THE CRYOGENIC REFOCUSSING MECHANISM OF NIRSPEC

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ABSTRACT

A novel cryogenic refocussing mechanism (RMA) has been designed by Galileo Avionica (GA) for the Near Infra-Red Spectrograph (NIRSpec) of the James Webb Space Telescope (JWST). The RMA shall refocus the NIRSpec by a rigid translation of a set of two mirrors in a 6 mm range, with an accuracy of 50 microns and 15 microns step size. The design is driven by the operation in performance at 30K temperature while being still fully functional at room temperature, by the need to incorporate two mirrors as part of the mechanism and by the tight envelope constraints specified by the instrument Prime Contractor (Astrium-D). This paper reports the design of the RMA and the tests performed on breadboards and engineering models. A description of the foreseen test plan and set-up at instrument level is also given.

Keywords: NIRSPEC, cryogenics, refocussing mechanism.

1. INTRODUCTION

The Near Infrared Spectrometer (NIRSpec) is one of the science instruments installed into the James Webb Space Telescope (JWST); it is provided to NASA by the European Space Agency. The NIRSpec prime contractor EADS-Astrium has commissioned the Refocussing Mechanism assembly (RMA) to Galileo Avionica (GA).

NIRSpec (Fig.1) is a near-infrared, multi-object, dispersive spectrograph, which will be cooled at a temperature of 37 K in order to achieve the required sensitivity in the near-infrared spectral region. One of the most critical subassemblies is the RMA which is needed to accommodate the changes of focus. This function is achieved by translating with high precision two plane mirrors positioned at 45°, both mounted to a support sled, along the common axis of movement. The design, production, integration and alignment of the two mirrors into the mechanism is performed by GA as well. The RMA must be mounted to the NIRSpec optical bench, made of silicon carbide (SiC).

The main design and functional requirements are:

- Move a set of two plane mirrors along a common refocussing direction, for 6 mm stroke;
- Mirror position and envelopes, see Fig. 2;
- Fully functional on ground in any orientation, and any position to be kept in unpowered condition;
- Sled position detection along the functional stroke;
- 1^{st} eigenfrequency >140 Hz;
- design loads 24g;
- operative temperature 30-40 Kelvin.

Main performance requirements:

- 15 micron step size;
- +/-50 micron position accuracy;
- mirror alignment shift <+/-0.1 mm along X, Y, Z;
- mirror alignment offset <+/-100 arcsec about X, and <+/-30 arcsec about Y and Z.;
- max power <0.6 W including harness losses;

One additional design driver was the use of proven technologies as far as possible.

The design choices were strongly restricted by the need to incorporate the mirror pairs in a position far from the mount interface, while remaining within the specified tight envelopes (Fig.2). The cryogenic temperature dictated the materials, the components and processes selection and their qualification.

2. MECHANISM DESCRIPTION

The RMA comprises (Fig.3):

- a support bench mounted to the NIRSpec optical bench via three pseudo-isostatic mounts;
- a sled mounted to the bench by means of three flexural blades (flexural parallelogram);
- two mirrors mounted on the sled;
- drive mechanism mounted on the RMA bench;
- position indicators.

The RMA is mounted to the NIRSpec bench made of SiC by means of three flexural bipods to compensate the differential thermal contraction when cooling down from ambient to 30K.

Three flexural blades are interposed between RMA bench and the sled, to form a flexural parallelogram along the refocussing direction. The sled is driven by a geared stepper motor connected to an eccentric camshaft and to a lever. The system operation is sketched in Fig. 4.

In launch configuration the parallelogram flexures are not bended and the lever axis pass through the cam shaft axis (Fig. 4a).

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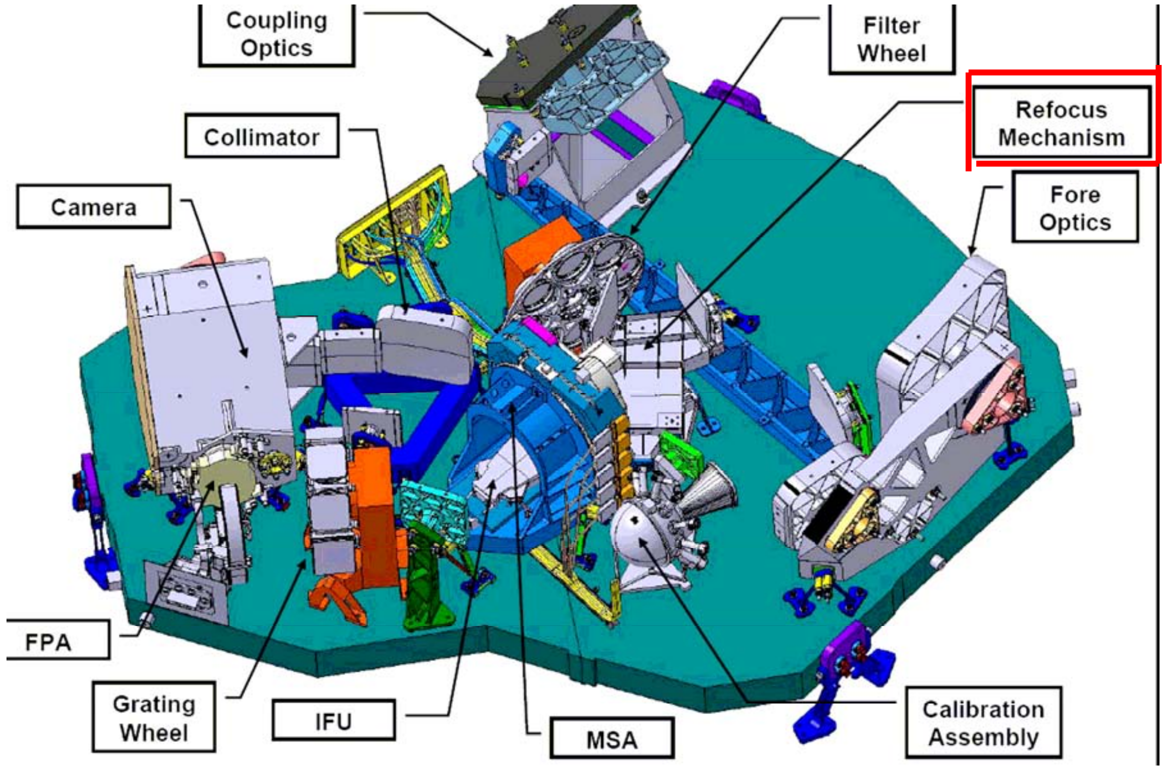

Figure 1 the RMA set into the tight envelope constraints of NIRSpec

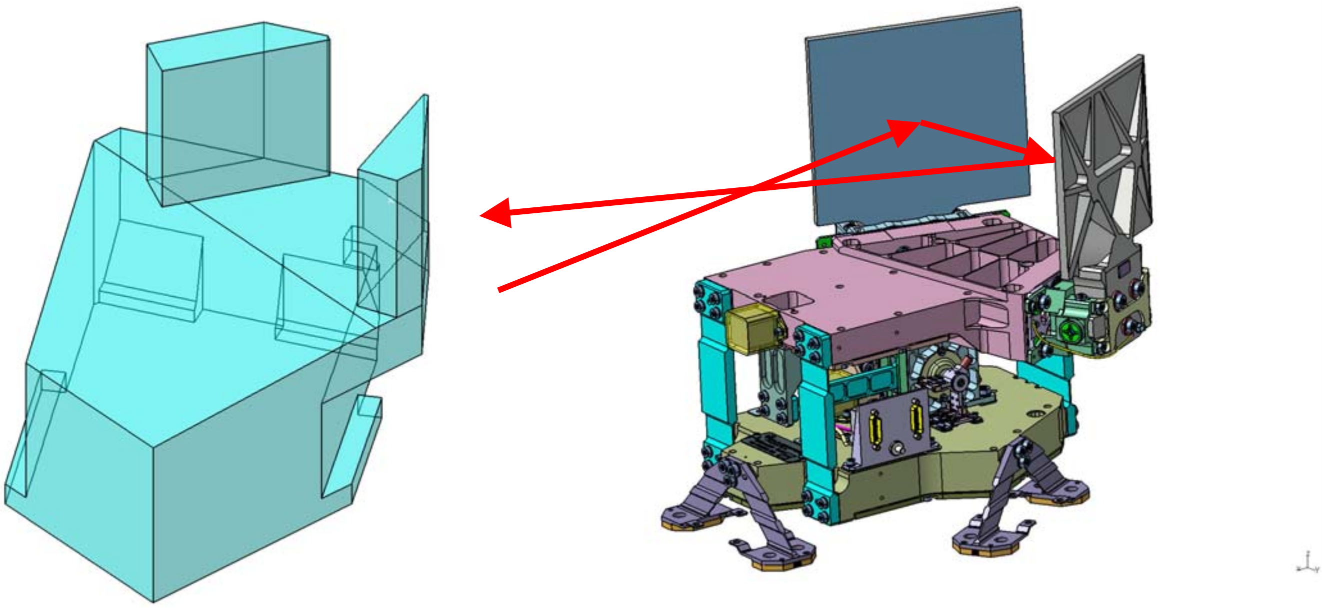

Figure 2 RMA isometric view with input and output beams (right) compared to the specified envelope (left)

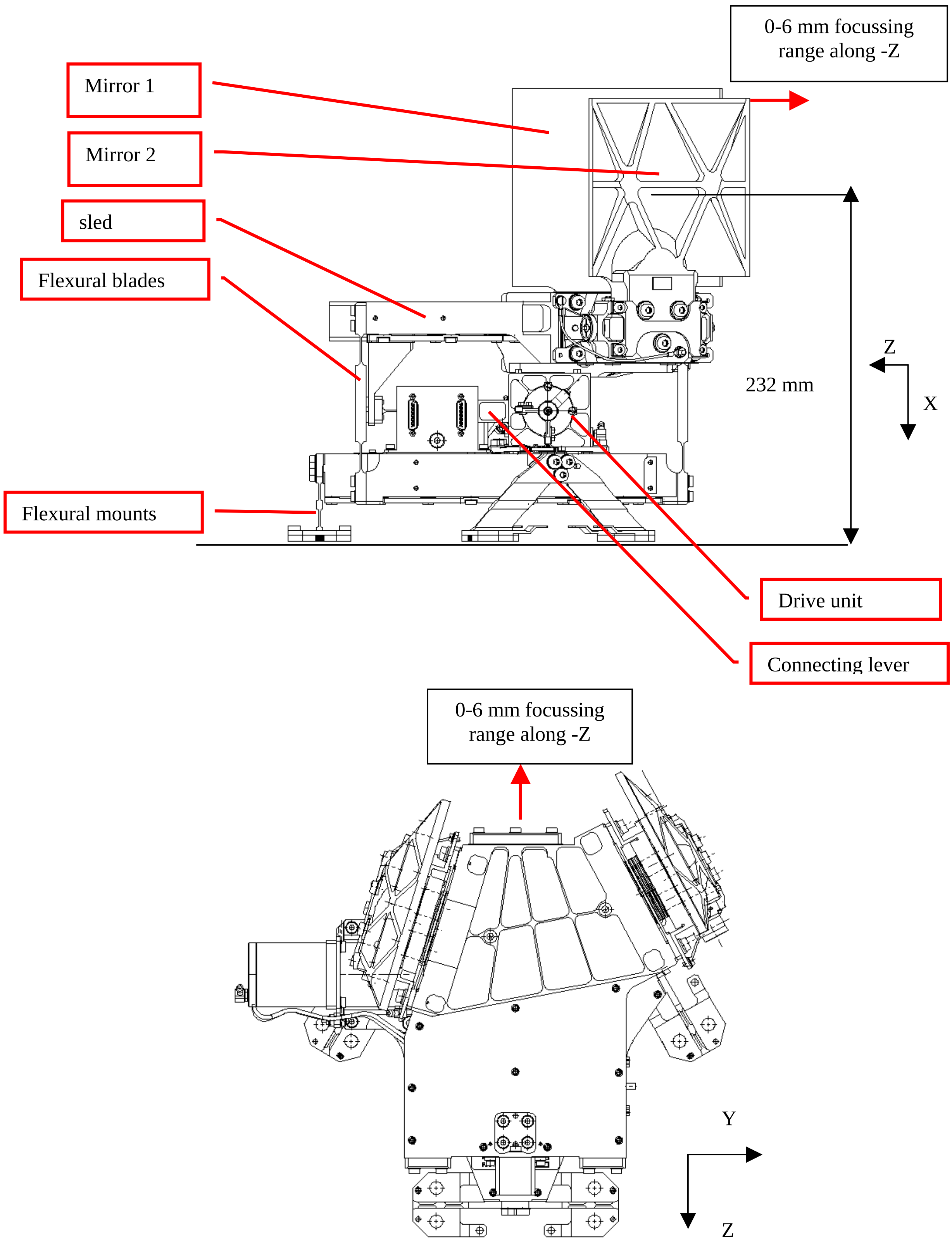

Figure 3 RMA mechanism lateral and top views

When in orbit, the drive mechanism rotates the eccentric camshaft of about 90deg corresponding to 3 mm sled translation. This corresponds to the nominal focus position (Fig.4b). The maximum stroke of 6 mm is obtained by rotating the shaft of 180deg, as shown in Fig.4c.
The crank-lever solution has the advantage to allow smooth and precise sled movement. Furthermore it avoids implementing a dedicated launch lock device. Infact in launch configuration the lever and the cam radius are co-aligned as shown in Fig.4a thus obtaining an intrinsic constraint against motion along the focussing direction.
Conventional materials have been chosen for the optics and the structural parts to reduce development risks: mirrors are in Zerodur and most of structural parts are in Titanium alloy. Invar has been chosen only for the pseudo-isostatic mounts and for the bracket which interfaces the Zerodur mirrors to the titanium sled.

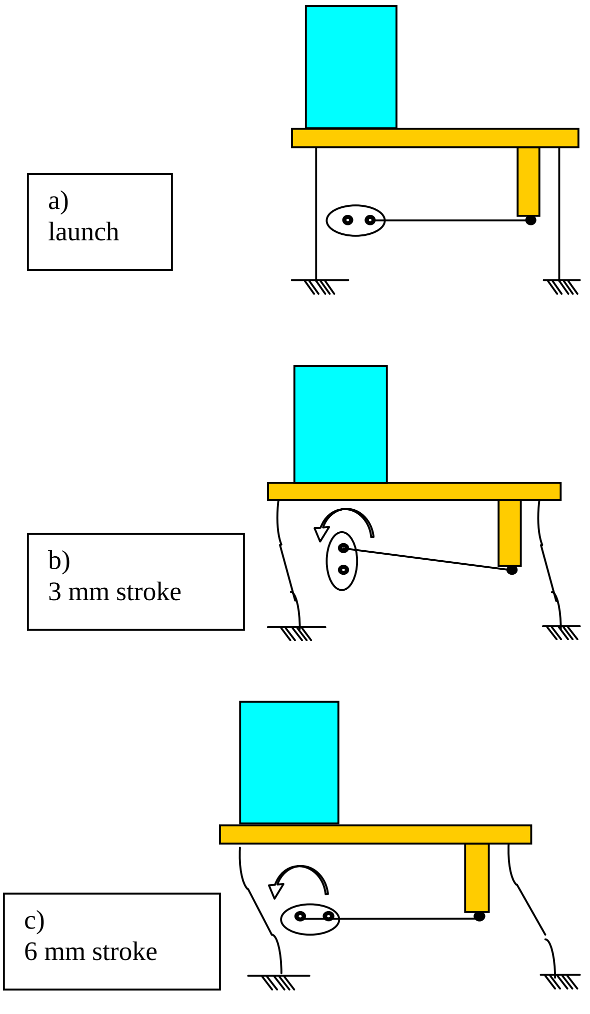

Figure 4 sketch of RMA operation

2.1. Mirrors and mount

Both mirrors are made of Zerodur. Their dimensions are respectively 127 by 142 mm for mirror n°1 and 114 by 117 mm for mirror n°2. The mirror mount design was deeply complicated because, due to envelope constraints, no clamping was allowed in the mirror back face close to its center of mass. The mount had to be designed in the mirror lower part as shown in Fig. 2, so that the mirror is supported in a cantilever configuration.
The design of the mirror mounts to the sled has been one of the most difficult and time consuming tasks of the project. The concept is based on elastic (spring) preloading of the mirror hub against a special bracket made of Invar; the bracket is in turn fixed to the sled by flexural mounts. Deep analyses have been implemented to predict the mirror optical distortions under the mount and thermal loads. The results showed that the mirrors wavefront error complies with the requirements.

2.2. Structure

The parallelogram movement is obtained by three flexural blades (Fig. 5) which also must have a strong structural function to support the sled and mirrors. Infact the total moving mass to be supported is higher than 3.3 Kg with a center of mass positioned very distant from the lower RMA bench. The hard structural constraints and the cryogenic temperature led to select titanium as material for the sled, the blades and the bench. The blades dimensioning and layout were carefully traded-off and finally brought to the configuration of two blades positioned in front and a single blade, yet functionally and structurally equivalent to the two front ones, positioned in the rear part of the RMA.

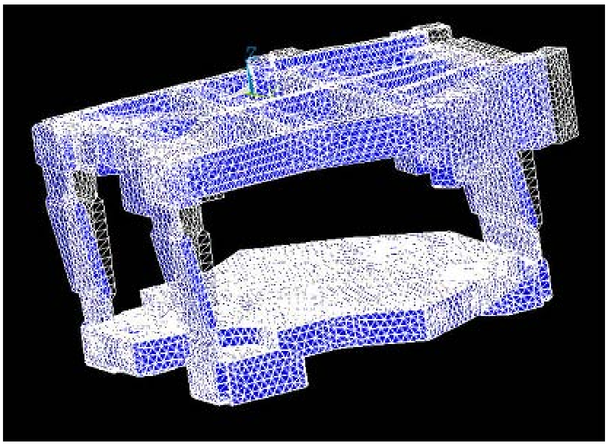

Figure 5 – Flexural blades layout

Each of the two front blades is 134 mm long, 30 mm width and with two flexural sections of 1 mm . The rear blade is equivalent to the front ones except its width which is doubled.

The blade design has been optimized since their elastic force has to be minimized to reduce the power needed to the motor. On the other hand their lateral stiffness must be very high to limit the mirrors lateral shifts and tilts when the RMA is operated on ground with 1g along the lateral direction.
The RMA bench also supports the drive unit, the static parts of the position sensors, a reference optical cube and the connector bracket.
The three mount bipods are positioned in such a way to minimize the optical axis shift from ambient to cryogenic temperature. They are made of Invar to cope with the CTE of the NIRSpec bench. Adjusting shims are foreseen to align the mechanism during integration.

2.3. Drive Mechanism

The drive mechanism is composed of:

- a cryogenic geared stepper motor, developed on the base of a standard vacuum-cryogenic motor design;
- a flexible coupling, specifically developed for the RMA project by the vendor;
- a cam shaft-connecting lever assembly (Fig. 6).

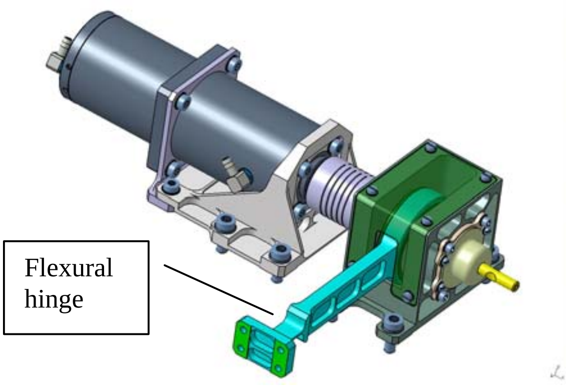

Figure 6 Drive Mechanism

The cam eccentricity of 3 mm provides the required 6 mm linear stroke with a 180 deg rotation of the shaft.
The cam shaft is supported by a couple of angular contact bearings. The lever is mounted to the cam through a single radial ball bearing and on the opposite end it is linked to the sled by means of a thin flexural-hinge segment, integral to the lever (Fig. 6).
A peculiar feature of this solution is that at launch the lever axis passes through the cam shaft axis so that the launch inertial forces transmitted by the sled through the connecting lever do not create a backdriving torque on the motor. This characteristics is used to avoid a dedicated locking mechanism along sled motion direction.
Due to the large thermal drop between ambient and 30K the drive mechanism geometry, tolerances, and materials have been designed to limit the differential dilatations to the minimum. The axial distance between the two angular contact bearings has been minimized. Either the flex coupling, the cam shaft and the housing are in titanium. Bearings are in steel but their mounting tolerances have been calculated to avoid barrelling effects or axial preload increase at cryogenic temperature.
The resistant torque in orbit is due to the flexural blades spring force and to the friction of the bearings. The higher contribution is the spring force which has been calculated taking into account the Young's modulus of titanium alloy at 30 K. The maximum spring force at cryogenic temperature, for the maximum sled stroke of 6 mm, is about 230 N. Yet, due to the cam-lever kinematics, the maximum resistant torque to the gear is for a cam rotation of 120 deg, i.e. for a sled stroke of 4.5 mm (Fig. 8). The sum of the torques generated by spring forces and friction, multiplied by the ECSS margins results in a maximum of 1300 Nmm.
The selected gear has a ratio of 184:1 and it can provide the required torque with a current of 60 mA at a speed of 100 steps/sec.

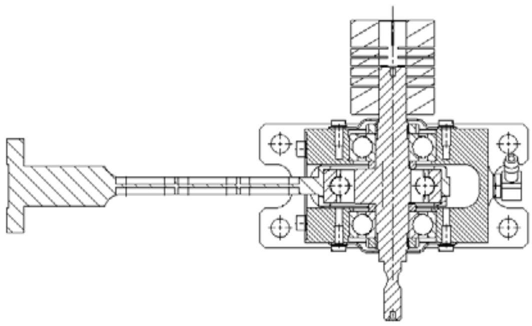

Figure 7 Cam-lever mechanism section view

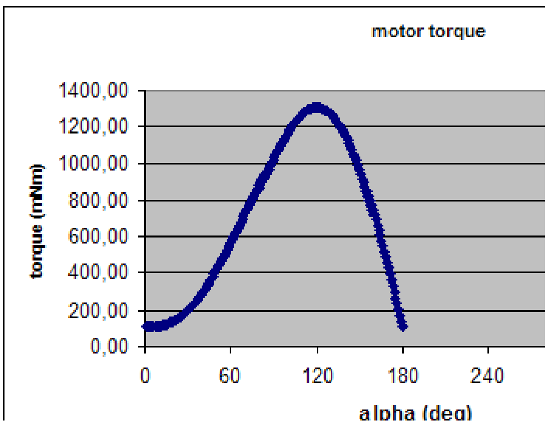

Figure 8 Torque vs. cam shaft rotation

Finally the needed gearmotor backdriving torque has been carefully calculated either in launch and in operating condition. The backdriving torque provided by the unpowered gearmotor is sufficient to maintain the sled in position against both conditions, the loads during launch and the blades elastic force when RMA is operating, with a large margin.

2.4. Bearings

The cam shaft is supported by a couple of angular contact bearings and the lever by a radial ball bearing.
The operational duty cycle is composed of different "reconfiguration cycles" corresponding to a translation of the sled to a certain offset position followed by a secondary cycling of very small oscillations (50 and 100 microns) around the offset position. Corresponding to this required sled motion, the bearing motion profile comprises oscillatory cycles, followed by a larger angle movement and more oscillatory cycles. Fig.9 provides details of the large angle and small angle movements. Typically, the large angle movements are from approximately 2.8 to 30 degrees. At each large angle, the bearings dither ten times around small angles, typically of approximately 1 degree.
Notwithstanding the complicate cycling, the overall life linearized stroke in orbit results in less than 300 mm.
After an extensive design trade-off it has been decided an hard preload mount of the angular contact bearings. Infact the presence of the axial constraint given by the lever could compromise the free axial sliding capability of the shaft. The hard preload mount has been carefully designed by accurate control of axial and radial tolerances.

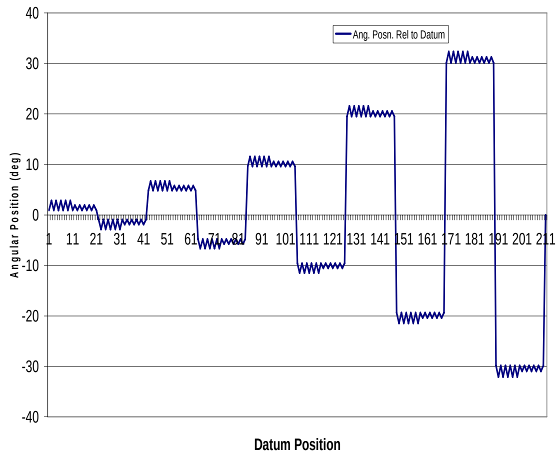

Figure 9 bearings duty cycle

A number of bearing and lubricant types were approached in order to identify the optimum solution. Lubrication is based on application of sputtered MoS_2 to balls and raceways together with the adoption of a PTFE- glass fibre-MoS_2 composite cage.
Advantage of sputtered MoS_2 applied to balls and races is that frictional torque at cryogenic temps will not change as the friction coefficient of MoS_2 is the same as at room temperature down to 20K or below.

2.5. Position sensors

Two sets of redundant Hall Effect Sensors (HES) (Fig.10) will monitor the cam shaft positions corresponding respectively to the launch and the nominal focus (mid stroke).
The HES sensors are positioned in stationary part on the RMA bench. The actuating magnets are fixed to the shaft and during rotation they actuate the sensors. A wheel with two arms placed at about 90° is mounted on the rotating shaft. Each arm provides support to two small magnets which excite the sensors placed in stationary part. One arm is in correspondence of the launch position, the other arm is for the nominal focus position. Each magnet can be finely adjusted in position with respect to the HES, independently from each other.
Each couple HES/magnet will be aligned in order to give the maximum or minimum (depending on the magnet polarity) voltage exactly in the position to be detected, either launch and mid stroke (nominal focus).
A simple maximum searching software algorithm applied to the HES output signal will guarantee that the position has been reached.
The HES are supplied by the vendor already mounted on a ceramic platelet of about 7 mm by 3 mm and they have been positively qualified for the cryogenic ambient.

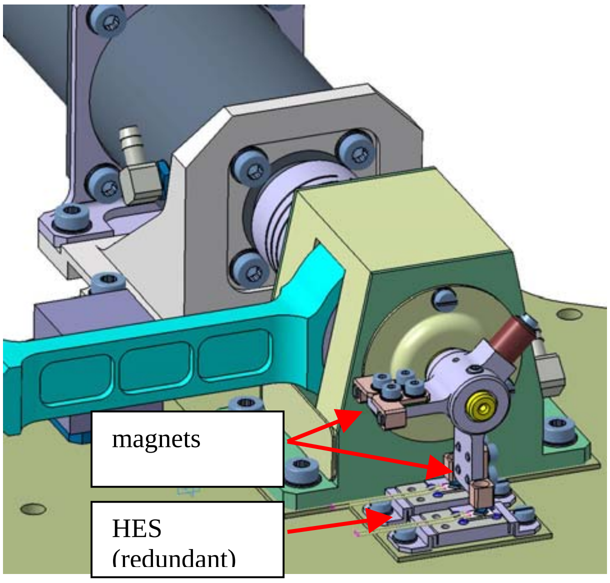

Figure 10 HES sensors in stationary and rotary part

3. ENGINEERING MODELS AND TESTS

3.1. Mechanism parallelogram EM

An engineering model of the flexural parallelogram has been tested. In Fig. 11 it is visible the EM (right), the dynamometer to apply and measure the force needed to perform the 6 mm stroke, and theodolites and micrometers to measure the sled lateral shifts and tilt during the motion.

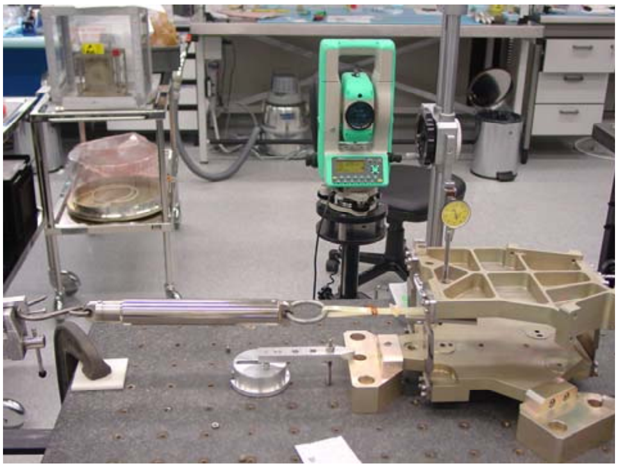

Figure 11 parallelogram EM test set-up

The measured elastic force exerted by the blades is about 200 N max for 6 mm stroke. The transverse stiffness resulted in 5000 N/mm, corresponding to a maximum sled lateral shift of 6 microns when 1g applied perpendicular to the direction of motion.

In the full stroke 0 to 6 mm the measured pitch and yaw of the sled was within 4 arcsec, and the roll was 8 arcsec. In the reduced stroke from 2 to 4 mm (more likely operative range around nominal focus) the sled measured pitch, yaw, roll are lower than the measurement accuracy of 4 arcsec, below the requirements.

3.2. Structural Model

A deliverable structural model has been manufactured and tested (Fig.12). It is representative of mass, envelopes, and main vibrational modes.
The SM has been vibrated at qualification random levels of about 7 grms along the three axes. Its mass is 6.4 Kg and the obtained first eigenfrequency is 158 Hz, versus a requirement of 140 Hz.

3.3. Drive Unit Test

A first unit of the gear motor has been succesfully submitted to a thorough characterization campaign as showed in Fig. 14. The vibration test at qualification level has been performed in order to evaluate also the gear-motor backdriving torque in a dynamic environment.

Figure 12 RMA structural model

For that purpose a dedicated set-up has been developed in order to apply on the gear shaft the same loads foreseen on the RMA during the launch phase. The gear-motor configuration for the test is shown in Fig. 13.

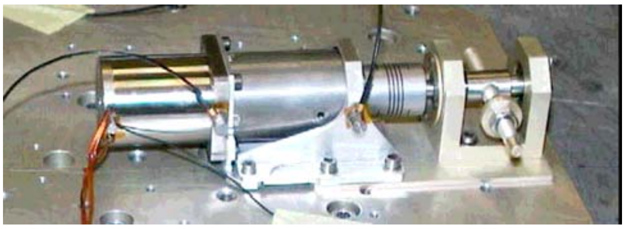

Figure 13 Gear Motor Vibration test configuration

The full qualification test program is in progress on a QM, taken from the same batch of the flight models.
Further details of the gear motor performance and qualification campaign will be provided in a future dedicated paper.

3.4. Future Tests

The full RMA QM will be subjected to an extensive test programme. Tests at operative temperature will be performed in a dedicated liquid helium thermal vacuum chamber specifically developed and installed at Galileo Avionica plant in Campi Bisenzio.

4. CONCLUSIONS

Galileo Avionica has developed a novel refocussing mechanism which includes two mirrors, operating at 37 Kelvin. Tests on EM of the flexural parallelogram structure have demonstrated its precision and stiffness.
A life test on the cryogenic stepper motor has been successfully completed.

Extensive tests have been also performed on the mirror mount assemblies, not reported in this paper.
A complete qualification model will be tested by end of 2007.

5. ACKNOWLEDGEMENTS

The work reported has been carried out under contract of EADS-Astrium (D) and coordinated by the ESA programme NIRSpec.
The cryogenic gear-motor is procured from Phytron (D).
The bearings selection and procurement has been subcontracted to ESR Technology (former AEA-ESTL).

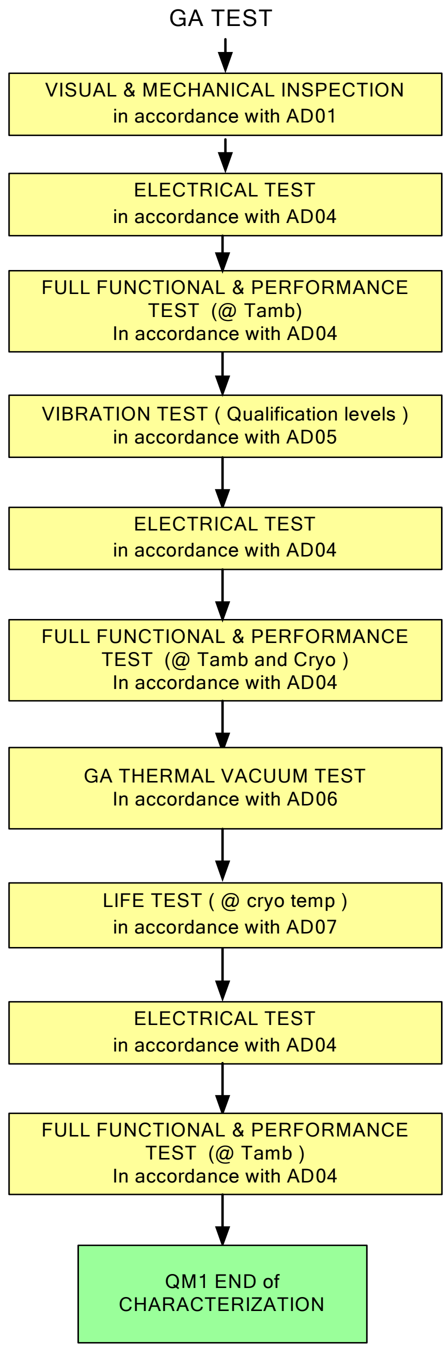

Figure 14 Gear Motor Test Flow