PRESENTATION OF THE HIGH ACCURACY POSITIONING SYSTEM DEVELOPED FOR TEST AND ALIGNMENT ACTIVITIES ON PLATO TELESCOPES

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ABSTRACT

PLATO (PLAnetary Transits and Oscillation of stars) ([3], [4] and [5]) is a mission of the ESA Cosmic Vision 2015-2025 program. This mission is dedicated to the discovery and cataloguing of exoplanets.

This paper presents the vacuum positioning system developed to qualify and carry out all the optical performance test activities on the Telescope Optical Unit (TOU). This positioner is composed of a hexapod used to move with high accuracy the detection system assembly in the telescope focal plane. All this assembly is then mounted on a gimbal to move all equipment in elevation and in azimuth.

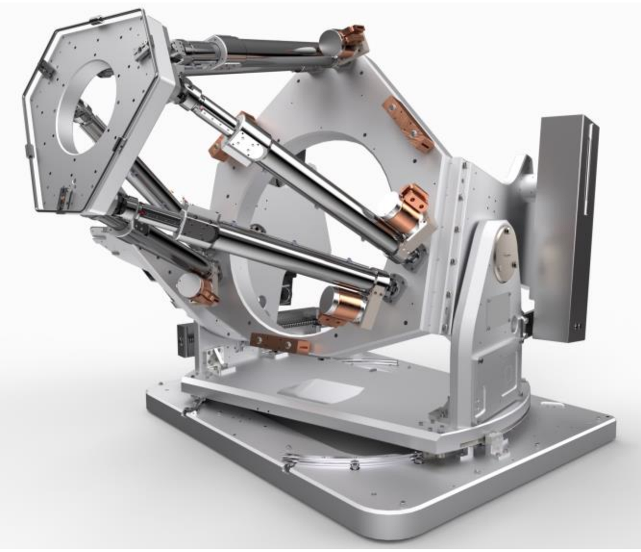

Figure 1 – Positioning system especially developed by SYMETRIE for the project (realistic CAD view)

After a brief description of the mechanical design, we explain the original qualification setup used to demonstrate the performance, based on the use of confocal sensors. Reached performances of this positioning system are shared. And we give a state of the art in terms of reachable accuracy performances, for future qualification and alignment of Ground Support Equipment (GSEs). The characterization of the performance's resolution, repeatability and accuracy is clarified.

GOAL OF THE EQUIPMENT (CONTEXT)

The Goal of the project for SYMETRIE was to provide a calibrated motion mechanism that is the positioning reference for the qualification of the TOU field of view performance at focal plane.

The positioning system has been developed by SYMETRIE, on behalf of LEONARDO company [2]. The system is used in the frame of the performance, evaluation, test and alignment activities for Plato telescope (TOU).

The PLATO payload is based on a multi-telescope approach, involving 26 cameras in total. The opto-mechanical sub-system of each camera is called Telescope Optical Unit (TOU). Each of the 26-flight models (plus 2 qualification models) will be assembled on the positioning system to conduct their qualifications. All tests are done within a large thermal vacuum chamber.

During the tests executed in vacuum conditions at ambient temperature, the positioning system moves the TOU telescope head and his thermal hardware GSE in elevation and in azimuth to keep in position and to move with high accuracy the detection system assembly in the telescope focal plane.

The positioner consists in a system composed by:

- two rotation stages (called later Gimbal device) that rotate the unit under test (TOU Telescope + Thermal hardware + hexapod)
- and by one hexapod that moves accurately the Detection system assembly to explore the Telescope focal plane.

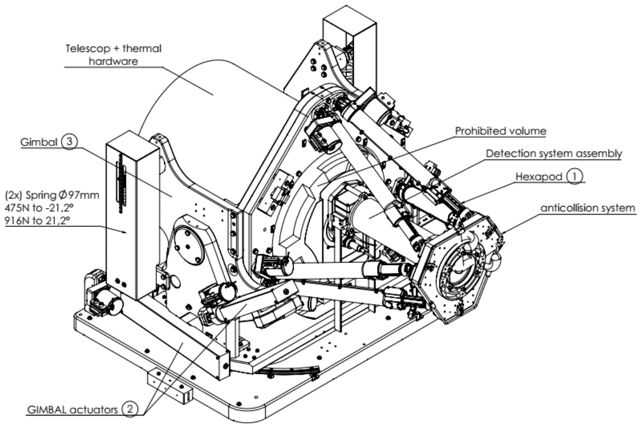

Figure 2 - Application overview

The purpose of this equipment is to accurately move the Detection system assembly in the {X, Y} plane without cross-coupling (Z translation or parasitic rotations), whatever the Gimbal orientation is. And this when all the equipment is installed in a vacuum environment.

Several challenges are required on this positioning system to respect the project constraints, in particular:

- high accuracy of the hexapod's actuators on large travel ranges
- to identify the hexapod kinematic model precisely to mitigate the cross-coupling errors
- to minimize the components heating (motors, encoders) to avoid thermal drift in the vacuum environment
- to guarantee the thermal stability of the mechanism
- to guarantee the hexapod accuracy for all gimbal positions: thanks to the high rigidity of the gimbal, we avoid deformation of the hexapod and uncentered payload on the gimbal is compensated.
- the working distance between the TOU telescope and the detection system assembly is small, so the system should provide software methods and sensing devices able to avoid any collision with the instrument under test
- the whole positioning system should be designed to fit inside the thermal vacuum chamber. Due to the limited space inside, a collision detection mechanism between the positioner and the TVC internal surfaces was provided.

POSITIONER PERFORMANCES

The positioning specifications of the hexapod are given in the table below:

Axis	Cumulated travel ranges (1)	Resolution (2)	Repeatability (3)
Tx	± 100 mm	0.4 µm	± 2 µm
Ty	± 100 mm	0.4 µm	± 2 µm
Tz	-100 to 0 mm	0.2 µm	± 1 µm
Rx / Pitch	± 0.5 deg	1 µrad	± 5 µrad
Ry / Roll	± 0.5 deg	1 µrad	± 5 µrad
Rz / Yaw	± 0.5 deg	1.7 µrad	± 7 µrad

(1) Performances are specified for simultaneous motions at the pivot point.
(2) Resolution should be understood as minimum incremental motion: i.e. the smallest motion increment that the system is able to reproduce in a consistent and reliable manner.
(3) According to ISO 230-2 standard: unidirectional repeatability given with +/- 1 standard deviation.

The positioning specifications of the Gimbal are given in the table below:

Axis	Travel range axis by axis	Resolution
Azimuth (Rx)	± 21 deg	15 arcsec
Elevation (Ry)	± 21 deg	15 arcsec

In addition to the previous requirements, the hexapod should meet the following specifications:

- Accuracy in Tz: 10 µm
- Be able to move in X and Y without parasitic Z movement. This error called cross coupling is particularly critical. Cross coupling requirement: 10 µm, target 5 µm.

This last requirement should be met for any Gimbal orientation (any angle). Rotation around the axis perpendicular to the gravity is the most demanding to guarantee.

MECHANICAL DESIGN (GIMBAL, HEXAPOD)

The hexapod positioner consists of a fixed platform and a mobile platform. Both platforms are linked together with six identical precision actuators. This structure makes it possible to realize fine positioning of the mobile platform, following six degrees of freedom with a centre of rotation virtually defined via software. The hexapod is based on an existing product: ZONDA. Here a customization is necessary to meet the required performance and the integration constraints.

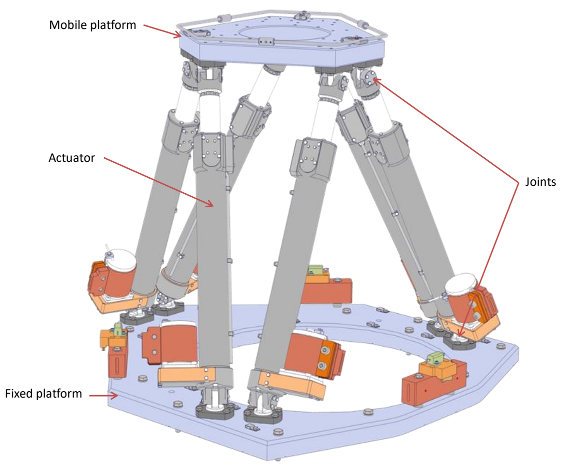

Figure 3 - Hexapod description

Precision actuators used on this hexapod have been designed by SYMETRIE. They have been used on ZONDA products for many years for ground space application and in vacuum environment. They integrate a stepper motor, a high precision ball screw and an absolute linear encoder.

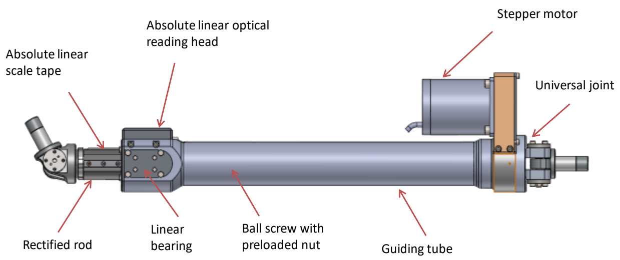

Figure 4 - Design of actuator and joints

Thermal stability is given by a metrological loop mainly composed of low thermal expansion materials. The guiding tube is in Invar. A Renishaw RESOLUTE encoder system [6] with ZeroMet™ linear scale is installed on each actuator - providing high-precision accuracy with near-zero thermal expansion and a nanometer resolution.

Mechanical stability is given by the stiffness of the transmission. Actuator screw, bearings and joints are preloaded, and some of the bearings are manually adjusted or paired, in order to ensure the highest stiffness.

RESOLUTE absolute encoders ensure high accuracy and stability of the ZONDA hexapod. To compensate, the residual a software calibration of each actuator in the controller, allows to reach an accuracy better than ±1µm on 260 mm stroke.

The Gimbal is especially designed to meet the requirements of this project and is based on similar component to those employed on the hexapod actuator: same motor, encoder… It integrates two rotations. The following picture describes the different main elements of the Gimbal:

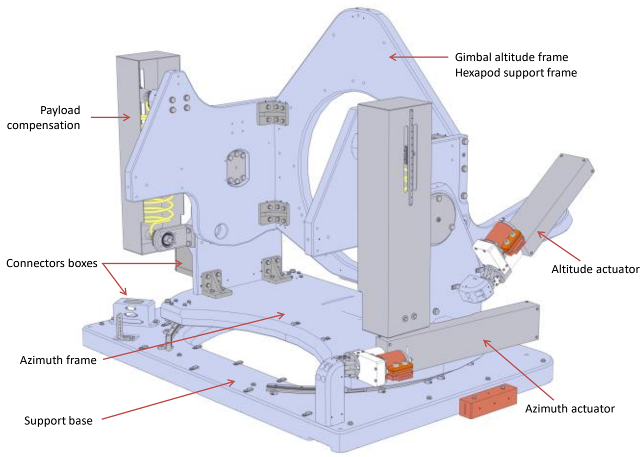

Figure 5 - Gimbal description

Payload mounted on the Gimbal is high (TOU Telescope + Thermal hardware, hexapod, Detection System Assembly). A payload compensation mechanism is included to mitigate the deformation.

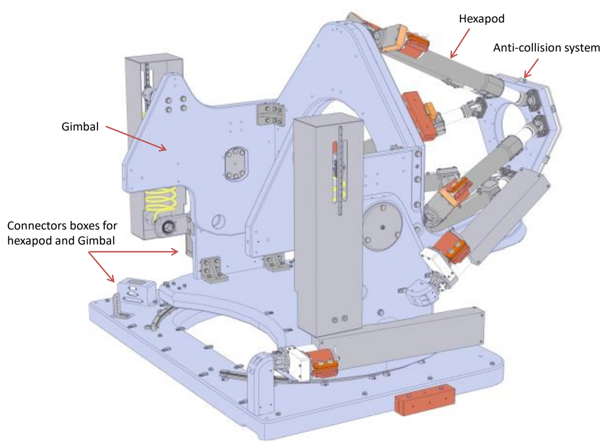

Figure 6 - Hexapod with Gimbal description

Each axis is motorized with a stepper motor. Stepper motor temperature can increase significantly during long operation time. To reduce the heat dissipation during their movement in vacuum environment, stepper motor heat is transferred with cooling braids. Each motor is also equipped with temperature sensors.

The thermal management solution has been designed and integrated in order to optimize the stability of the hexapod and the Gimbal. The telescope thermal hardware and the support frame are thermally regulated at 20°C.

The principle involves to: heat is collected from each stepper motor by two coppers braids which are attached on the fixed platform of high thermal inertia and transferred to the Telescope thermal hardware.

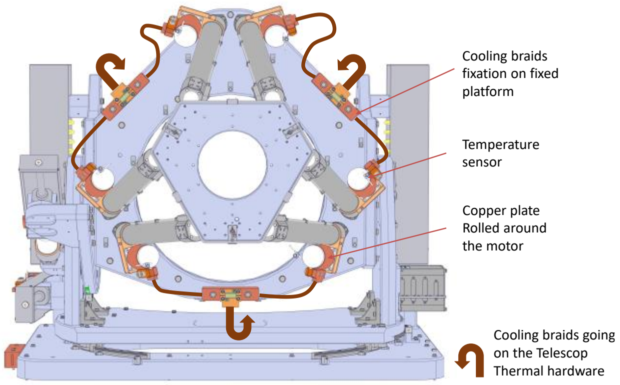

Figure 7 – Thermal braids on hexapod motors

For the Gimbal, the same principle is applied excepting that cooling braids are fixed directly on the support plate. In total, there are four cooling braids for the Gimbal.

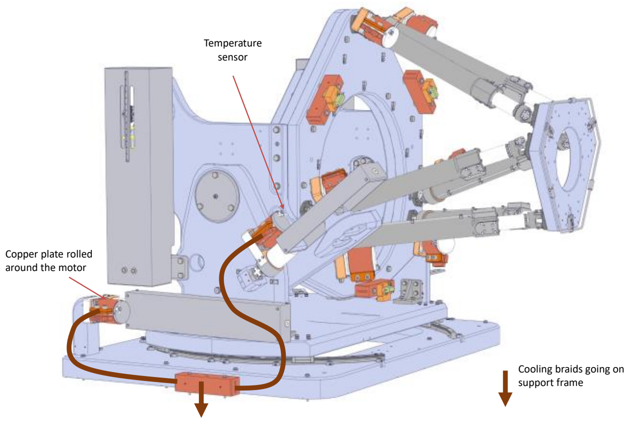

Figure 8 - Thermal braids on Gimbal motors

The positioning system axes are given on the figure below. Dimensions are also specified to get an idea of the overall system size.

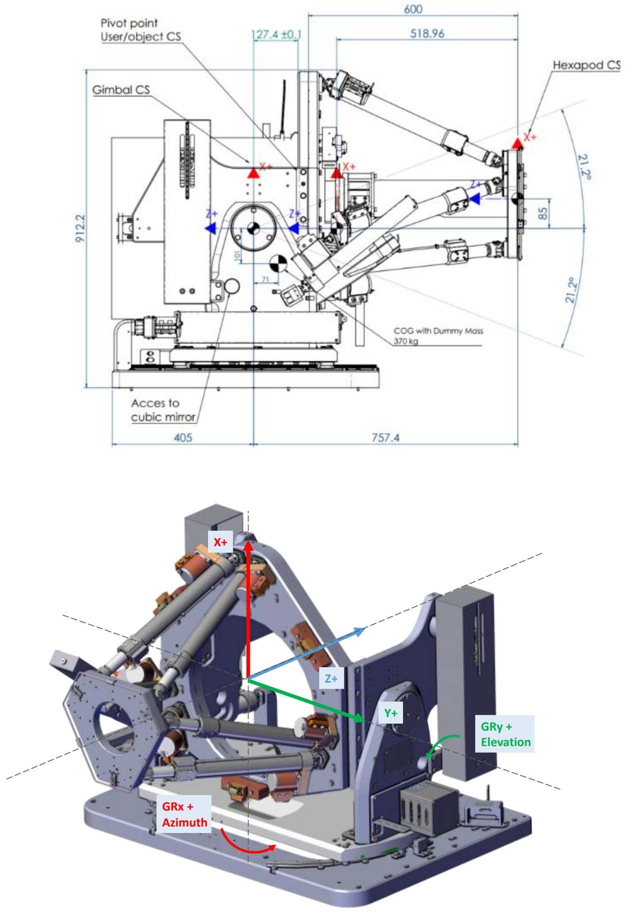

Figure 9 – Complete positioning system with the axes and dimensions

CONTROL DESIGN AND SENSORS SUB ASSEMBLY

The hexapod and Gimbal are controlled by one control enclosure which includes a Delta Tau motion controller, power supplies and associated protections. The motion controller ensures that actuators are controlled in closed loop, with a high accuracy.
The software embedded on the motion controller interprets commands sent over Ethernet. The control software realizes the transformations between the displacements requested by the user (following the six degrees of freedom) and the lengths of the hexapod actuators.

Hexapod and Gimbal require a control computer to operate. A dedicated Graphical User Interface (GUI) allows the control of the hexapod and Gimbal via an ergonomic and intuitive software interface. The software is called “SYM_Positioning”.

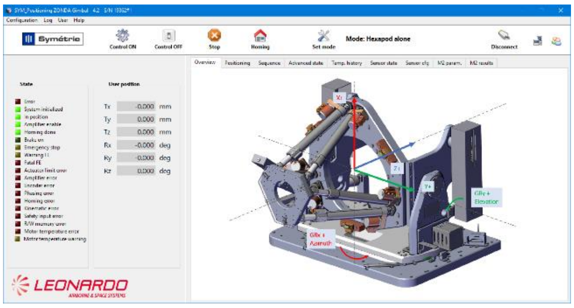

Figure 10 - “SYM_Positioning” software on the project

Micro-Epsilon confocal sensors for distance measurements has been integrated on the positioning system [8]. They are suitable for a use in vacuum environment. Associated with a dedicated controller, the sensor gives a measuring range of 2.5 mm with a resolution of 24 nm and a maximum linearity of 0.75 µm. The sensor is connected to the controller with an optical fiber.

Three confocal sensors are mounted on the detector assembly. The sensors play different roles during the qualification:

- First, confocal sensors are used as an anti-collision system during the telescope qualification.
- Then, each confocal sensor is used to detect a relevant gauge to align the Detection system assembly with respect to the TOU telescope.

The second feature has requested specific software development. The confocal sensors are moved by the hexapod until they intercept the optical gauges surfaces (target). On the gauges a very precise groove is present; after detection of several points on the circle groove, the center position is calculated. With all these measurements, the Detection system assembly (hexapod movement) is aligned with respect to the TOU telescope reference system, ready to start the optical tests. Thus, hexapod is used as a measuring machine to determine the center of each target.

The confocal sensors are managed by a control enclosure, which includes the confocal controllers, power supplies, associated protections and a network switch. The optical fibers mounted on the confocal sensors are connected to this control enclosure. Confocal sensor measurement is given in “SYM_Positioning” software, especially adapted on this project.

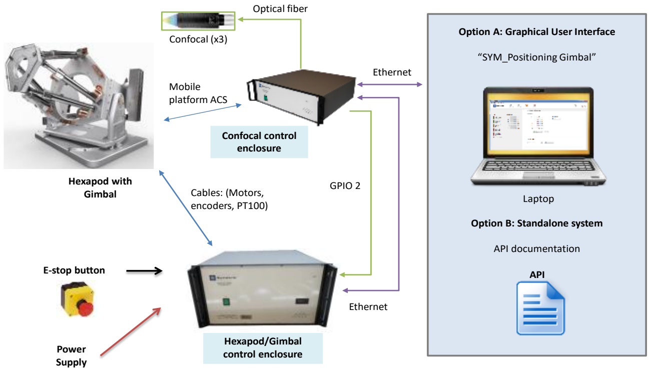

Figure 11 - Control architecture

QUALIFICATION SETUP

The complete positioning system has been commissioned and qualified in factory. The overall machine was mounted on a large coordinate measuring machine (CMM) for this phase. All measurements have been done inside SYMETRIE metrology laboratory which is stabilized at 21°C ±0.5°C.

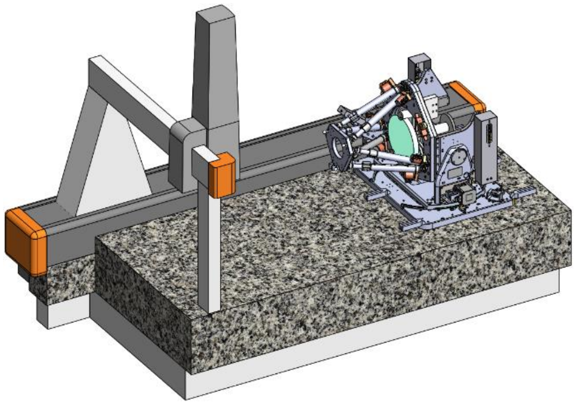

Figure 12 - Complete machine is qualified on a CMM (CAD view)

All requirements have been measured/verified with the CMM, a laser interferometer and the confocal sensors.
The CMM was used to precisely identify the kinematic model of the hexapod thanks to an automated measurement process. This process is commonly used by SYMETRIE to improve its hexapod accuracy and minimize cross-coupling values.

Without a large coordinate measuring machine, it would be difficult to reach such level of performances.

To demonstrate the cross-coupling performances for different gimbal positions, we have considered a specific setup using a large flat mirror with a diameter of 370 mm and also the three confocal sensors discussed above.

Cross-coupling is verified by moving the confocal sensors which are supported by the hexapod mobile platform, in front of the flat mirror surface. The mirror flatness is better than 1 µm.

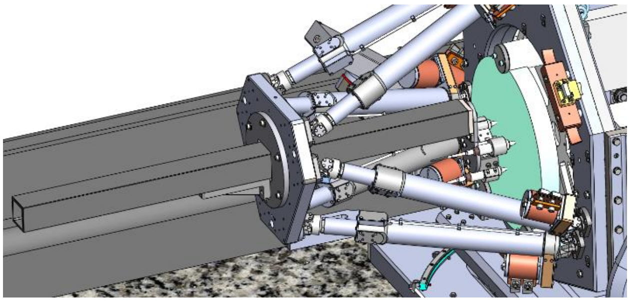

Figure 13 - Qualification setup principle (CAD view)

During this test campaign, the flat mirror is rigidly attached on the Gimbal with additional parts. This dummy load simulates the unit under test. The mass of the unit under test (TOU telescope + thermal hardware + TOU interface plate) is around 70 kg.

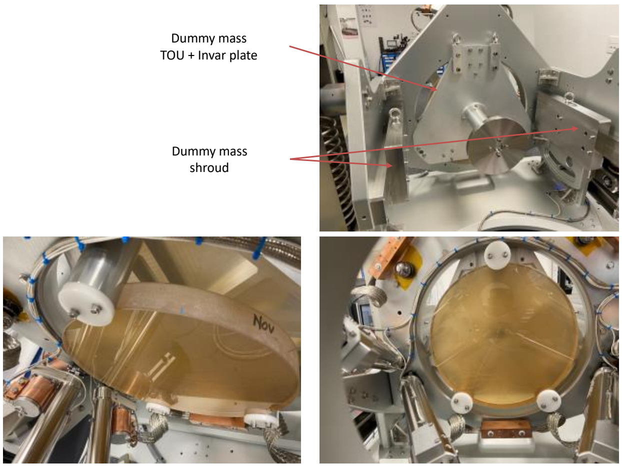

Figure 14 - Dummy load of the Unit Under Test (UUT)

In a same way, we have simulated the detection system assembly with a dummy support on which the three confocal sensors are fixed.

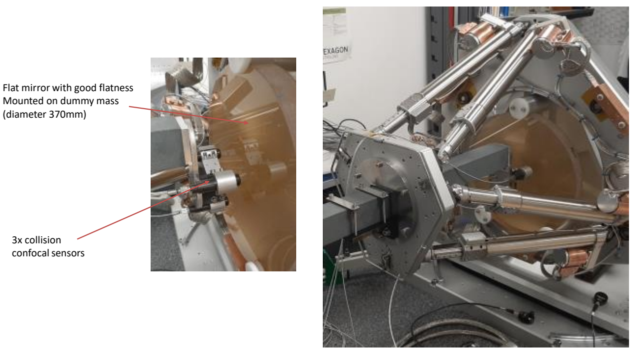

Figure 15 - Dummy detection system assembly

To support the confocal sensors, we used a bar made in silicon carbide to provide high stiffness. The mass of this dummy equipment is about 10 kg. The optical fibers from the confocal sensors are attached to the mobile platform.

MEASURMENT CAMPAIGN AND RESULTS

In this paragraph, we go through all main criteria qualified on this positioning system. This overview shows all tests done in factory to demonstrate the performances. Here only single axis results are given but this exercise is performed on all axes during the qualification.

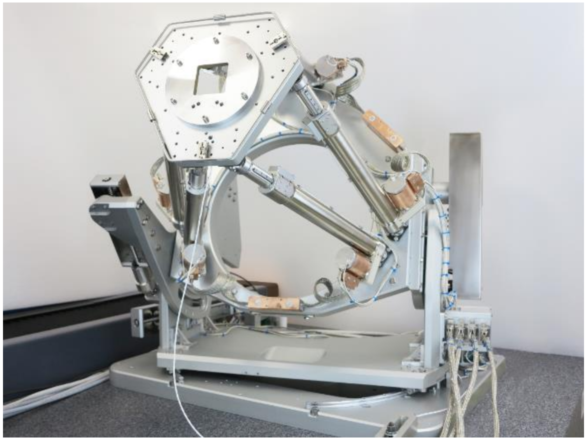

Figure 16 – Machine overview when mounted on the CMM without dummy load

Resolution verification

There is no consensus on the definition of resolution and its evaluation. The International Vocabulary of Metrology (VIM) defines resolution as the ‘‘smallest change in a quantity being measured that causes a perceptible change in the corresponding indication” [9].
SYMETRIE consider the resolution has the minimum incremental motion (M.I.M.), which is the smallest increment that the machine can perform significantly. Methodology is described in publication [10].

To verify the resolution, we use here a Renishaw XL-80 laser interferometer with angular optics [11]. Figure 18 shows the measurement setup used to verify the hexapod angular resolution.

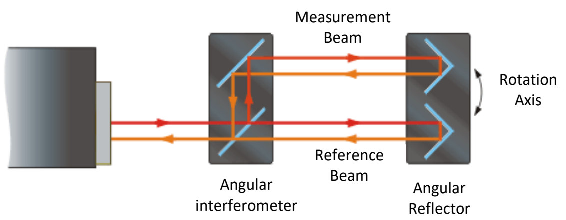

Figure 17 - Angular measurement principle with laser interferometer

Figure 18 - Angular measurement setup

On the plot hereunder, small steps of 1 µrad (~0.2 arcsec) are verified with the laser interferometer. We observe a good stability on each step. And, there is no relaxation behaviour when the system has reached the commanded position.

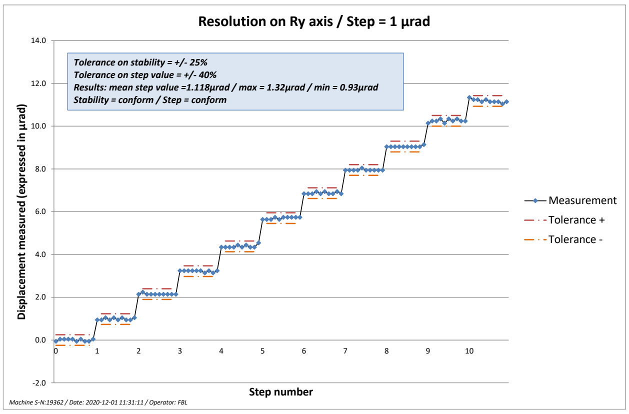

Figure 19 - Resolution around Y axis

Accuracy measurement

Accuracy of the hexapod is measured with a laser interferometer. This is achieved by making three round trips on the travel range around the center position. The accuracy error is defined with M parameter according to ISO 230-2 standard [12].
Following plot shows accuracy of hexapod along the Z axis. Accuracy (M parameter) is better than 10 µm and unidirectional repeatability (R+ and R-), which is also calculated during this qualification, is better than ±0.5 µm.

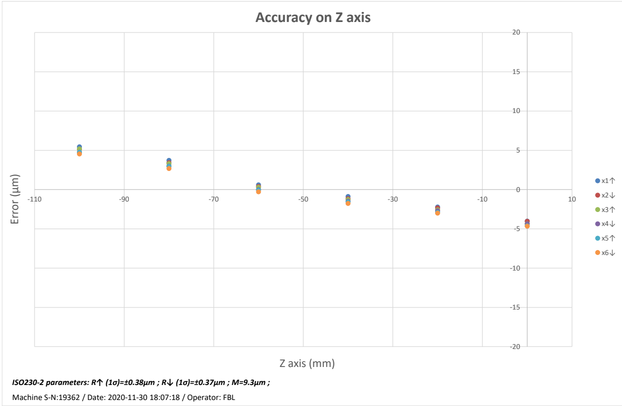

Figure 20 - Accuracy plot on Z axis

This measurement is performed with the hexapod mounted on the Gimbal and with the dummy detection system. Accuracy showed above concerns the complete positioner (hexapod and Gimbal), which is more restrictive.

Cross-coupling measurement

We use the three confocal sensors to measure the cross-coupling (or parasitic displacement) in Z direction when traveling following pattern (in X and Y). This pattern (circle with a diameter of 160 mm) is reproduced for various gimbal Elevation / Azimuth. In total, cross-coupling is measured in 16 different positions (orange circled).

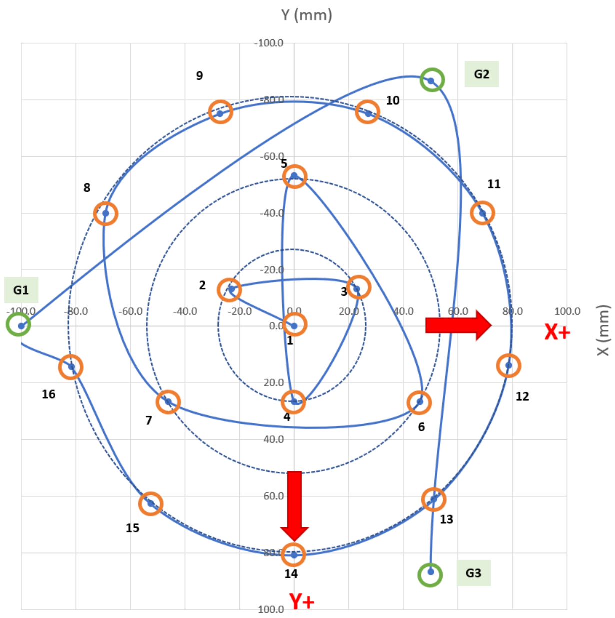

Figure 21 - Travelling pattern for cross coupling measurement on the flat mirror

Elements identified G1 to G3 (green circled) on previous figure correspond to the gauges used to align the Detection system assembly (hexapod movement) with respect to the TOU telescope reference system.

Next figure shows the cross-coupling measured thanks to the three confocal sensors for various Elevation (GRy) / Azimuth (GRx) of the Gimbal.

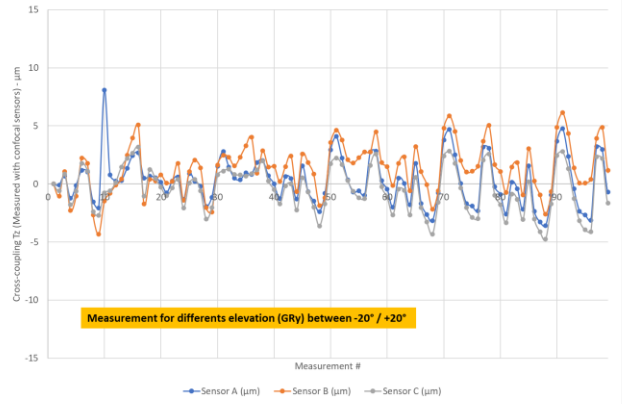

Figure 22 - Cross-coupling measurement

We observe that cross-coupling slightly increases when elevation angle increases. This result was expected because the Gimbal frame, which support the hexapod, is deformed when applied load changes. Which is the case here for the hexapod centre of gravity.

A statistical analysis of the error, from previous measurements, allows to obtain the following plot. We observe that the cross-coupling error is most of the case below ±5 µm.

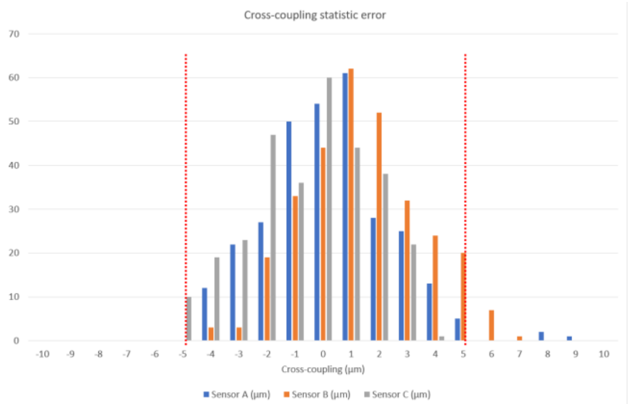

Figure 23 - Cross-coupling statistic error

Results achieved are excellent for such complex mechanism with large travel ranges. Demonstrating the positioner performances in terms of cross-coupling was challenging. The measurement sensors and their implementation on this positioner are quite innovative.

To move further and reduce the cross-coupling error a stiffness compensation model of the positioner could be considered. This solution should compensate the deformation of the system when changing the elevations angle.

CONCLUSION

The PLATO telescopes production is challenging and the positioning system helps to take up this challenge by including some measurement sensors and by automatizing the qualification process.

This positioning system is composed of a hexapod mounted on a Gimbal. It has been especially developed to conduct the alignment activities and carry out the optical performance tests (qualification) on the Telescope Optical Unit (TOU). It is a fully automated system, reaching a high level of precision.

We have demonstrated that the hexapod is able to measure and adjust the focal plane using the 3 grooves with a high accuracy. The translation of the hexapod in the focal plane (X-Y) is very accurate and allows moving a sensor without cross coupling. Cross-coupling error is lower than +/- 5 µm, for any orientation of the Gimbal in elevation and azimuth. Such performances are possible thanks to the calibration of the actuators and the kinematic model. Moreover, it would not be possible to achieve such requirements without a thermal dissipation strategy and use of low thermal expansion materials for the metrology loop of the actuators. It is important to notice that all measurements made on the positioning system are close to the state of the art of dimensional metrology. The accuracy was demonstrated by using a CMM and specific setup with uncertainties close to the requirements.

The positioning system presented here gives an example on how innovations can improve qualification phases for space instruments. We thank our customer LEONARDO for this nice project. Always pushing us to our limits to develop positioning systems with always higher level of performances.

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