific crossing guiding with flexible blades (also called free flex pivot) (Patent: FR0753521 27/02/2007):

The system requires deployment and then pointing around two axes. To fulfil this function, two HR²A are mounted together in a gimballed configuration to form the MADPM; the layout is shown in Figures 2 – 4.

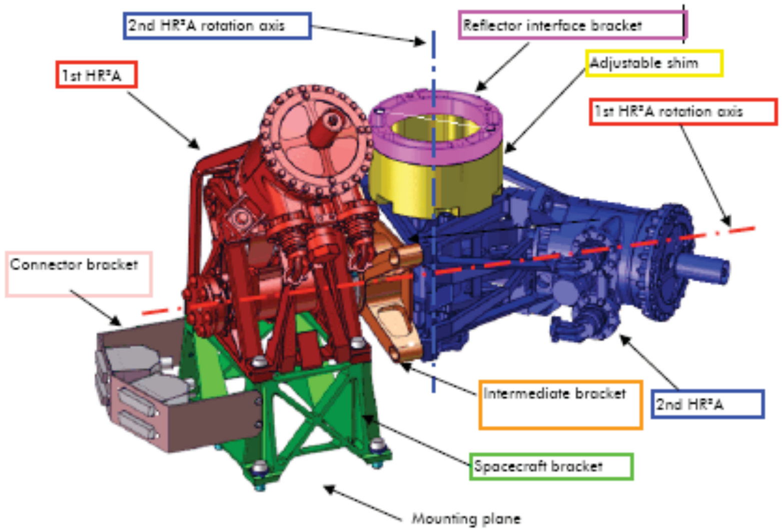


Figure 2. MADPM layout in deployed configuration

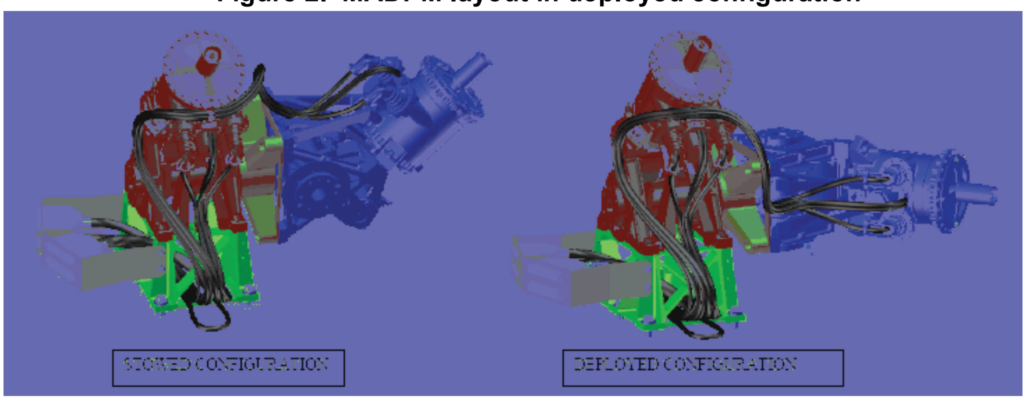


Figure 3. MADPM stowed and deployed configurations

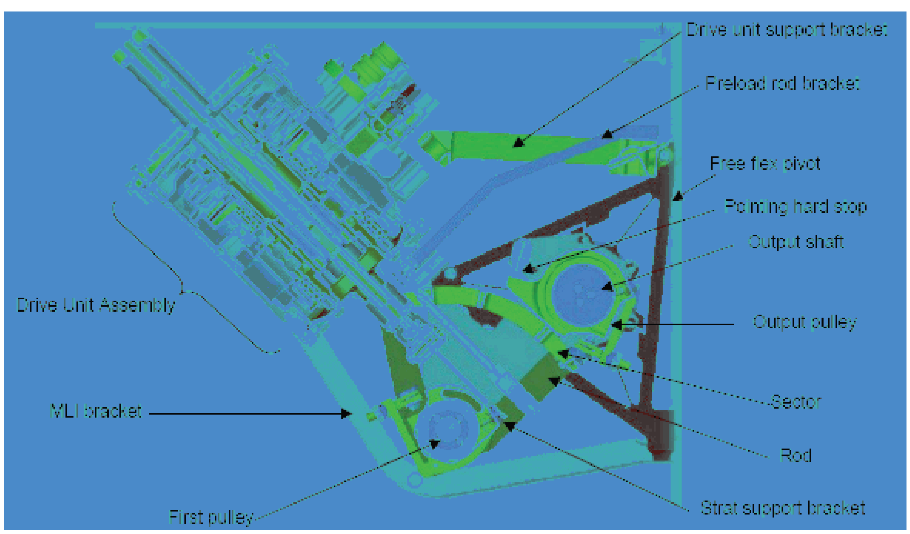


Figure 4. Mechanism Kinematic

Deployment
Once the reflector is released, the stepper motor of the linear drive unit is powered on. The stepper motor drives the bolt of the roller screw in rotation. As the screw is stopped in rotation by the bellows, the screw moves in translation. The linear drive unit output step is equal to 2.2 10^{-3} mm/step. The rotational potentiometer is linked to the stepper motor rotor to provide fine position. The linear potentiometer is linked to the screw to provide coarse position.
- The strap support bracket, linked to the linear drive unit output moves in translation.
- Straps unwind and wind at the same time around the first pulley.
- The first pulley radius is 20 mm.
- The sector with a higher radius (63 mm) turns in the same movement. Its straps unwind and wind in the same time around the output pulley.
- As a consequence, the output step is equal to: $\theta_{output} = \frac{63mm}{20mm} \times \frac{0.0022mm}{20mm} = 0.00035 rad = 0.02° / step$

End of deployment:
At 1.25° before the operational deployment position, a pointing hard stop on the output pulley comes in contact with the rod. As the rod supports the first pulley and sector, the rotational movement of both is stopped with respect to the rod. There is no more movement of the first pulley ball bearing and output pulley ball bearings. As the linear drive unit continues to push the strap support bracket, the rod unsticks from the preload rod bracket and moves the free flex pivot. The output rotational movement is obtained by bending of the three blades of the free flex pivot. The end of deployment is when the potentiometers give the right value. This position corresponds to a rotation of the free flex pivot of 1.25°.

In pointing phase
In this phase, the linear drive unit can move in two ways. The free flex pivot is always bending. The operational range is ±1° (specification) but might be increased up to ±1.25° (design margins). The output step value is given by the distance between the output rotation axis and the axis of the linear drive unit (63 mm). The range of HR²A movement is limited thanks to the hard stop inside the drive unit.

$$\theta_{output} = \arctan\left(\frac{\Delta l_{linear\_output}}{63mm}\right) = \arctan\left(\frac{0.0022mm}{63mm}\right) = 0.00202° / step$$

Linear Actuator Description and Maturity

The linear drive actuator is a sealed linear actuator with a complete oil bath. This technology enables a high number of micro-cycles in a harsh thermal environment. The movement is performed due to the screw of a spindle. The nut of the spindle is linked to the rotor of a stepper motor. A redundant rotational potentiometer gives the position of the stepper motor (fine potentiometer). A redundant linear potentiometer gives the position of the screw (coarse potentiometer). The combination of both potentiometers' information gives the position of the screw with accuracy inferior to the step. Power and measurements are sent by two hermetic connectors, one nominal, and one redundant. The dynamic sealing is performed by metallic bellows (which stop the spindle screw in rotation) and static sealing due to metallic joints.

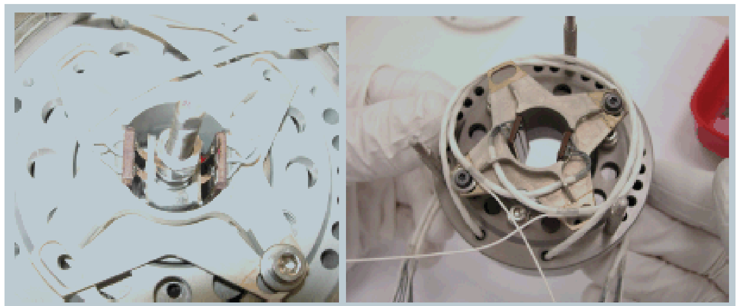


Figure 5. Potentiometer assembly

The stepper motor, the spindle, the potentiometers, the oil, the ball bearings, the bellows, the joints and the hermetic connectors are procured elements and represent 90% of linear the drive unit.

Both bellows at the front and back of the linear drive actuator are the same in order to have no variation of volume inside the mechanism. However, it is still necessary to have a volume balancer due to the thermal expansion of the oil. Actually, the inside volume of the mechanism is constant but the mechanism is not fully filled of oil. The volume not used by the oil if filled with a neutral gas. The oil / gas ratio is calculated such that the maximum pressure is not exceeded at temperature.

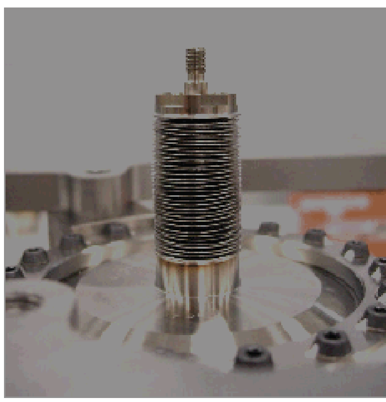


Figure 6. Metallic bellow

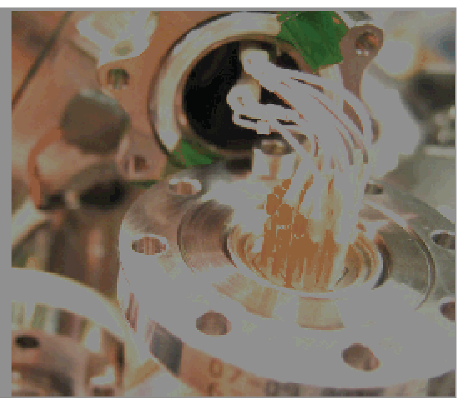


Figure 7. Hermetic connector

The oil is the same as the one used on the heritage Scan Drive Unit mechanism. It has the main characteristic to not have emulsions even in a moving bath. It can survive the radiation environment without degradation.

The screw of the spindle has a diameter of 12 mm. The spindle is composed of 7 rollers with a solid preload. The solid preload allows a reversibility limit higher than the elastic preload. The lubrication environment of the spindle has no effect on the reversibility limit. The main requirements to the supplier were the reversibility and the resistive torque.

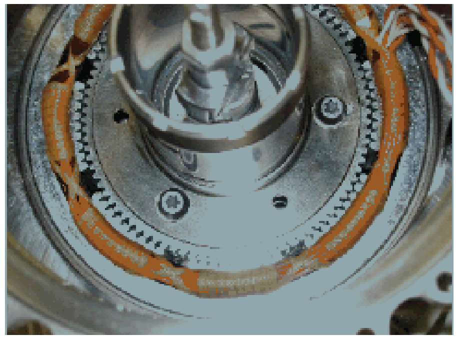


Figure 8. Stepper motor and roller screw assembly

The ball bearings are super duplex back-to-back mounted with a solid preload.

The main characteristics measured for this unit are:

- sealing: <1.10^{-9} atm-cm^3/s under helium at 50000 Pa
- linear resolution of 0.0022 mm/step
- linear range: 24 mm
- Torque margin >3
- Maximum load capability = Reversibility load. (This is due to the duty cycle voltage command of the stepper motor)
- Qualification Temperature: [-50°C; +100°C], the drive unit temperature is maintained up to 10°C with its own thermal control.
- Vibration: 25g mounted in HR^{2}A configuration
- Velocity: nominal 2.1 mm/mn, tested successfully up to 26 mm/mn
- Mass <2 kg

The linear drive unit has been fully qualified and six flight units are on one spacecraft.

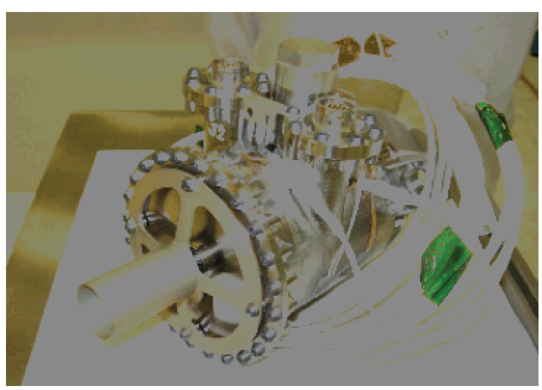


Figure 9. Stepper motor and roller screw assembly

Reducer unit

The reducing unit is a mechanism that transforms the linear movement of the drive unit to a rotational movement with accuracy and high stiffness, with an output range of 180° for deployment and ±1° for pointing. The output step resolution is 0.02° for the deployment and 0.002° for the pointing. In the range of pointing, the design of the mechanism is free of any tribological link to ensure a high cycle life time. There is no movement of ball bearings. The transformation of the translation in rotation is performed by metallic straps winding and unwinding on a pulley.

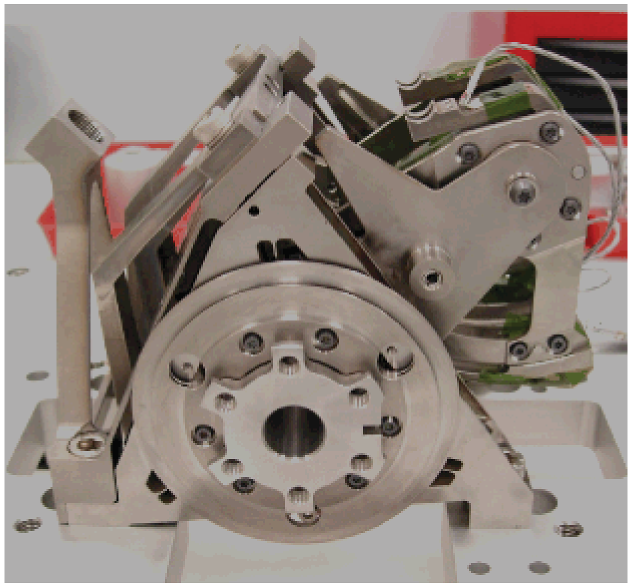


Figure 10. Reducer unit assembly

Design development and qualification plan

At linear drive unit level

This product was based on the heritage of the Scan Drive Unit mechanism. All the suppliers have been kept to reduce the risks with regard to the chemical environment of the oil and gas. But due to the re-packaging of the mechanism, all the supply units have been reduced in size. The main concern was the internal wiring of the mechanism. Indeed, the number of cables was more important than heritage number because there was no coarse potentiometer on the Scan Drive Unit. These cables had to be routed in a far more compact design compared to heritage. That is why a mock up of the linear drive unit in Plexiglas was built to verify the internal cable routing. This mock up allowed validation of the internal design of the drive unit.

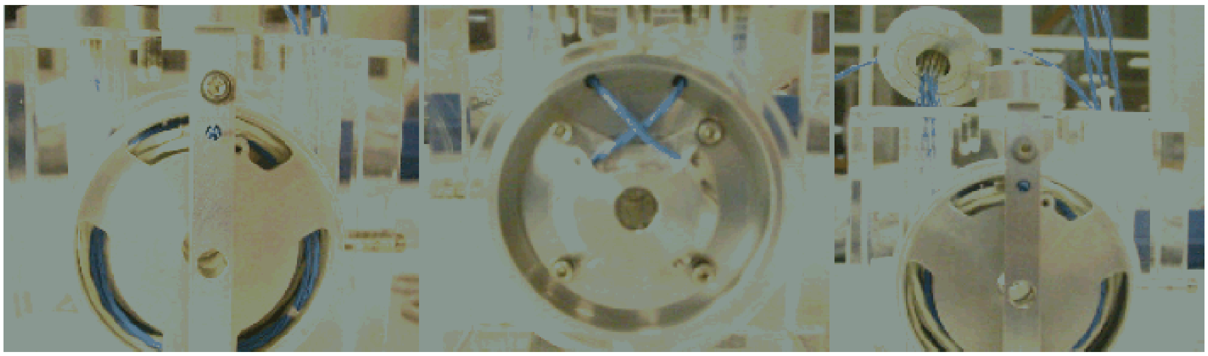


Figure 11. Mock up of the drive unit internal cabling

Once the QM was assembled and tested, six flight linear drive units were assembled in parallel and submitted to a complete acceptance test including functional and mechanical characterization tests (sealing, motorization margin, reversibility, motion range, max output load, power consumption…).

At reducer unit level

Due to very stringent planning constraints, the delivery schedule imposed from the start of the project forced production of the flight hardware in parallel of the QM model. It was therefore decided to verify the capability of the metallic straps and the free flex pivot new design to perform the number of cycles required at the earliest stage. Mock-ups were built to validate the design.

Metallic strap mock up

Strap design:
One of the issues with the strap design wais the resistance of the interface under strap load. Either the interface is held by friction, or is held by opposition. In the first case, we need to know the friction coefficient and the tension in the screw to guarantee the link. In the second case, we need only to verify the capability of the strap under peening and solicitation under clevis but we are limited by the thickness of the strap.

The first mock up test was to verify the threshold tension load for which the stiffness behavior of the metallic strap winding on a pulley is linear.

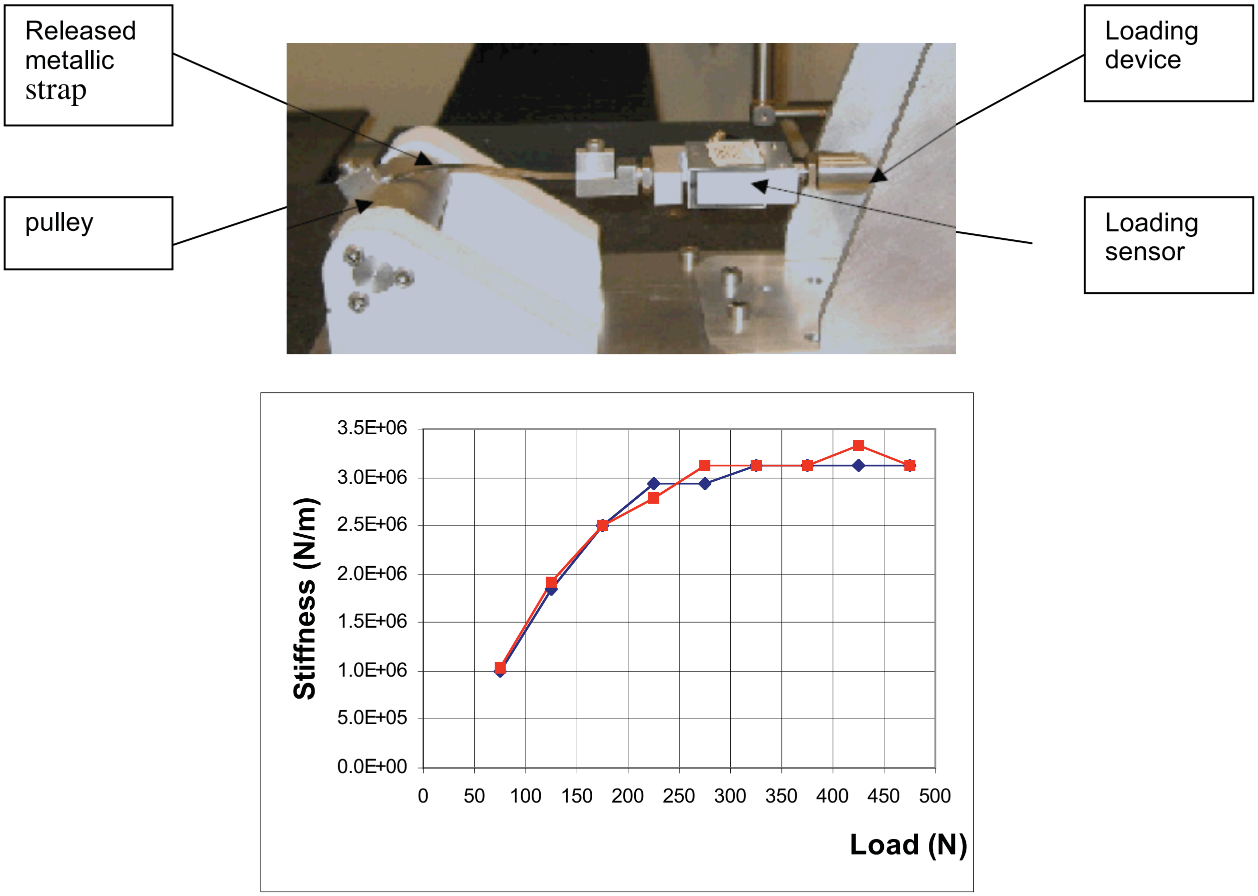


Figure 10. Metallic strap stiffness behavior

This test showed that the strap must be tightened to a minimum of 300 N to have linear behavior. This is due to the local bending around the output of the strap with the pulley.

The second mock up objective was to verify the capability of the strap in life time. During the life time, the straps wind and unwind locally on a pulley. So the strap sees constant stress due to tension and an oscillation stress due to the wind and unwind on the pulley.

Before and after life test, a dye penetrant test was performed on the strap to verify the non presence of crack.

Free flex pivot mock up
Due to the design, the behavior of the free flex under an imposed rotation is non linear. So we needed to verify by test the predicted behavior with regard to stiffness, the back torque and the buckling.

The first mock up consisted of three sample blades fully identical to the flight one to verify if the non linear model was good.

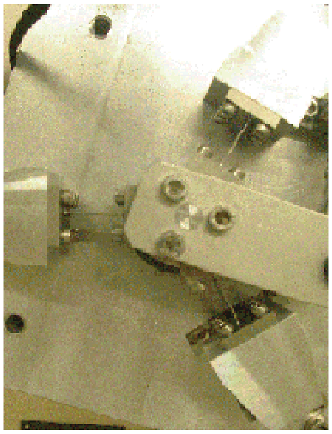


Figure 13. Free Flex mock up 1

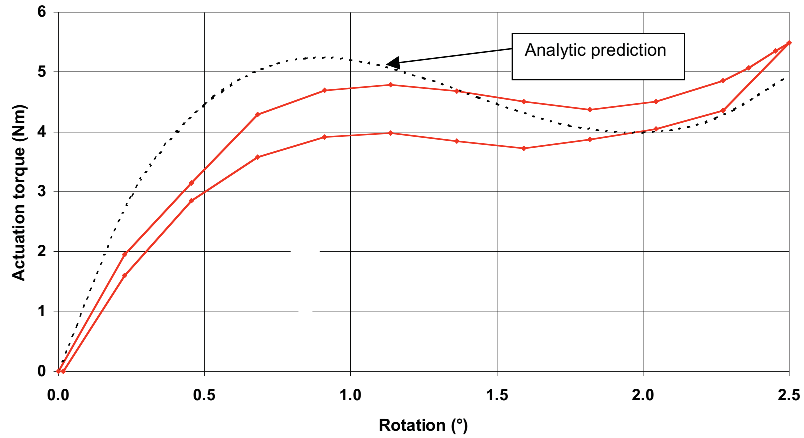


Figure 14. Free flex stiffness behavior correlation

The second mock up consisted of a free flex fully representative of the flight one. The objective of this test was to verify the limit of buckling of this design when it was submitted to a bending moment. For this, the free flex was equipped with a strain gauge all along both sides of the three blades. The test is performed in imposed displacement and the buckling is detected when the strain gauge signal becomes non linear.

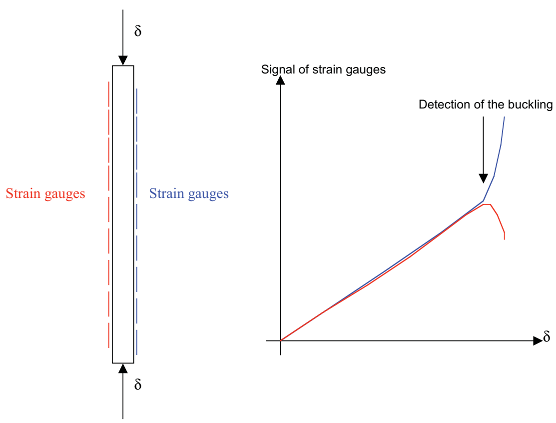


Figure 15. Detection of the free flex buckling

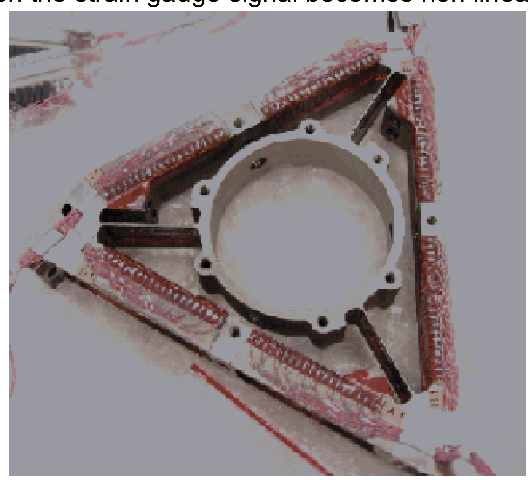


Figure 16. Free flex equipped with strain gauges

The results obtained confirm the prediction.

At HR²A level

The objective of the development was to qualify the MADPM with only one HR²A. That is why the following test plan has been performed with some particularity for the vibration and shock test.

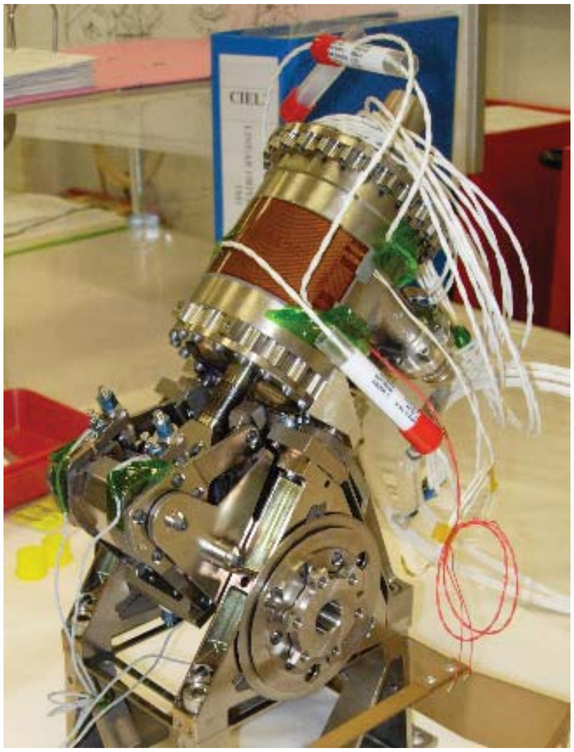
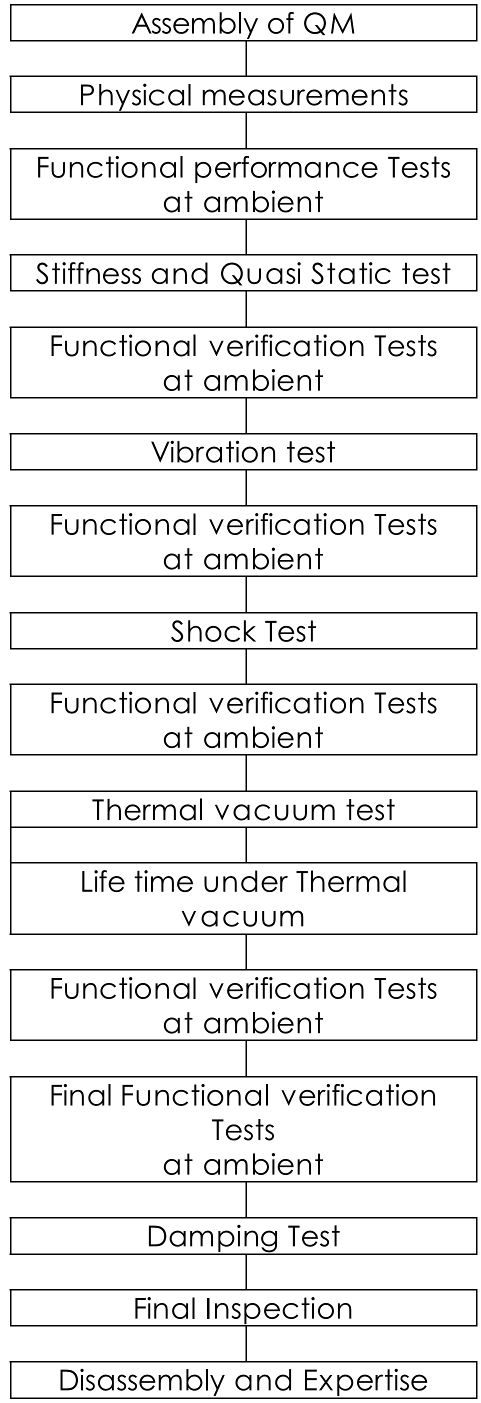


Figure 17. HR²A Assembly



Vibration and shock test

The HR²A was tested in vibration in three configurations. The first configuration corresponded to the HR²A in position 1 on the MADPM and loaded by the HR²A in position 2. The HR²A in position 2 was simulated by a dummy mass representative in mass, Cdg position and inertia. This dummy mass was connected to the test support thanks to a tool representing the reflector arm stiffness.

The second configuration corresponded to the HR²A in position 2 on the MADPM. In this configuration, the HR²A QM was submitted to the envelope level of the configuration one and the level seen by the interface of the dummy mass of the first configuration.

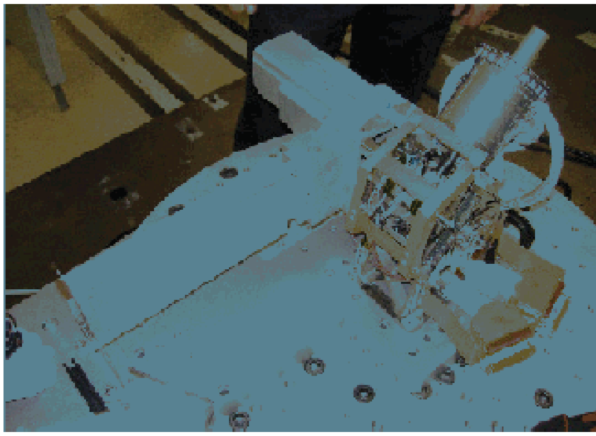


Figure 18. First vibration configuration test

Figure 19. Second vibration configuration test

The third configuration corresponds to the HR²A vibration configuration of the complete flight model. In this configuration, the HR²A QM only saw low level sine. This allowed a comparison of the flight model behavior with the qualification model. This configuration is close to the first one with no spacecraft bracket.

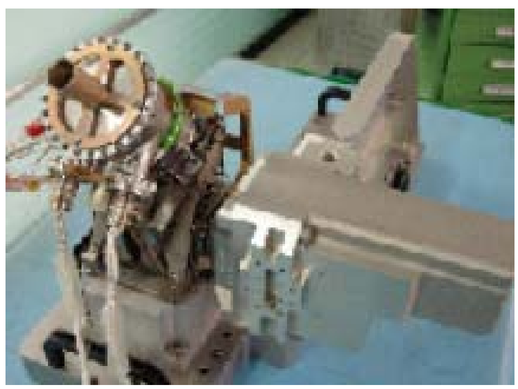


Figure 20. Third vibration configuration test

At MADPM level

In order to deploy and then point around two axes, two HR²A are mounted together in a gimbal configuration to form the MADPM; the layout is the presented in Figure 21. Figure 22 shows the MADPM (Multimedia Antenna Deployment and Pointing Mechanism) assembly and on the spacecraft (3 flight unit on the same spacecraft)

Figure 21. MADPM without and with MLI

Figure 22. Three MADPM on the same spacecraft

Lessons Learned

One of the main challenges was to develop a new mechanism and deliver flight hardware in 24 months. The design of the HR2A is far from the heritage design. The first lesson learned was that the schedule challenge was made possible only because technologies involved in the design concept were well assessed before the development (blades, straps, oil bath, sealing).

The second lesson learned concerns the suppliers. Major design evolutions compared to the heritage were analyzed deeply and led to no surprise for this development. Due to the size reduction needed, some components were slightly modified. Suppliers were kept unchanged compared to the heritage for all components. New requirements ended up being not well taken into account due to lack of close communication and reviews with the suppliers.

The third lesson learned concerns the way to manage FM hardware integration in parallel to QM assembly and testing. A QM is a first model and always needs some adjustments. It was decided to tackle the FM deadline with two rules:

- allow assembly or test step on FMs only when the QM operation step had been performed and return of experience well taken into account
- the engineering manager is part of the production tiger team and work in the clean room on both QM and FM models

The bet was that even though the QM planning was drifting due to first adjustment needed, the FM delivery date would be kept by having clear production file and learning experience of the operators. It was challenging not to delay some QM testing in order to deliver the flight models more quickly.

The fourth lesson learned concerns the difficulty of comprehension of the design (detailed kinematics, consequences of failure modes …). To help the understanding, we built a Plexiglas mock up. Thanks to this mock up, most of the points raised were more easily addressed. This mock up helped to understand and solve the difficulties met during integration. It also eased the communication with the final customer during design reviews.