THE CRYOGENIC REFOCUSSING MECHANISM OF NIRSPEC - DESIGN VALIDATION BY TESTING OF THE QUALIFICATION AND LIFE TEST MODELS

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ABSTRACT

A novel cryogenic refocussing mechanism (RMA) has been designed by Selex Galileo 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 was 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.
This paper reports the verification campaigns carried out separately on the qualification model and on the life-test model in order to validate the RMA design, the main findings and lessons learned.
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.
NIRSpec is a near-infrared, multi-object, dispersive spectrograph, which will be operated at a temperature of 37 K in order to achieve the required sensitivity in the near-infrared spectral region. One of its subassemblies is the Refocusing Mechanism Assembly (RMA) which is needed to accommodate the changes of focus. This function is achieved by a rigid translation of two plane mirrors positioned at 45°, along the common axis of movement.
The NIRSpec prime contractor EADS-Astrium has commissioned the RMA to Selex Galileo (SG).

Figure 1 shows the actual configuration of the RMA.

It comprises:
- a support bench mounted on the NIRSpec optical bench via three pseudo-isostatic mounts;
- a sled mounted on the bench by means of three flexural blades;
- 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 operating temperature.
Three flexural blades are interposed between RMA bench and the sled, in the form of flexural parallelogram along the refocussing direction. The sled is actuated by a geared stepper motor connected to an eccentric camshaft and to a lever. In launch configuration the flexural parallelogram is not bended.
When in orbit, the drive mechanism rotates the eccentric camshaft of about 90deg corresponding to 3 mm of sled translation. That configuration is the nominal focus position. The maximum stroke of 6 mm is obtained by rotating the shaft of 180deg.
A detailed description of RMA is available in [1] and [2].

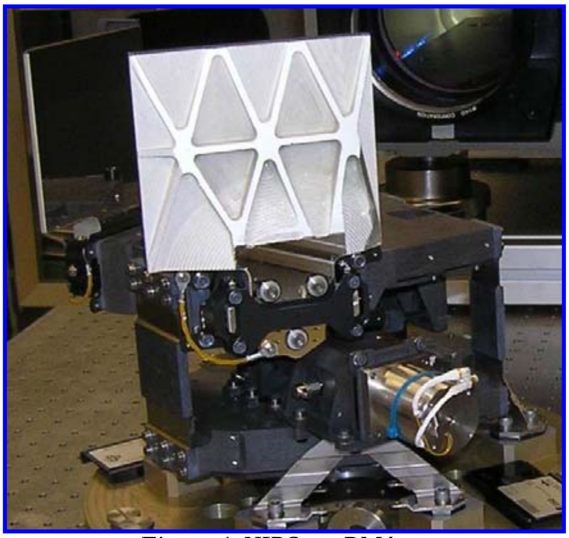

Figure 1 NIRSpec RMA

The RMA design has been submitted to verification and qualification testing using two models: the deliverable assembly qualification model (AQM) and the life test model (LTM). The latter was not envisaged at the beginning of the programme and it has been

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introduced in order to reduce the throughput time of the deliverable one.
The AQM is fully representative of the flight model for all the engineering, PA and built standard aspects. The AQM RMA test campaign has demonstrated that the equipment hardware functions within the technical specifications under simulated conditions at qualification level.
The LTM, instead, is representative from mechanical and electrical point of view. It has been assembled using the mechanical parts of the Flight Spare model and the motor used for qualification of the motor lot. This model has been submitted to a reduced test program including a life test.

2. QUALIFICATION TESTING

A qualification campaign according to ECSS-E-30 part 3A (standard for space mechanism) and based on the two models approach has been applied to the RMA taking into account the mission needs.
The test campaign foresaw Electromechanical functional and performance test, vibration, optical accuracy/stability, optical performance, EMC and life test.
The qualification philosophy and the related detailed tests sequence is reported in the following *Figures 2, 3* and *4.*
In addition a complete bake-out procedure at different integration stage and on both models have been performed to reduce the outgassing rate, due to the presence –even if limited – of polymeric materials within the main RMA subassemblies, and to improve the cleanliness level .

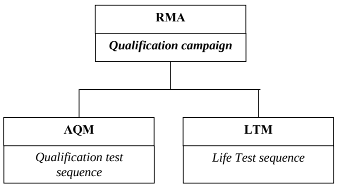

Figure 2 NIRSpec RMA qualification phylosophy

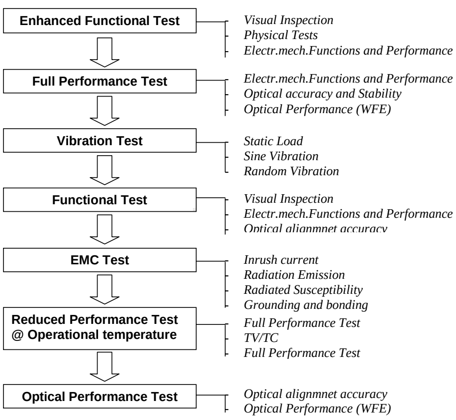

Figure 3 NIRSpec RMA qualification test sequence

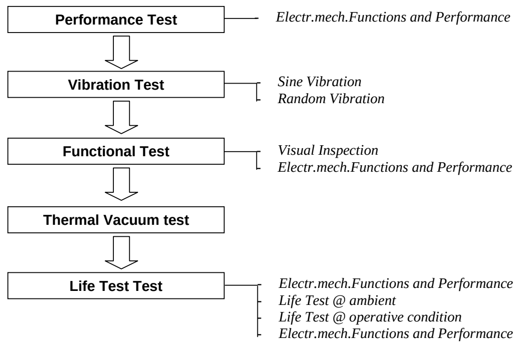

Figure 4 NIRSpec RMA Life Model test sequence

3. AQM QUALIFICATION TEST CAMPAIGN

3.1. Vibration

The RMA AQM has been subjected to a sinusoidal dwell dynamic, sine and random test to withstand the environmental load at qualification level. A notched input approach has been applied in order not to exceed the maximum design load at RMA COG of 30g.
The RMA AQM passed the tests successfully without any failure.
The RMA AQM on the vibration slip table at Selex Galileo is shown in *Figure 5* .

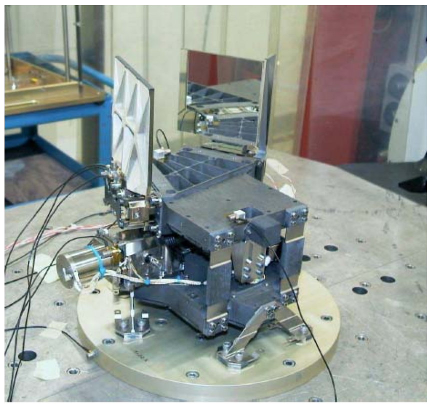

Figure 5 RMA AQM on the vibration table

3.2. EMC

The EMC tests verified design and performance under environments simulated in the laboratory according the specified requirements. Tests were carried out successfully apart for a “minor” non conformance related to the radiated emission.

3.3. Reduced performance test at operative condition

3.3.1. Thermal Vacuum test set-up

To have a representative mounting I/F to be used during the tests campaign a dedicated mechanical I/F has been designed and developed.
The mechanical I/F consist of:

1. A cold-pressed sintered Silicon Carbide Disk with a reference mirror;
2. A copper cylinder connecting the SiC disk with the thermal chamber plate.
3. A copper plate (I/F with the Thermal Vacuum chamber plate)

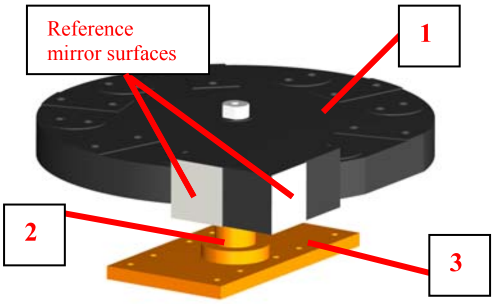

Figure 6 TV/TC mechanical interface

The Silicon Carbide disk is representative of the NIRSpec SiC optical bench. The disk central fixation allows the symmetric thermal deformation of RMA.

The adopted set-up has been supported by dedicated analysis.

3.3.2. TV/TC profile

The specified thermal cycling for RMA AQM was 8 cycles in vacuum between 22K and 323K. The actual thermal profile applied on the AQM is reported in *Figure 7*
The TV test has been performed in a dedicated Cryogenic Chamber at Selex Galileo premises.
In *Figure 8* is shown the RMA AQM in the Cryo chamber mounted on the representative mounting base plate.

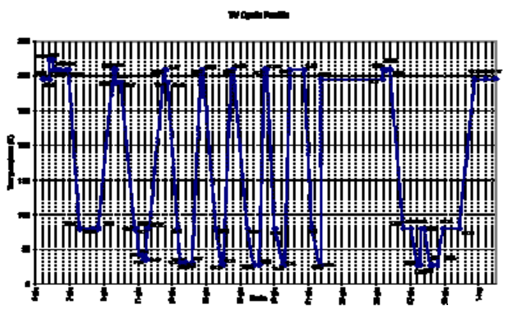

Figure 7 Actual thermal cycling applied on the AQM

The temperatures profile of the control and auxiliary sensors is reported in *Figures 9 and 10*

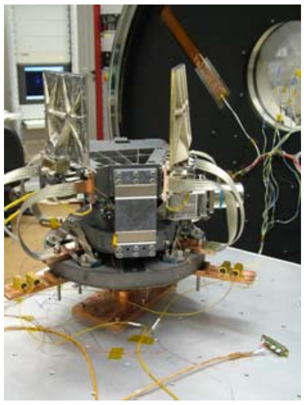

Figure 8 AQM TV/TC set-up

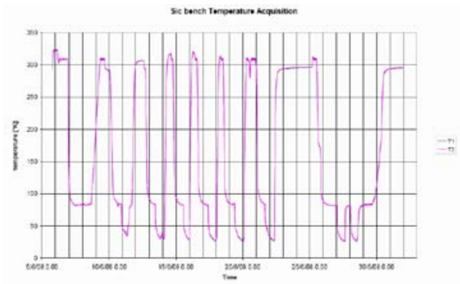

Figure 9 Control sensors temperature profile

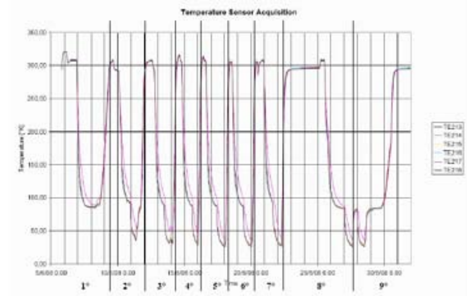

Figure 10 Auxiliary sensors temperature profile

The RMA AQM was subjected to a total of nine cycles (during the first of them only 80K was reached). The non operating temperature of 22K has not reached due to the low thermal conductance between the SiC plate and chamber plate.
In agreement with customer, the qualification for the non operating temperature has been postponed to the RMA-FM thermal cycling after introducing an improvement on the thermal set up.

3.4. Electro-Functional and performance Test

After having performed successfully the initial and intermediate verification (after vibration and EMC), the electro-functional and performance tests have been carried out during each of the foreseen operating phases of the thermal cycling. The following is the list of performed tests:

- Electrical tests
- RMA power measurements to verify the dissipation

- Motor drive test (including also the test harness) to verify the RMA functionality with different currents and step rates.
- Hall effect sensors and CERNOX temperature sensors input current reading to verify the fixed current provided to the sensor for each channel
- HES data acquisition around reference positions test to verify its functionality
- Mechanical stroke, step size and step accuracy test to verify the functional requirements of the RMA
- Relative Current Motorization Ratio test (RCMR) to verify the actuator capability to drive the RMA.

3.4.1. Electrical tests

These tests have been performed successfully at both ambient and operative conditions with the RMA standalone (with internal harness only) and with test harness (representative of flight harness).

The following measurements have been carried out:
-Measurement of the DC resistance between each connector shell to the RMA chassis (RMA standalone only).
-Measurement of the DC resistance between each shields and the connector shell (RMA standalone only).
-Insulation of each pins wrt chassis
-Motor resistance for both phases (main and redundant)
-Hall generators input resistance (main and redundant)
-Hall generators output resistance (main and redundant)
-Cernox sensors input resistance (main and redundant)
-Cernox sensors output resistance (main and redundant)

3.4.2. Motor drive test

This test has been carried out to verify the RMA operation, including "test harness", driving the motor with different current levels and step rates. These tests have been carried out at both Ambient Temperature (AT) and Operative Temperature (OT). The measured motor currents used in the following tests together with the corresponding resistance values measured during previous electrical tests contributed to the measure of power dissipation and calculation of the "Average sum of motor/sensors dissipation and ohmic harness losses " applying the duty cycle requirement.

The current values applied during this test are the max. values fulfilling ECSS torque margin.

Figure 11 shows the phase current of the geared hybrid stepper motor driven in full step mode.

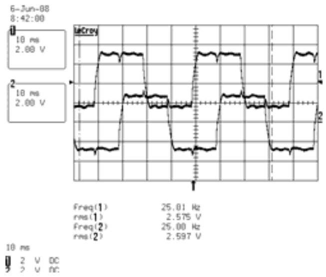

Figure 11 Motor current = 103 mA Step rate 100pps

3.4.3. Hall sensors and CERNOX sensors input current reading

This test has been carried out to verify the fixed current provided to Hall Effect Sensors (HES) and temperature sensors (CERNOX) for both main and redundant channels.

The measured HES and CERNOX currents involved in this test together with corresponding resistance values measured during electrical tests, including harness, contributed to the power dissipation and calculation of the "Average sum of motor/sensors dissipation and ohmic harness losses" applying the duty cycle requirement.

3.4.4. RMA Power Dissipation

Tables 1 and 2 show the RMA power dissipation at maximum operation temperature and at the minimum operating temperature respectively as measured in the previous tests (as per §3.4.1 and 3.4.2) for both main and redundant:

RMA TOTAL POWER @ Ambient Temperature and Top high (RM-599)					
RMA Component	Measured Power [mW]				Ambient Expected Value [mW]
TVTC test Phase :	Ambient Initial @ 294K	Top High first cycle @ 308K	Top High second cycle @ 308K	Ambient Final @ 294K	
MAIN					
Motor phase A Main	746 mW	746.16 mW	743.55 mW	715.37 mW	< 776 mW
Motor phase B Main	743 mW	741.7 mW	735.20 mW	706.33 mW	< 776 mW
HES Main	48.17 mW	48,72 mW	48.81 mW	48,03 mW	< 51.5 mW
TS CERNOX Main	0.000878 mW	0.000882 mW	0.000907 mW	0.000782 mW	< 0.00093 mW
TOTAL	1537.17 mW	1536.58 mW	1527.56 mW	1469.73 mW	< 1603.5 mW
REDUNDANT					
Motor phase A Red.	727 mW	742.84 mW	738.85 mW	707.45 mW	< 776 mW
Motor phase B Red.	725 mW	753 mW	746.41 mW	715.98 mW	< 776 mW
HES Red.	47.81 mW	47,39 mW	48.45 mW	47,71 mW	< 51.5 mW
TS CERNOX Red.	0.000883 mW	0.000886 mW	0.000888 mW	0.000709 mW	< 0.00093 mW
TOTAL	1499.81 3mW	1544.23 mW	1533.71 mW	1471.14 mW	< 1603.5 mW

Table 1 Power dissipation at top high temp.

RMA TOTAL POWER @ Operative Temperature - (RM-599)					
RMA Component	Measured Power [mW]	Avg. Power Power x Dcycle [mW]	Measured Power [mW]	Avg. Power Power x Dcycle [mW]	Expected value [mW]
TVTC test Phase :	Top Low first cycle @ 27K		Top Low second cycle @ 27K		
MAIN					
Motor phase A Main	282.57 mW	0.0093 mW	300.8 mW	0.00998	< 0.013 mW
Motor phase B Main	282.04 mW	0.0093 mW	304.4 mW	0.0101	< 0.013 mW
HES Main	47.22mW	0.00156 mW	47.34 mW	0.00157	< 0.0017 mW
TS CERNOX Main	0.000037mW	neglibile	0.00388mW	neglibile	Negligible
TOTAL	611.83 mW	0.02031 mW	652.54 mW	0.0216 mW	< 0.027 mW
REDUNDANT					
Motor phase A Red.	280.78 W	0.0093 mW	295.7 W	0.009817	< 0.013 mW
Motor phase B Red.	276.81 mW	0.0091 mW	300.7 mW	0.00998	< 0.013 mW
HES Red.	46.93 mW	0.00155 mW	46.99 mW	0.00156	< 0.0017 mW
TS CERNOX Red.	0.000032 mW	neglibile	0.00351mW	neglibile	Negligible
TOTAL	604.52 mW	0.02007 mW	643.39 mW	0.0214 mW	< 0.027 mW

Table2 Power dissipation at minimum temp.

3.4.5. HES data acquisition around launch and nominal focus positions

This test allows the acquisition of the HES signals around both launch and nominal focus positions. It verifies the functionality of HESs used to define the two reference positions (launch and mid-stroke/nominal focus) through a max. signal seek algorithm.

This test has been carried out at both ambient (AT) and minimum operative temperature (mOT) and for main and redundant channels. Figures from 12 to 15 show the HES signals.

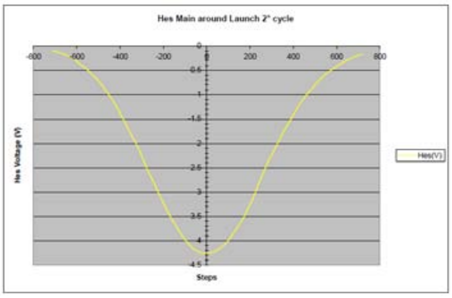

Figure 12 HES signal (main) around Launch position at mOT

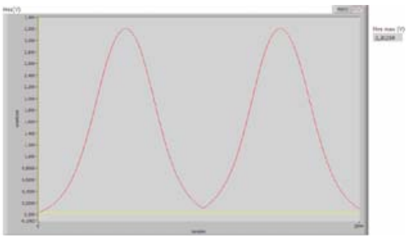

Figure 13 HES signal (main) around mid-stroke position at AT (two acquisitions)

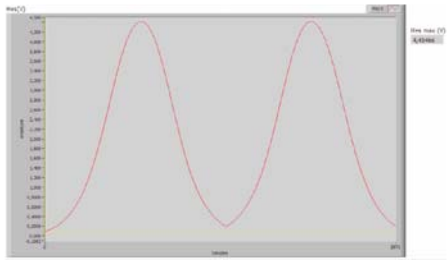

Figure 14 HES signal (main) around mid-stroke position at mOT (two acquisitions)

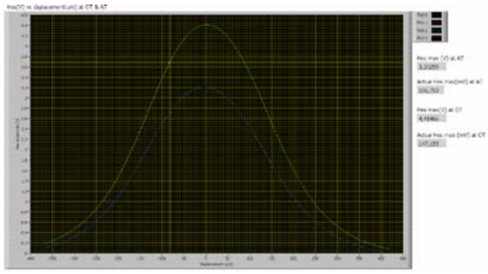

Figure 15 HES voltage vs. displacement at AT and mOT on the same diagram (main)

3.4.6. Mechanical stroke and step size test

This test verifies the mechanical stroke and step size of the RMA. It has been carried out at both AT and mOT. According to *Figure 16*, for a commanded *ΔZ* displacement a relevant *ΔZ1* displacement has been measured using a Zygo displacement measuring interferometer.
The relationship between *ΔZ* and *ΔZ1* is known as the *δ1* angle has been measured during RMA AQM optical test.

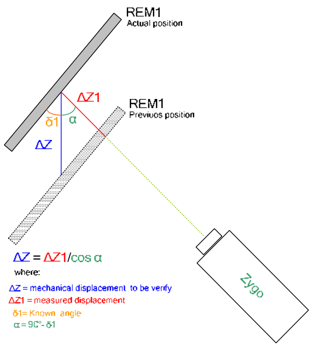

Figure 16 Set-up for displacement measurement in TVC

Table 3 reports the results of measurements at mOT and AT.

Mechanical stroke and step size test (2) RM-915 ; RM-919							
Test step n	Displacement ΔZ expected	Displacement ΔZ 1 Expected	Displacement ΔZ1 measured	Test step n	Displacement ΔZ expected	Displacement ΔZ 1 Expected	Displacement ΔZ1 measured
TVTC test Phase :	Top Low second cycle @ 27K			Ambient Final @ 294K			
18	3 mm ±50µm	0.86874 mm ± 14.5µm	- 0.8621 mm	18	3 mm ±50µm	0.86874 mm ± 14.5µm	- 0.868194 mm
23	6 mm ±50µm	1.73748 mm ± 14.5µm	- 1.726 mm	23	6 mm ±50µm	1.73748 mm ± 14.5µm	-1.7218 mm
27	3 mm ±50µm	0.86874 mm ± 14.5µm	-0.8605 mm	27	3 mm ±50µm	0.86874 mm ± 14.5µm	-0.8672 mm
39	15 µm	4.34µm	OK	39	15 µm	4.34µm	OK

Table 3 – Mechanical stroke and step size test results

3.4.7. Step Accuracy test

This test verifies the RMA displacement accuracy requirement (±50 µm) and it has been carried out for both AT and mOT.

It verifies the positioning accuracy around three offset positions:

1. Offset = 0 µm (around mid-stroke position)
2. Offset = +1500 µm
3. Offset = -1500 µm

For each offset position 5 reconfigurations of ±100 µm and ±50 µm have been applied and measured with the Zygo interferometer (*Figures 17, 18* and *Table 4)*.

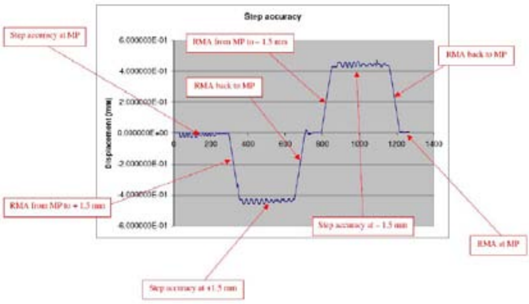

Figure 17 Displacement measurement during "Accuracy test" at AT

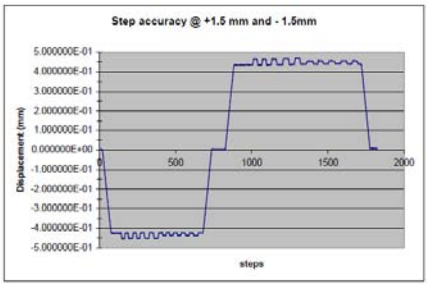

Figure 18 Displacement measurement during "Accuracy test" at mOT

Step Accuracy test - RM-920							
Test step n	Displacement ΔZ expected	Displacement ΔZ 1 Expected	Displacement ΔZ1 measured	Test step n	Displacement ΔZ expected	Displacement ΔZ 1 Expected	Displacement ΔZ1 measured
TVTC test Phase :	Top High first cycle @ 308K			Top Low first cycle @ 27K			
13	3 mm ±50µm	0.86874 mm ± 14.5µm	- 0.85683 mm	13	3 mm ±50µm	0.86874 mm ± 14.5µm	-8.644 mm
32	100µm ±50µm	29 µm ± 14.5µm	Ok see relevant plot in the test reports	32	100µm ±50µm	29 µm ± 14.5µm	Ok see relevant plot in the test reports
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	
	100µm ±50µm	29 µm ± 14.5µm			100µm ±50µm	29 µm ± 14.5µm	
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	
	100µm ±50µm	29 µm ± 14.5µm			100µm ±50µm	29 µm ± 14.5µm	
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	
TVTC test Phase :	Top High second cycle @ 308K			Top Low second cycle @ 27K			
13	3 mm ±50µm	0.86874 mm ± 14.5µm	See mech stroke	13	3 mm ±50µm	0.86874 mm ± 14.5µm	See mech stroke
32	100µm ±50µm	29 µm ± 14.5µm	Ok see relevant plot in the test reports	32	100µm ±50µm	29 µm ± 14.5µm	Ok see relevant plot in the test reports
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	
	100µm ±50µm	29 µm ± 14.5µm			100µm ±50µm	29 µm ± 14.5µm	
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	
	100µm ±50µm	29 µm ± 14.5µm			100µm ±50µm	29 µm ± 14.5µm	
	50µm ±50µm	14.5 µm ± 14.5µm			50µm ±50µm	14.5 µm ± 14.5µm	

Table 4 – Step accuracy results

3.4.8. Relative Current Motorization Ratio test (RCMR)

The RCMR is defined as the percentage ratio between minimum current able to drive the motor without loosing steps and the max. current available to drive the motor. In order to verify the RCMR, the minimum current able to drive the RMA with the requested accuracy has been found.

This test has been carried at both AT and mOT (*Figure 19* and *Tables 5* and *6)*.

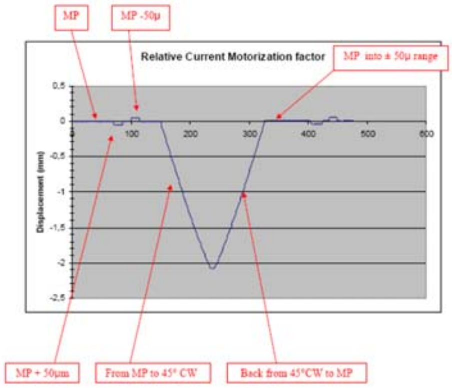

Figure 19 RCMR sequence.

Relative current motorization ratio test (1) RM-654							
I_{MAX} [mA]	I Nom [mA]	Vhes @ Nom [V]		I [mA]	Vhes @ I [V]		Mr (I-Imax)/Imax*100 [%]
TVTC test Phase :	Ambient Initial @ 294K						
107 @ AT	97	Vhes @ refocus + 50µm	+ 2.982 V	45	Vhes @ refocus + 50µm	+ 2.982 V	57.94
		Vhes @ refocus	+ 3.193 V		Vhes @ refocus	+ 3.192V	
		Vhes @ refocus - 50µm	+ 3.171 V		Vhes @ refocus - 50µm	+ 3.029 V	
TVTC test Phase :	Top High first cycle @ 308K						
107 @ AT	97	Vhes @ refocus + 50µm	+ 2.971 V	45	Vhes @ refocus + 50µm	+ 3.042 V	57.94
		Vhes @ refocus	+3.186 V		Vhes @ refocus	+ 3.181 V	
		Vhes @ refocus - 50µm	+ 3.022 V		Vhes @ refocus - 50µm	+ 2.940 V	

Table 5 RCMR test results (initial)

Relative current motorization ratio test (3) RM-654							
I_{MAX} [mA]	I Nom [mA]	Vhes @ Nom [V]		I [mA]	Vhes @ I [V]		Mr (I-Imax)/Imax*100 [%]
TVTC test Phase :	Top Low second cycle @ 27K						
132 @ OT	122	Vhes @ refocus + 50µm	+ 4.132 V	55	Vhes @ refocus + 50µm	+ 4.132V	58.33
		Vhes @ refocus	+ 4.419V		Vhes @ refocus	+ 4.420V	
		Vhes @ refocus - 50µm	+ 4.169V		Vhes @ refocus - 50µm	+ 4.171V	
TVTC test Phase :	Ambient Final @ 294K						
107 @ AT	97	Vhes @ refocus + 50µm	+2.995 V	50	Vhes @ refocus + 50µm	+ 2.995 V	53.27
		Vhes @ refocus	+ 3.203 V		Vhes @ refocus	+ 3.203V	
		Vhes @ refocus - 50µm	+ 3.016 V		Vhes @ refocus - 50µm	+ 3.017 V	

Table 6 RCMR test results (final)

3.5. Optical performance tests

From an optical point of view the RMA is an all reflective pentaprism equivalent (*Figure 20*). After two reflections the incoming beam is deviated by 90° and when the two mirrors are displaced, as result of the mechanism movement, the orientation between incoming and outgoing beam directions remains unchanged. Due to the variation of the optical path length between different mechanism positions, the assembly can be used to adjust the focus position of NIRSpec within a range of few millimetres.

Many optical tests have been performed at sample and at mirror level to identify and confirm the best design solution and to select the mirrors for the flight models.

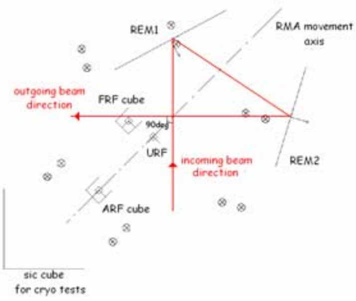

Figure 20 RMA layout

These tests, mentioned in *Figure 21* for completeness, are not discussed because this paper is focussed on the campaign validation of the mechanism.
The optical validation of the RMA can be divided in two different kinds of test aiming at:

- alignment verification between incoming and outgoing beam direction
- measurement of degradation of the instrument wavefront error (WFE) due to the mirror surface errors

Both aspects require dedicated test setup for the verification at ambient and operative temperatures.
These tests are briefly described and the major findings and lessons learned during the measurement campaign of the AQM model are reported.
It has to be noticed that the two mirrors assembled on RMA AQM are not of the required WFE quality. The verification of the mirrors WFE has been carried out separately, following a specific test flow at mirror assembly level.

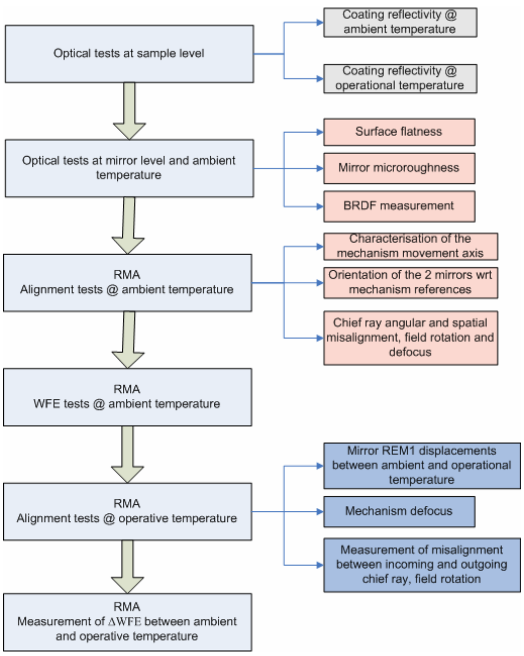

Figure 21 Optical tests at sample, mirror and RMA level

3.5.1. Alignment verification at ambient temperature

After assembly the position of each mirror with respect to the mechanism reference frames is measured with a 3D machine with an accuracy of few microns. The orientation of the mirrors with respect to the reference cubes is measured with a theodolite.
If these measurements indicate a wrong orientation the two mirrors are dismounted and a proper shimming is applied to adjust the mirror orientation.
After these preliminary checks two theodolites are aligned, one along the nominal incoming beam direction and the second one along the outgoing beam direction (*Figure 22*). The misalignment between the two theodolites is a direct measurement of the alignment error introduced by the mechanism. Measurements are repeated for different mechanism positions to verify that the movement doesn't affect the alignment.

Figure 22 Alignment verification at AT

After the measurement of the angular error, one of the 2 theodolites is replaced with a cross reference target and the remaining theodolite is focussed in order to have a perfect alignment of the internal reticle with the target itself.
When the mechanism is moved, a very small displacement of the target image, corresponding to a maximum lateral misalignment between incoming and outgoing beams of about 10 µm has been measured.
The cross target was perfectly aligned for all the mechanism positions meaning that the field rotation introduced by the mechanism is negligible.
The characterization of the defocus introduced by the RMA with respect to the mechanism movement has been done with a displacement measuring interferometer. When the mechanism is moved the instrument can measure continuously the optical path change with a micrometric accuracy.
The main result of the alignment campaign at ambient temperature is that it is possible to reduce the misalignment within few arc seconds after a couple of iterations with different shims.
When the mirrors are correctly aligned, the misalignments introduced by the mechanism

movements are very small compared to the requirements.

3.5.2. Alignment verification at cryogenic temperature

The alignment verification set-up at operative temperature (*Figure 24*) is quite complex because it is required to perform simultaneously three different measurements:

1. the rigid body rotations and displacements of the RMA inside the thermal vacuum chamber
2. the displacements and rotations of at least one of the two mirrors
3. the misalignment between incoming and outgoing beam direction

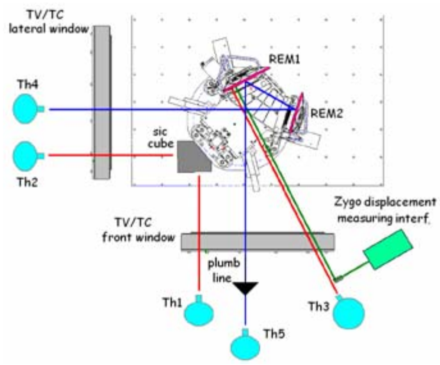

Figure24 Alignment verification set-up for TV cycling

The first one is a systematic error due to internal movements of the chamber during cool-down. It is measured with two theodolites (Th1 and Th2) looking at the reference SiC cube mounted on the RMA SiC interface plate.

The second one is needed to measure the mirror movements between ambient and operative temperature due to shrinkage of the mechanism. These movements are measured with a theodolite (Th3) in autocollimation with REM1 and with a Zygo displacement measuring interferometer.

For the third one the set-up is in principle the same of the ambient temperature test with two theodolites oriented along the incoming and outgoing chief ray.

The results obtained for the AQM mirrors tilts after removal of systematic errors are summarised in the following tables. HA is the horizontal angle measured by the theodolites and it is the angle between the mirror plane and the movement axis. VA is the vertical angle measured by the theodolites with respect to the gravity vector. In nominal conditions the surface normal of the two mirrors should lie in the same horizontal plane corresponding to a VA of 90°.

REM1	HA	VA
Measured	**16°50’11’’**	**89°59’38’’**
Nominal	16°50’09’’	90°00’00’’
Difference	0°0’2’’	0°00’22’’

Table 7 REM1 orientation at mOT

REM2	HA	VA
Measured	**28°09’51’’**	**89°59’32’’**
Nominal	28°09’52’’	90°00’00’’
Difference	0°0’1’’	0°00’28’’

Table 8 REM2 orientation at mOT

The values indicate a bending of the mirrors between warm and cold conditions of about 25”. The main impact of this bending is an out of plane deviation of the outgoing beam of about 1.5 arcmin.

The main lesson learned from the AQM campaign is that to compensate this cryogenic misalignment effect the mirrors need to be mounted at ambient temperature with an offset tilt of the opposite sign.

3.5.3. Measurement of ΔWFE between ambient and operative temperature

The wavefront error of the RMA changes between ambient and cryogenic temperature due to the tensions introduced by the CTE mismatch between the silver reflective coating and the mirror zerodur substrate.

The set-up for the measurement of the RMA WFE at cryogenic temperature is shown in the *Figure 25*.

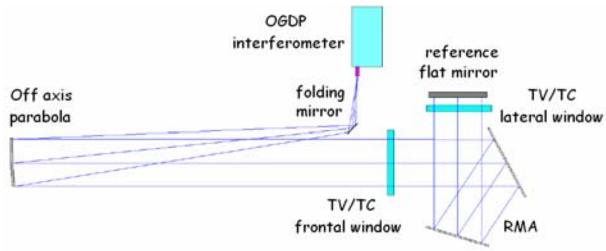

Figure 25 WFE test set-up at cryogenic temperature

The measurements are performed with a vibration insensitive interferometer developed by Selex Galileo. Due to the quite small aperture of the interferometer (~20 mm) the laser test beam is focussed and expanded by a 300 mm diameter off axis parabola and directed toward the RMA inside the chamber. A flat mirror is placed outside the chamber to fold back the test beam.

Due to the complexity of the test set-up with many optical elements each affecting the WFE, it is not possible to measure directly the RMA contribution at cryogenic temperature but it is necessary to compare the interferogrammes at ambient and operative temperature to obtain the ΔWFE between the two conditions.

The main lesson learned during the AQM campaign is that in order to reduce the uncertainty of the measurements a much simpler set-up is mandatory. In order to improve it a new Zygo GPI Flashphase interferometer has been procured and installed for the verification of the next RMA models. This instrument has very low sensitivity to vibration and large output beam aperture that allows using it directly in front of the RMA without additional optics.

4. LTM test campaign

4.1. Vibration

The RMA LTM has been subjected to a sine and random to withstand the environmental load using a notched input approach.
Tests has been performed at Selex Galileo premises and the RMA LTM passed the tests successfully without any failure.
The RMA on the vibration table is shown in *Figure 26*.

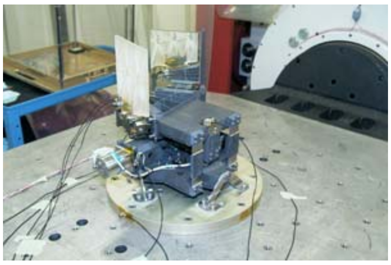

Figure 26 RMA LTM on the vibration table

4.2. TV test

For timing optimization it was decided to locate the LTM in the TV chamber together with the RMA AQM. For the purpose of the LTM TV testing it was without the mirrors assembly. The configuration adopted during the TV test is reported in *Figure 27*.

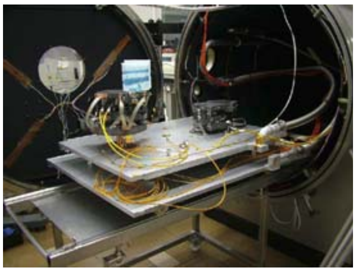

Figure 27 TV/TC configuration

Basing on the thermal cycling applied during the AQM testing, the temperature profiles of the LTM temperature sensors are reported in *Figure 28*.

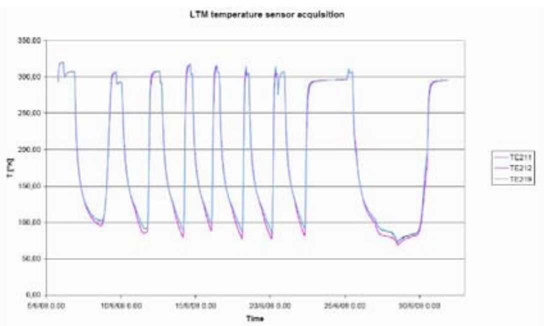

Figure 28 RMA-LTM temperature sensors

4.3. Life Test

This test demonstrated the capability of the mechanism to withstand the number of cycles/reconfigurations reported in *Table 9*.

		No. of reconfiguration		Reconfiguration average displac.	Type of Reconfig./cycle
		nominal	life test including ECSS margin	(mm)	
a) Ambient temperature		255	1620	2.82	A
		8	48	12	C
b) Cryo temperature (ground cycles)		103	612	2.82	A
		4	32	12	C
		18	72	10	B
c) Cryo temp. (in-orbit cycles)	1	74	356	10	B
	2	426	1704	10	B

Table 9 RMA environmental condition

It has to be noticed that the reconfigurations named C2 (1704) have to be considered as an "extended" life cycle. In fact they are not part of the RMA specification and they have been introduced just before starting with the test itself.

4.3.1. Reconfiguration/Cycle description

During the life test three different type of operations (reconfig./cycle) have been considered

Reconfiguration A
The RMA sled is positioned in 10 different offset positions in the range +/-1.5 mm, and perform 5 oscillation cycles of +/-100 microns and 5 oscillation of +/-50 microns around these offset positions as reported in *Figure 29*.

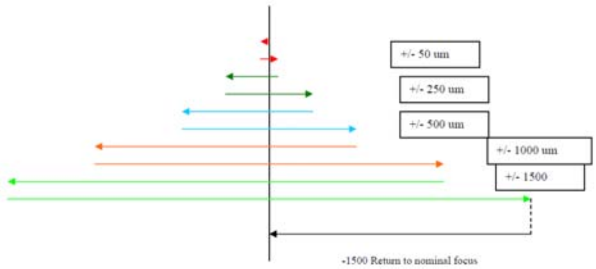

Figure 29 Reconfiguration A

Reconfiguration B
It consists in a RMA displacement of ±2.5mm about the nominal focus position, performed part in continuous motion and part at steps of 200µm.
The average stroke of one reconfiguration is 10mm

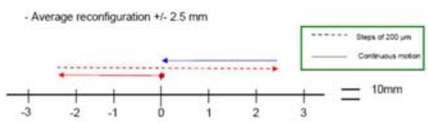

Figure 30 Reconfiguration B

Reconfiguration C
It consists in a RMA displacement of ±3mm about the nominal focus position, performed part in continuous motion and part at steps of 200µm.
The average stroke of one reconfiguration is 12mm.

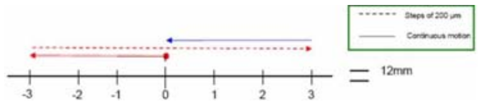

Figure 31 Reconfiguration C

The thermal profile applied during the Life test is reported in *Figure 32*.
The RMA LTM inside the TV chamber is shown in *Figure 33*. The REM2 mirror only is present while a representative dummy mass has been used in place of REM1 mirror.

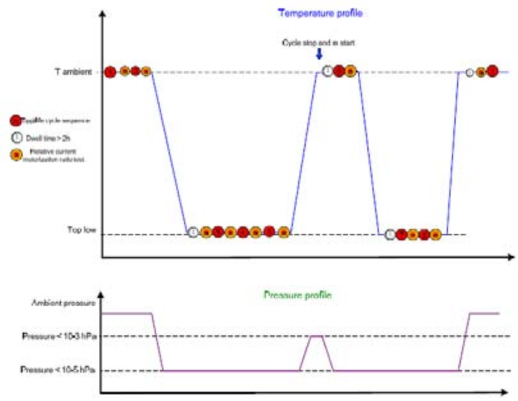

Figure 32 – LTM Temp. and pressure profile

During each phase (from 1 to 7) the following tests have been performed:

1. Initial and Final Functional and performance test
   - Power dissipations measurements
   - Mechanical stroke and step size
   - Relative Current Motorization Ratio test
2. Ambient temperature test sequence: Phase “a” of table 9
3. Minimum operating temperature test sequence (ground cycles): phase “b” of table 9
4. Minimum operating temperature test sequence (in-orbit nominal cycles): phase “c-1” of table 9
5. Minimum operating temperature test sequence (in-orbit extended cycles): Phase “c-2” of table 9

   During phase c-2 the RCMR test have been performed about every 200 cycles.
6. Intermediate @AT test: RCMR test
7. Intermediate @mOT test: RCMR test

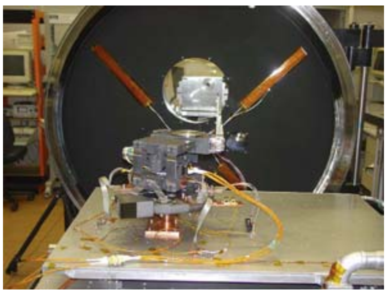

Figure 33 LTM TV/TC set-up

4.4. Life test results

The test results are summarized in Table 10 and *Figure 34*.

		Type of Reconf./Cycles	N° of Reconfig./Cycle	Motors steps (*1) Partial [n]	Motors steps (*1) Total [n]	Average Motor revolution (*2) Partial [n]	Average Motor revolution (*2) Total [n]
a) Ambient Temp.		A	0	67'786		338.93	
			450	2'660'717		13'303.59	
			900	1'737'704		8'688.52	
				981'379		4'906.90	
			1350	2'654'467		13'272.34	
			1620	1'605'344		8'026.72	
		C	48	902'220		4'511.10	
				902'532		4'512.66	
				69'955	11'582'104	349.78	57'910.52
b) Cryo Temp. (ground cycles)		A	0	957'980		4'789.90	
			300	909'020		4'545.10	
			612	1'784'588	3'651'588	8'922.94	18'257.94
		C +B	32C + 72B	3'881'290	3'881'290	19'406.45	19'406.45
c) Cryo temp. (in-orbit cycles)	1	B	240	5'598'814		27'994.07	
			356	2'728'716	8'327'530	13'643.58	41'637.65
	2	B	260	6'126'361		30'631.81	
			400	3'156'271		15'781.36	
			700	7'003'016		35'015.08	
			820	2'840'552		14'202.76	
			950	3'056'962		15'284.81	
			1230	6'534'682		32'673.41	
			1360	3'055'144		15'275.72	
			1360 (*3)	51'028		255.14	
			1360 (*3)	102'234		511.17	
			1380	563'428		2'817.14	
			1670	6'806'733		34'033.67	
			1670(*4)	71'229		356.15	
			1670(*5)	56'358		281.79	
			1704	863'602		4'318.01	
			1704(*6)	218'456		1'092.28	
			1704(*7)	51'028	40'557'084	255.14	202'785.42
				Total	67'999'596	Total	339'997.98

Table 10 LTM No. of cycles and motor revolutions

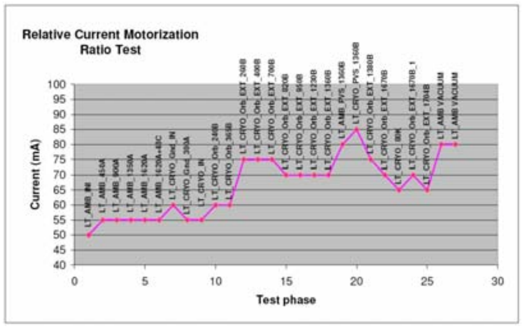

Figure34 Min. current behaviour during RCMR test

The results have been evaluated separately for:

1. “nominal” number of test cycles
2. “extended” life test (ref to § 4.3)

4.4.1. Nominal life test evaluation

The comparison of the measurements performed at beginning and at the end of the ambient and cryo–cycles of the “nominal” phase (reported in Table 11) shows that no degradation occurred on the RCMR.

Test Phase	RCMR (mA) Initial	RCMR (mA) Final
Ambient	55	55
Cryo	60	60

Table 11 RCMR results for nominal life test

Consequently, it can be stated that no increase of torque of the whole mechanical chain occurred during that phase.
Therefore the nominal life test has been successfully performed.

4.4.2. Extended life test evaluation

A significant change on the RCMR occurred during the “extended life test”, from 60 mA up to 85 mA at mOT. In addition it increased at AT from the initial value of 50 mA to the final one of 80 mA.

Together with EADS ASTRIUM and ESA it has been decided to perform the activities reported in the so called “post life test verification flow” (*Figure 35)* in order to evaluate the causes of that behavior.
The main result of all the evaluation steps is the degradation of RMA torque performance due to the lubricant deterioration of the gear-motor parts leading to some metal to metal contact.

Additional results of the post life test investigation are reported in [3], where details on the development of a new actuator, suitable to withstand the extended number of cycles, are also provided. It has to be noticed in fact that the extended number of cycles are now part of RMA specification.

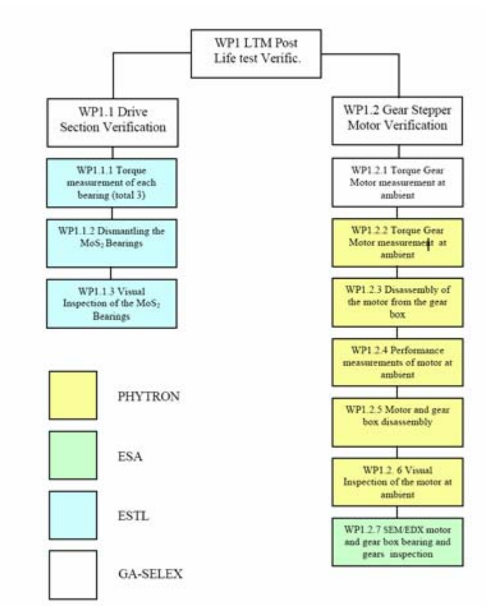

Figure35 Post Verification after Life Test

5. CONCLUSIONS

The testing activities carried out on RMA AQM and LTM confirmed the suitability of the RMA design to satisfy most of the relevant requirements. Only few of them needs to be addressed as delta-qualification to be performed in the frame of the acceptance test of RMA FM/FS. In particular it has been pointed out the improvement to be introduced in the following areas:

- thermal vacuum test set-up in order to reach the minimum non operating temperature and to have a better accuracy in the WFE measurement;
- alignment of RMA mirrors at ambient temperature to compensate the cryo-deformation;
- gear-motor to fulfil the extended number of life cycles, included in the RMA specification only after the completion of the life test.

6. ACKNOWLEDGEMENTS

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Several people gave fundamental contribution to the development of this work. Our thanks to Maurizio Giustini, Adelmo Scarpelli, Alessandro Donati, Stefano Perferi and Fulvio Grifoni.

7. REFERENCES

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[3] Hans Jürgen Jung et al., “Extreme Fast Development of a Cryo Actuator”, 13th ESMATS September 2009– ESA-SP653