GAIA M2M POSITIONING MECHANISM

Eduardo Urgoiti [(1)], **Argine Ramirez** [(1)] , **Pierre Coste**[(2)]

[(1)] *SENER-Structures & Mechanisms Section, Av. Zugazarte 56, 48930 Las Arenas (Vizcaya) Spain*
Tel: 34944817500 Fax: 34944817603 email: eduardo.urgoiti@sener.es
[(2)] *ESTEC. P.O. Box 299. 2200 AG Noordwijk, The Netherlands*

ABSTRACT

This paper presents the results from ESA technology preparatory program for Gaia Astrometric Mission to develop a Positioning Mechanism for the secondary mirror. The description of the design process from requirements and concept selection to presentation of verification activities and test results will be the scope of this paper.

1. INTRODUCTION

The GAIA Secondary Mirror Mechanism, M2M in short, is the link between the optical bench and the secondary mirror. It serves to provide adjustment capability, with sub-micrometer accuracy, of the M2 secondary reflector to ensure optical quality of the GAIA telescope from ground verifications to in orbit and operations. It has to recover the misalignments that can appear due to the launch effects and maintain the commanded position without power demand.

The M2M shall provide pointing capability in five dof, three translations and two rotations and maintain the position defined during system level TV tests from this event to the in orbit operational phase passing through the on ground, launch and in orbit transfer environment.

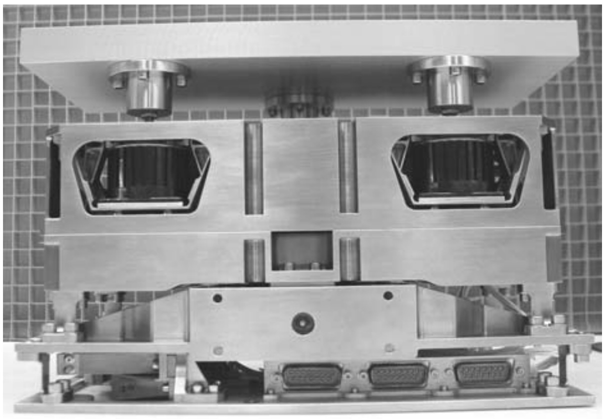


Fig. 1 Gaia M2M Positioning Mechanism and Mirror Dummy

The novelty of the mechanism resides in the small envelope, operational temperature of 120K and the capability to withstand launch environment without a Hold down and release mechanism maintaining the position from the on ground adjustment. This has led to a new mechanism design, capable to withstand the low temperatures and launch loads and at the same time provide the desired motion stroke, accuracy, resolution and stability.

The M2M concept is based on a serial-parallel configuration with five actuators, which provide the desired 5 dof motion. The motion in X and Y directions is achieved directly with one actuator respectively. The displacement in Z is obtained with three Z-oriented actuators acting at the same time. The two rotations RX and RY are obtained by a differential linear displacement of the Z-oriented actuators which are placed in a triangular arrangement.

The actuator is based on structural reduction mechanism and provides 0,2 micrometer resolution over a travel of 400 microns. It gives stable positions and high load capability to withstand launch loads without losing a given position in a compact volume about 85 x 65 x 40 mm^3.

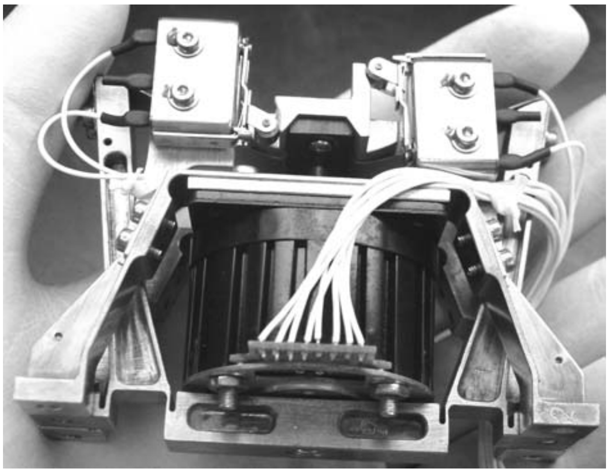


Fig. 2 Gaia M2M Actuator development model.

The actuator uses a stepper motor which actuates a spindle-nut, providing a linear displacement in the axis of symmetry of a mechanism. This motion is coupled to the output through a structural part that provides a reduction ratio. The permanent magnet stepper motor has a detent torque that provides stable positions of the spindle-nut when de-energized.

A full scale model of M2M has been manufactured and tested. The tests results at actuator and M2M level are presented in this paper.

2. DESIGN REQUIREMENTS

The major requirements for the Gaia M2M can be summarised as follows:

2.1 Performance Requirements

- 5 dof adjustment (Displacement along axes X, Y & Z and Rotation around axes X & Y)
- Linear capability: range ± 150 µm from the nominal centre position.
- Rotational capability: range ± 2 mrad from the nominal centre position.
- Linear accuracy better than 1 µm.
- Rotational accuracy better than 10 µrad.
- The linear and angular resolution no greater than half the positional accuracy.
- Linear stability < 1 µm, Radial stability < 10 µrad for ±50 µK.
- Linear Repeatability better than 0.1 µm, radial repeatability better than 1 µrad.

2.2 Structural stiffness

- First natural mode frequency higher than 100 Hz.

2.3 Mass

- Mass less than 5 kg including harness.

2.4 Volume

- The M2M excluding electronics shall be contained within a volume of 110 x 260 x 130 mm^3.

2.5 Interfaces with mirror dummy

- Mirror dummy mass 1.3 kg, +/- 0.1 kg.
- Mirror CoG Z=170 mm.

2.6 Environmental requirements

- Operational temperature from 296 ºK at ambient to 120 º K in orbit and TV verification.
- Quasi-static acceleration of 20 g in any direction.
- Random vibration environments of 20 grms in any direction.

3. M2M CONCEPT MAIN TRADE-OFFs

The analysis of alternatives was divided in two parts: The first part focused in the disposition of the actuators to achieve the 5 DOF motion. The second part is to define the actuator concept to better fit the requirements.

3.1 Actuators arrangement trade off

In the study of the alternatives for the disposition of the actuators, three main concepts were studied: Stewart platform or Hexapod, an hybrid serial-parallel mechanism, and a serial configuration. The main evaluation criteria were mass, volume & I/Fs, pointing performances (range/resolution/precision), sensitivity to external disturbances and load capability. Fig. 3 shows the alternatives considered:

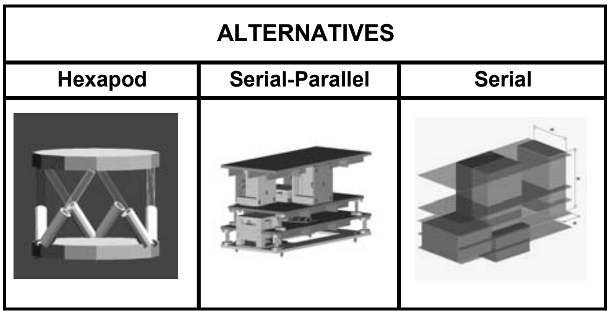


Fig. 3. Actuators disposition Trade off Matrix.

Hexapod configuration that is a standard arrangement in this type of mechanism was rejected mainly due to the envelope constraints of the mechanism, which lead to a small I/F and slim actuators. This configuration also imposes higher demands to the actuators with higher load capability and better resolution

The hybrid serial-parallel configuration was in front of the serial configuration because of the mass and complexity scores. The hybrid-serial configuration have slightly lower stiffness then the hexapod but the envelope constraints, which limits the size of the individual actuator permits the use of the available volume more efficiently.

3.2 Actuator concept trade off

In the analysis of the actuator concept three alternatives were studied: Inchworm based on piezo-actuators, a micrometer with differential threads and structural reduction. All three were analysed in terms of positioning performances, load carrying capability volume and mass, and the necessity of implementation of Hold Down to withstand the launch loads was also considered. Fig. 4 shows the alternatives considered.

The inch-worm actuator features the best performances in terms of resolution, mass and volume. However the main disadvantages were the limited load capability that imposes a specific hold down for launch with the subsequent mass penalty and operational restrictions.

The micrometer concept main disadvantage is the mass and the tribological aspects. This concept requires larger motor to comply with torque margin requirements. In addition the concept has two cinematic couplings on which the output load is applied directly.

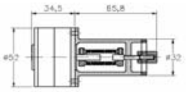
Inchworm	Micrometer	Structural Red.
		

Fig. 4 Actuator concept Trade off Matrix.

The selection of the structural reduction actuator had a key point in the load carrying capability and the unique cinematic joint that is not high loaded.

4. DESIGN DESCRIPTION

4.1 Actuator Description

The final baseline coming from the trade off consists on an actuator based on a structural reduction concept. The different components of the actuator are:

- A CuBe support structure where the motor is installed.
- A permanent magnet stepper motor that drives a spindle.
- A spindle with a small pitch thread.
- A Vespel SP3 nut where the spindle is threaded.
- A CuBe symmetrical flexure structure composed of two pieces: a thin plate attached in both ends to the second piece which provides the reduction ration by a lever arm.
- Two micro switches attached to the motor support structure as electrical limit switches activated by the spindle nut movement.

In the development model the components used to build the actuator were selected to have a replacement of flight quality standard as it is the case for the motor and the micro-switches.

For the development model the motor used was an ESCAP turbo disk 430 stepper motor modified in order to comply with the thermal environment by replacement of the bearings arrangement. This solution was adopted to have the possibility to test the mechanism in TV environment within budget constraints.

Micro-switches are ABB LGDS3 model which have their equivalent for flight use.

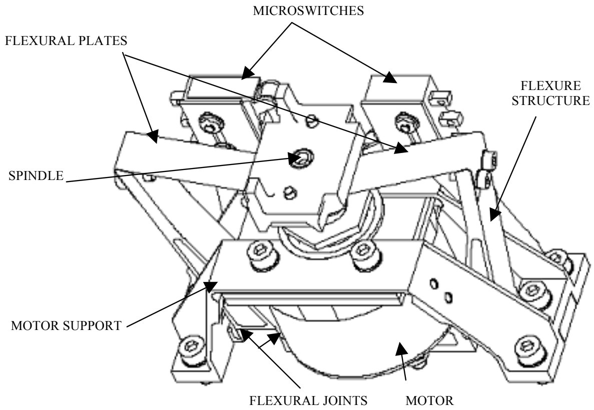


Fig. 5 Actuator main parts.

Almost all parts of the actuator are made of the same material in order to avoid thermo-elastic stresses and distortions with the exception of the motor and the nut. Because of that, the overall system is thermally stable. The main chosen materials are Beryllium Copper (because of the high strength, high fatigue strength and good behaviour in cryogenic environment) and Vespel SP3 for the nut (to reduce the friction at the spindle-nut contact in vacuum environment).

The electronics send the pulses to the motor that drives the spindle in rotation. When the spindle rotates the nut moves along the actuator axis. This movement of the nut pulls and deforms the two flexural plates that are working in tension over the full travel to avoid backlash. These flexural plates are connected to the spindle-nut and to the lever. When the nut moves the flexural plates pull the levers, which rotate with respect to the flexural joints (the hinges) of the support structure approaching itself to the central axis. The lever rotation, as it is also connected to the output through a short lever arm, produces a reduced displacement at the output interface.

The mechanism is adjusted to guarantee a minimum tension on the flexural plates along the operational range. This guarantees that the spindle nut contact is always preloaded in the same sense and therefore avoiding undesirable backlash that would reduce the accuracy and repeatability of the mechanism. The monitorization of the mechanism position is performed by step counting from extreme positions given by micro-switches.

4.2 M2M Description

The selected baseline coming from the trade off is the hybrid serial-parallel configuration. The different components of the M2M are the following :

- Base Plate made of INVAR to prevent stresses and thermo-elastic distortions with the Optical Bench I/F (from 20 ºC to –165ºC) which is made of a material with a very low CTE (α=1.75 µm/mºC).
- Intermediate tray made of T6Al4V and attached to the baseplate with four Ti6Al4V flexible blades that are flexible in Y direction.
- Top tray made of Ti6Al4V which is attached to the intermediate tray through four flexible blades providing flexibility in X direction.
- The Y-actuator is mounted on the baseplate and drives the intermediate tray
- The X-actuator is on the intermediate tray and drives the top tray and
- The actuators Z1, Z2 and Z3 are mounted on the top tray and provide the I/F to the secondary mirror.

The motion in X and Y directions is achieved directly with one actuator respectively. The displacement in Z is obtained with the three vertical actuators acting at the same time. The two rotations are obtained by a differential linear displacement of the vertical actuators which are placed in a triangular arrangement. Due to the accuracy required, the actuators have been positioned in the most symmetrical configuration possible.

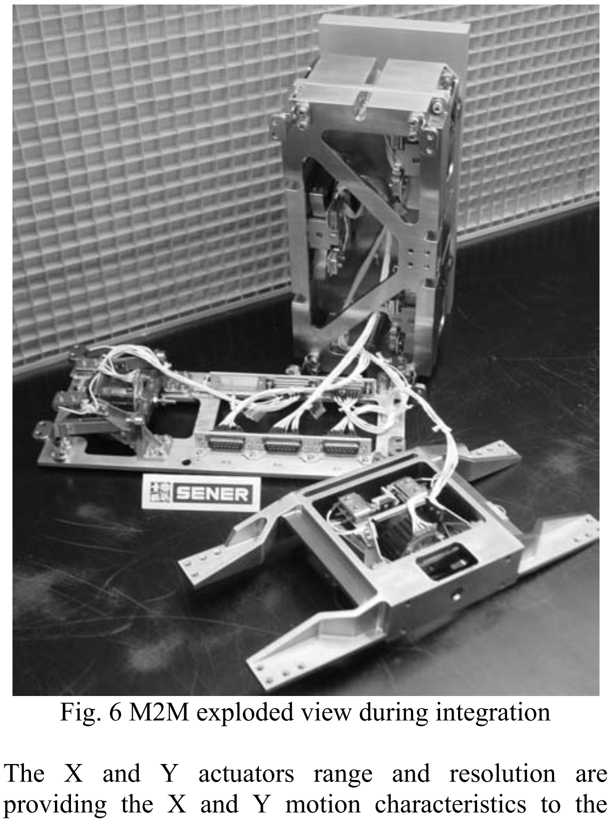


Fig. 6 M2M exploded view during integration

The X and Y actuators range and resolution are providing the X and Y motion characteristics to the mirror in these directions. The dimensioning of the blades joining the trays are defined minimizing off-axis displacements and resistant force to the actuator output while maintaining adequate stresses and stiffness for structural performances.

5. ANALYSES OF PERFORMANCES

The analyses have been divided in two levels: analyses at actuator level and analyses at M2M level. The results obtained from actuator level have been included at M2M level.

5.1 Actuator stroke, resolution and reduction ratio

Actuator resolution and reduction ratio have been analysed as a mechanism including the flexible joints, the spindle and the blades in order to have a first dimensioning of the mechanism to meet the desired performances. However there are several inaccuracies in the analytical model due to the following reasons:

- The flexible joints are not a rotational joint as it is defined in the mechanism model
- The flexural plate does not follow a straight line.

Therefore a non linear analysis of the actuator concept has been built to correlate the analytical model with the non linear FEM with good results.

The actuator resolution calculated by analysis is 0.25 µm approximately, which meets the requirements of resolution and accuracy for the M2M motion.

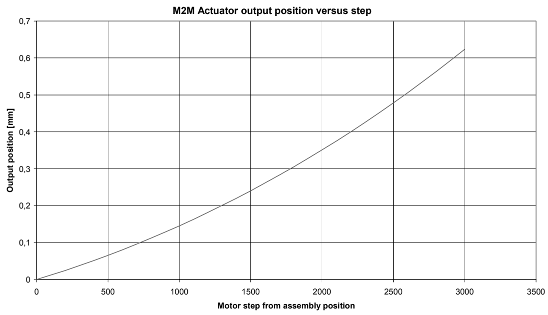


Fig. 7 Actuator output displacement vs step

5.2 Actuator stability

The actuator maintains a commanded position with the stepper detent torque even when applying the maximum design load to the actuator output. The stability is achieved for a given thermal condition. The actuator design is such that it tries to minimize the thermo-elastic distortions due to temperature changes. This is achieved by having both output and support interfaces at the same plane and having the complete structural path made of the same material.

However there are two effects that affects the stability and temperature induced deformations:

- The difference of the material CTE where the actuator in mounted
- Temperature gradients within the actuator (due to the motor power)

Even accounting these effects the stability obtained is better than the required 1 µm for thermal excursion of ±50 µK. However this performance is very much enhanced after temperature stabilization because the motor power induces most of the deformations at output level.

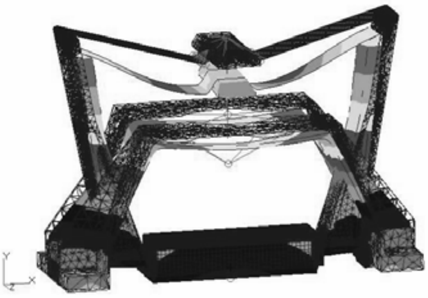


Fig. 8 Actuator thermal structural and model

5.3 Actuator Torque margin

During operation the stepper must provide the necessary torque against the friction of the spindle joint. This friction is dependant on the level of force at this joint that comes from different sources:

- Deformation of the flexure structure to provide a minimum preload to null the backlash
- Motor fiction (bearings and magnetic losses)
- External load

The external load transferred to the spindle is divided by the reduction ratio of the structural mechanism. This reduces the torque demand to the motor but is a significant source of resistant torque. The main sources of external force are the followings:

- External load under 1g due to the mass of the mechanism and mirror.
- External load due to M2M flexural elements deformation.

5.4 M2M Structural and thermal requirements

The structural and thermal requirements were analysed using Nastran for the optimisation of the structural concept and the verification of the thermal performances of the M2M.

The first and second natural frequencies are higher than the required 100 Hz and come from the bending of the Flexible Elements in the direction of the motion that they transmit respectively. The third mode corresponds to the torsion of the 2nd stage flexible elements.

It has been found that the actuators stiffness and the flexible blades between trays define the overall mechanism stiffness. The increase of these parameters give a better structural behaviour, however they impose more strict requirements to the actuator that need to be more powerful to overcome the increased torque required to move a more rigid structure.

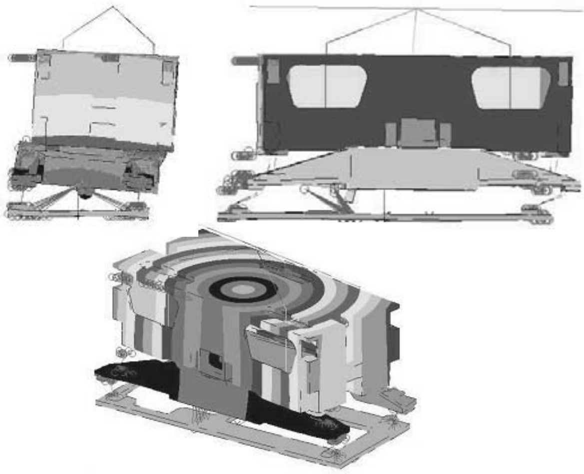


Fig. 9 M2M Structural model and first modes

5.5 M2M Pointing Performances requirements

The main requirement for the M2M pointing performance is the displacement in Non-Commanded Directions.

When commanding one motion to the M2M there is a parasitic movement in the other DOF due to the structural concept. This effect has been analyzed with FEM. The analysis shows that the off-axis displacement in any dof is smaller than the required accuracy when commanding other DOF the full range.

6. DEVELOPMENT MODEL DESCRIPTION

6.1 BBM actuator

The BBM actuator is shown in Fig.2. Due to budget constraints there are several parts that have not been built Flight Standand:

- The stepper motors is commercial motor which cannot be used for launch and TV cryogenic environments. It has been modified to be able to operate at low temperatures with modifications on the bearings.

- The spindle shaft thread has been built by machining instead of rolling process, and no coating has been applied
- Bearings was lubricated with MoS2 applied by brushing.

In order to have confidence in the motor modifications it was tested in LN2 after the modifications to verify its operation at low temperatures with success. The eventual Flight design should include a qualified stepper motor, rolled thread and sputtered lubrication of bearings and thread.

6.2 BBM M2M

The BBM M2M is shown in Fig.1. It is mainly made of Titanium and is representative of the Flight H/W. However there is still potential for mass saving in the top tray.

The I/F to the mirror is defined as the attachment points to the three vertical actuators and this definition is no more valid for the actual mirror due to the material of the mirror with low CTE. The tests at M2M level are performed with a mirror dummy made of Aluminium with the corresponding thermo-elastic effect on the interface to the actuators.

The eventual Flight design should include a specific support with interface to the mirror and to the three vertical actuators.

7. TEST CAMPAIGN RESULTS

7.1 Actuator level tests

Prior to the M2M integration, different test on the actuator mechanism were performed:

Actuator resolution, accuracy and repeatability were measured with good results and correlation with analysis. As it can be shown in Fig. 7 and Fig. 11 the displacement is slightly no linear with the step.

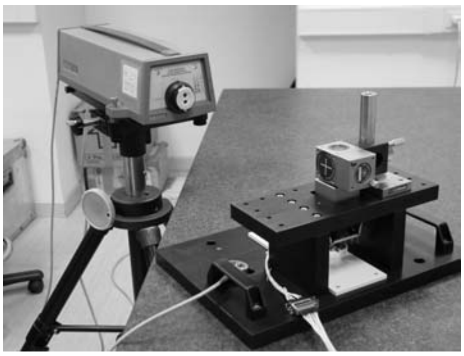
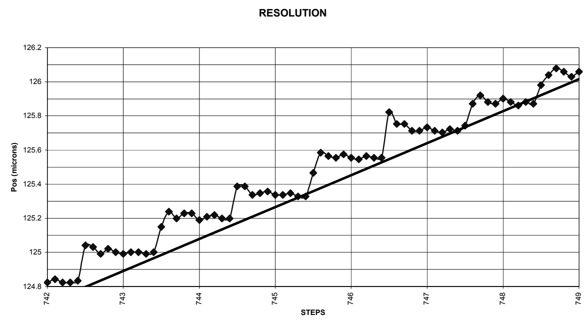


Fig. 10 Actuator resolution, accuracy & repeatability test

The test showed that the reduction mechanism was transferring the spindle motion very accurately and even the step oscillations due to the rotor dynamics were apparent in the position measurements. It showed that the structural reduction concept could also be applied to lower resolutions.



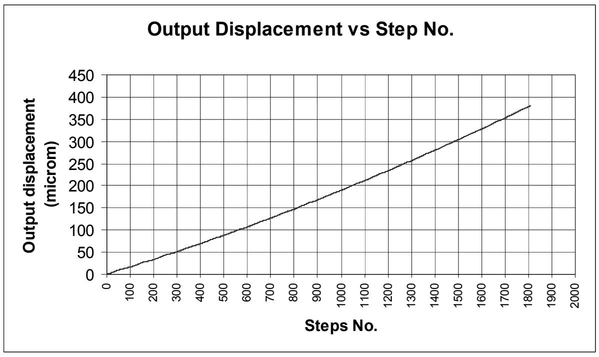


Fig. 11 Actuator position measurement

The position error was also determined from the measurements being less than 0,2 micrometers. This value can be lower if the temperature effects are considered because the temperature increase of the actuator during operation have influence in the results obtained that were not compensated.

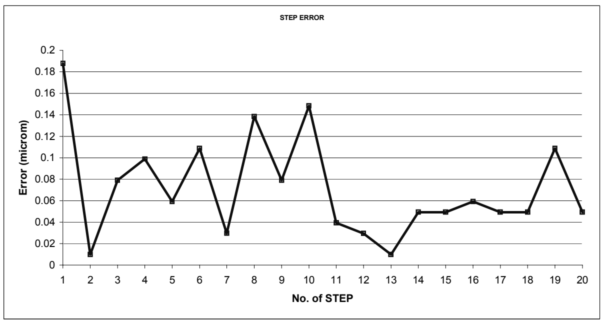


Fig. 12 Repeatability of actuator position

The stiffness and load capability of actuator output was measured. The results showed that the stiffness value is not constant, and it depends on the position of the actuator along its range. This behaviour was also predicted by the FEM non linear analysis however a slightly lower stiffness value was measured.

The stiffness test also shows that the mechanism preload disappears at a tension load of 250 N approximately and above this value the stiffness of the actuator is significantly reduced.

Table 1. Actuator stiffness in compression

CASE	Expected Stiffness [N/mm]	Measured Stiffness [N/mm] COMPRESSION
		From 0 to 500 N
Preload Position	7500	6564
Half of Stroke	7500	6181
End of Stroke	7500	5861

The actuator was tested in vacuum conditions to measure the resistant torque at the level of the motor and operation was also verified at -100ºC. The stability of the actuator position over temperature variations was measured by auto-collimation with the actuator placed in a climatic chamber for temperature excursion from ambient to –150ºC. The actuator was operated to verify step by step movement and the variation of its position during cool down. The results showed wide margin of stability against the requirement. During the cool down up to –150ºC, the operation of the actuator was verified every 30 ºC showing good operation at every stage.

7.2 M2M level tests

The scope of these tests is the verification of the requirements of the M2M:

- Pointing Performance test, to demonstrate the capability to meet the pointing requirements and determine the cross coupling of axes movement
- Torque Margin test, to measure the resistant forces that the actuator has to overcome as an input for the torque margin verification requirement.
- Vibration test to verify the structural behaviour and correlate the FEM.

The M2M Test campaign was performed with a representative dummy of the M2 Mirror mounted on the M2M.

The pointing performance tests were performed on a test set up in which the position of the mirror dummy was performed in six points and three directions. The arrangement allowed to get the position and the angular motion in all six dof.

The test consisted on the commanding of one dof the full range in both directions from a central position and measuring the movement in all dof. Therefore in the commanded dof the reported value should be the range of motion while in the other non commanded axes the results should be as small as possible.

Fig. 13 M2M Pointing Performance Test set up

The pointing performances results showed that the actuation of the Z actuators to get the motion in Z and the two tilts in RX and RY require the commanding of the actuators Z1, Z2 and Z3 in turns (a small motion each time) or at the same time in order to avoid disturbances in other axes. In any case, these inaccuracies can be corrected afterwards by commanding the corresponding d.o.f. motion.

The M2M vibration tests were performed at INTA facilities. The mechanism was submitted to qualification levels in the worst case axis showing good correlation with FEM predictions.

8. LESSONS LEARNT

The use of “low-cost” approach for precision mechanisms with high performance demands (vibration, low temperatures, vacuum) is always difficult, and leads to unpredicted limitations on the mechanisms performances.

Modification of commercial elements to meet specific project requirements should be performed with the support of the suppliers of these elements and the modification effort anticipated at the appropriate level.

9. CONCLUSIONS

Gaia Mirror Mechanism has proven to be a reliable concept, although the implementation of space qualified motors are still pending.

The main requirements have been proven including the pointing performances, stability and the actuator concept capability to withstand launch loads.

10. REFERENCES

1. Precision displacement Mechanism J.I. Bueno, F. del Campo, Sener, 5th ESMATS October 1992