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Performance of the VST secondary mirror support system

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ABSTRACT

The VST telescope is equipped with an active optics system based on a wavefront sensor, a set of axial actuators to change the primary mirror shape and a secondary mirror positioner stage. The secondary mirror positioning capability allows the correction of defocus and coma, caused by incorrect relative positions of the two mirrors arising from the deformation of the telescope tube and of the optical train under the effect of gravity and thermal espansion. Periodically the image analyser calculates the deviation of the image from the best quality and the telescope control software decomposes the deviation into the single optical contributions. The new position and orientation of the secondary mirror is computed by the telescope control software and transmitted to the secondary mirror support system for execution. The secondary mirror positioner is a hexapod, i.e. a parallel robot with a mobile platform moved by six linear actuators acting simultaneously. This paper describes the secondary mirror support system and the qualification test campaign performed both in laboratory and at the telescope.

Keywords: Active Optics, Telescope, Parallel Robot, Hexapod

1. INTRODUCTION

The concept of the VST secondary mirror support system was updated and simplified after a Critical Design Review held in 2007 that pointed out several weak points; afterwards reliability and performance had to be much improved. The telescope error budget was revisited and, in the partially new design, both performance and maintenance operations were considered (a similar work was done for the primary mirror support system [1]). The mechanics was refurbished by ADS International srl, while the control part was shared between the Local Control Unit (INAF) and the legs electronics (ADS); the hardware was basically replaced in order to agree as much as possible to the ESO standards (see also [2], [3]). INAF wrote a new control software replacing the old one, suddenly obsolete because of the new hardware. At the end of 2008 the secondary mirror support system was successfully tested at system level by INAF and ADS in Italy, and then shipped to Chile where in early 2009 has been installed at the telescope and tested on site: a residual sporadic problem was carefully pointed out and removed by a firmware update.

2. WHY A HEXAPOD

The appropriate positioning device for a specific application depends on the motions to be implemented: in our case the secondary mirror has to be moved in order to compensate defocus and coma. Defocus is corrected by motions along the optical axis z, and coma by displacements along x and y combined with tilts around the same axes, in order to implement rotations around the mirror centre of curvature. Thus, the periodic compensation during the exposures of both defocus and coma needs movements of the secondary mirror in 5 degrees of freedom (x, y, z, ϕ, θ), where ϕ and θ are the rotation angles around x and y. Only positioners which can follow very accurately trajectories in these five degrees of freedom, without moving the image on the focal plane, can be used during the exposures. The choice for VST is a hexapod (Fig. 1): it has 6 degrees of freedom, including also the redundant rotation ψ around the optical axis. The hexapod is a parallel robot composed by six legs driven by motors, linking a fixed platform (connected to the telescope structure) to a mobile platform (connected to the mirror); the motors adjust the length of the legs, driving the mirror to the desired position and orientation. The hexapod, also known as Stewart platform, was introduced by Gough [4] and then used by Stewart for a flight simulator [5] in 1965; afterwards it has been used for many different applications including telescope mounts.

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The VST hexapod mechanics is a replica of the TNG implementation [6]; the motion control, the electronics and the kinematics algorithms are totally new. The compensation of defocus and coma has been initially studied applying the theory of two mirror telescopes (see the two Wilson's books [7], [8]). Nevertheless VST is not a classical two mirror telescope, because it incorporates also refracting elements: a set of field corrector lenses, and a removable Atmospheric Dispersion Corrector (ADC) for observations at large zenith angles. Thus, ray-tracing simulations for both optical configurations (with or without ADC) have been compared to the classical two mirror telescope theory, in order to cross-check the results. The difference between the two computation methods is 13% for the constant between defocus r.m.s. coefficient and movement along the optical axis, and 5% for the constant between coma r.m.s. coefficient and the rotation around the mirror centre of curvature.

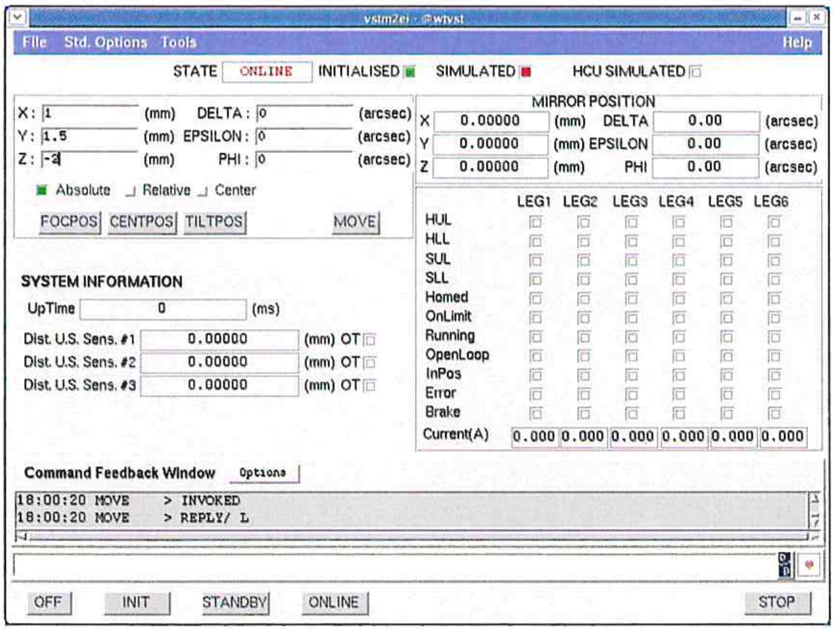
Fig. 1 – The VST hexapod connected to the astatic levers support system and to a metallic dummy of the mirror.

3. KINEMATICS

In robotics, kinematics is always needed to translate the coordinates from the work-space, (usually a Cartesian reference frame) to the joint-space (defined by the linear or rotational degrees of freedom of the robot) and vice-versa. With serial robots, the forward kinematics (from joint-space to work-space) is straightforward and the inverse kinematics is much more complex; with parallel robots as the hexapod, the situation is exactly the opposite. In our case, the inverse kinematics problem is the determination of the six leg lengths necessary to drive the secondary mirror to the appropriate position and orientation. The leg lengths are the distances between the joints of the fixed and mobile platforms p_{fi} and p_{mi} (hereafter the subscript i is used, ranging from 1 to 6). Introducing the vector $q=[x\ y\ z\ \phi\ \theta\ \psi]^T$, a generic movement of the hexapod can be described by the vector Δq, which causes the mobile points move from the generic p_{mi} to p'_{mi}. Representing the rotational part by the 3x3 matrix R_{rpy} and the translation by the vector $T=[\Delta x\ \Delta y\ \Delta z]^T$, in terms of homogeneous coordinates:

$$P'_{m_i} = RP_{m_i} \tag{1}$$

where $P_{mi}=[p_{mi}\ 1]^T$, $P'_{mi}=[p'_{mi}\ 1]^T$ and the 4x4 matrix R is:



STATE ONLINE INITIALISED 🟩 SIMULATED 🟥 HCU SIMULATED ☐

X: 1 (mm) DELTA: 0 (arcsec)
Y: 1.5 (mm) EPSILON: 0 (arcsec)
Z: -2 (mm) PHI: 0 (arcsec)

■ Absolute ☐ Relative ☐ Center

MIRROR POSITION

X	0.00000	(mm)	DELTA	0.00	(arcsec)
Y	0.00000	(mm)	EPSILON	0.00	(arcsec)
Z	0.00000	(mm)	PHI	0.00	(arcsec)

	LEG1	LEG2	LEG3	LEG4	LEG5	LEG6
HUL	☐	☐	☐	☐	☐	☐
HLL	☐	☐	☐	☐	☐	☐
SUL	☐	☐	☐	☐	☐	☐
SLL	☐	☐	☐	☐	☐	☐
Homed	☐	☐	☐	☐	☐	☐
OnLimit	☐	☐	☐	☐	☐	☐
Running	☐	☐	☐	☐	☐	☐
OpenLoop	☐	☐	☐	☐	☐	☐
InPos	☐	☐	☐	☐	☐	☐
Error	☐	☐	☐	☐	☐	☐
Brake	☐	☐	☐	☐	☐	☐
Current(A)	0.000	0.000	0.000	0.000	0.000	0.000

SYSTEM INFORMATION

UpTime 0 (ms)

Dist. U.S. Sens. #1	0.00000	(mm)	OT ☐
Dist. U.S. Sens. #2	0.00000	(mm)	OT ☐
Dist. U.S. Sens. #3	0.00000	(mm)	OT ☐

Command Feedback Window

```
18:00:20 MOVE     > INVOKED
18:00:20 MOVE     > REPLY/ L
```

Fig. 2 – The hexapod control GUI.

$$R = \begin{pmatrix} R_{rpy} & T \\ 0 & 1 \end{pmatrix} \tag{2}$$

Then, defining:

$$s_i = P'_{m_i} - P_{f_i} = RP_{m_i} - P_{f_i} = \begin{pmatrix} x'_{m_i} - x_{f_i} \\ y'_{m_i} - y_{f_i} \\ z'_{m_i} - z_{f_i} \\ 1 \end{pmatrix} = \begin{pmatrix} s_{i_x} \\ s_{i_y} \\ s_{i_z} \\ 1 \end{pmatrix} \tag{3}$$

the computation of the leg lengths to drive the mirror to a new position and orientation follows straightforward:

$$L_i = \sqrt{{s_{i_x}}^2 + {s_{i_y}}^2 + {s_{i_z}}^2} = G(s_i) \tag{4}$$

Thus the inverse kinematics problem admits the unique analytic solution (4), in closed form. This is not the case for forward kinematics, i.e. the computation of position and orientation of the mirror starting from the six leg lengths; this is a much more complex computation, that is needed before relative corrections. There is a wide literature on the forward kinematics of Stewart platforms (see [9] for a review), nevertheless rarely related to astronomical instruments. In VST an algorithmic iterative approach is used, which leads to the correct result within a predetermined error threshold. Its main drawback is the lack of a priori knowledge of the number of iterations; nevertheless this is not a problem in the specific application of VST active optics: small corrections are foreseen only once in a minute, so the forward kinematics computation time is not a concern. The problem unknown is Δq, knowing L_i. Following the Newton's method, linearizing around an initial point q_0 and stopping the series expansion to the first order term:

Fig. 3 – The hexapod control cabinet installed on the telescope.

$$\Delta q \approx \left(\left. \frac{dG}{dq} \right|_{q=q_0} \right)^{-1} \Delta L_i = J^{-1} \Delta L_i \qquad (5)$$

where J is the Jacobian matrix. The (5) is just a first order approximation, thus embedding an error on Δq estimate. The numerical approach presented here removes totally this error, even though it is not based on closed mathematical forms. The iterative algorithm starts from an initial guess of the degrees of freedom vector, that is translated by the inverse kinematics to a guess of the leg lengths. These are compared with the known leg lengths, verifying if their difference is lower than the predefined threshold ε. If this is not the case, a correction to the guess of the degrees of freedom vector is computed, applying the inverse of the Jacobian to ΔL and then adding the result to the old guess. The algorithm terminates when the error is lower than the threshold. The number of iterations depends very much on the threshold and the initial guess. In the case of VST the motion range is small, so the initial guess is never very far from the real position. Setting the error threshold to 0.1 nm, a negligible value for practical purposes, the algorithm normally converges in less than ten iterations, in a time well within the application necessities. For a detailed description of forward kinematics algorithm and the computation of the Jacobian matrix, see [10].

4. CONTROL SYSTEM

The operation of the hexapod are controlled from the Telescope Control Software (TCS) [11] workstation. The secondary mirror position is controlled by several motion commands available at the hexapod engineering interface (Fig. 2). They allow to move the secondary mirror to any desired position and orientation, as it is needed for engineering purposes or for specific tasks as the telescope alignment. Also, two dedicated commands are available for defocus and coma corrections: they are called by the active optics software which coordinates the activities of wavefront sensor, primary mirror supports, and secondary mirror positioner. All commands can be applied both in absolute and in relative mode.

Each of the six hexapod legs is a linear actuator, driven by a synchronous brushless DC motor; the position feedback comes from a rotary encoder.

The actuators are controlled by a Hexapod Control Unit (HCU) based on commercial components (CPU, axes controllers, communication boards, power amplifiers for the motors) installed in an electronic cabinet mounted on the telescope (Fig. 3). The HCU manages real-time forward and inverse kinematics and, for each movement, computes the trajectories for the six actuators, that start and stop simultaneously. The trajectories are kept consistent, moving only the desired coordinates, and avoiding cross-talks on the other mirror degrees of freedom.

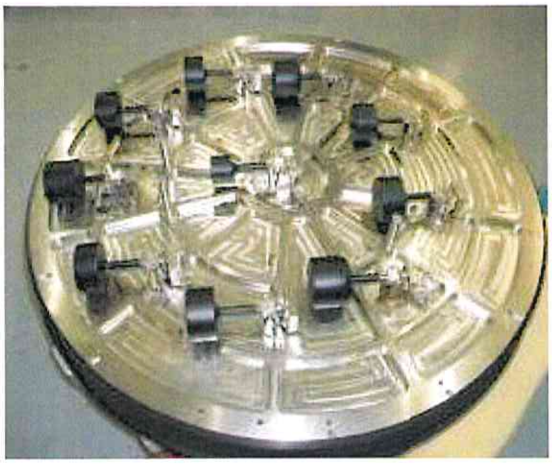


Fig. 4 – The astatic lever support system during the integration

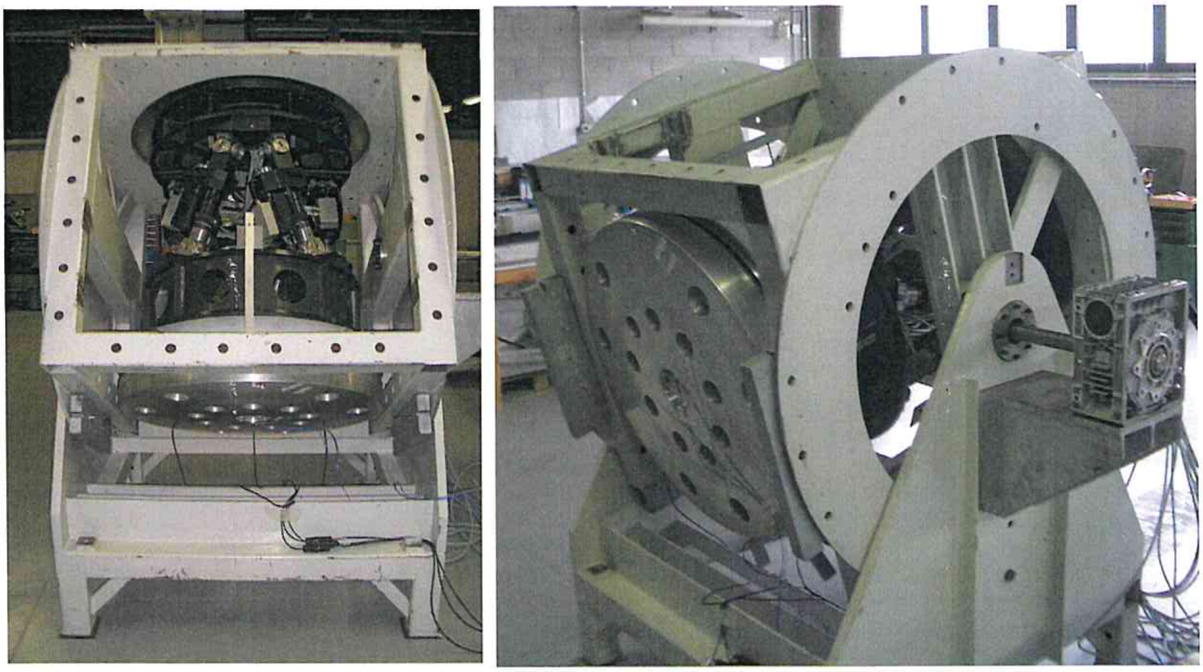


Fig. 5 – The secondary mirror support system on a tilting device, during tests at ADS International s.r.l. premises.

A Local Control Unit (LCU) based on Versa Module Eurocard (VME) bus, running VxWorks 5.5 real-time operating system, sends the position commands to the HCU and receives back telemetry. The LCU communicates also with the TCS workstation, running Scientific Linux operating system, which coordinates the active optics activities. LCU and workstation follow strictly the ESO standards in terms of hardware and software infrastructures, in order to favor maintenance operations.

TCS workstation, LCU and HCU are all nodes of the telescope Local Area Network (LAN). The LCU and workstation software is developed in C and C++, using Tcl-Tk for the user interfaces as in the ESO VLT scheme. The programming environment is provided by ESO through the annual releases of the VLT Common Software package. The standards set by ESO define programming style, naming conventions, directory structure for software modules, standard Makefile for module compilation and installation.

Fig. 6 – A phase of the installation of the hexapod in the telescope.

Fig. 7 – The secondary mirror support system integrated in the telescope in Chile.

5. PERFORMANCE

Each of the six legs was individually tuned and characterized before the assembling of the complete unit and the start of the overall system tests. The positioning error of the single actuators proved to be within 1-2 encoder counts (1 encoder count = 62.5 nm) under operational load conditions.

The operating envelope is defined by the 25 mm stroke of the legs: the hexapod can perform simultaneously ±4 mm displacements along X and Y, ±7 mm along Z, ±0.5 deg tilts around X and Y; it can also exceed these values for some degrees of freedom, restricting the range for the others.

The maximum linear speed is about 1 mm/s; this allows a relatively short initialization procedure, the only situation where the hexapod travels several millimeters.

After the tests of the single actuators, the performance of the whole hexapod unit have been tested taking into account the telescope error budget [12], and the operating conditions.

The active optics scheme foresees the application of an absolute correction based on a look-up table at the end of telescope slewing; afterwards, relative corrections are applied in closed-loop based on the feedback coming from the wavefront sensor, with a 1 minute correction period (there is also the possibility to work in open-loop using always the look-up table data, rather than the wavefront sensor feedback). Therefore the capability to perform small relative corrections with high accuracy is the most important for the image quality.

The budget for errors coming from inaccurate positioning of the secondary mirror was set to 0.5 μm for motions along the optical axis Z (for defocus correction); 5 μm for decentering motions along X and Y, and 0.5 arcsec for rotations around the mirror vertex (for coma correction).

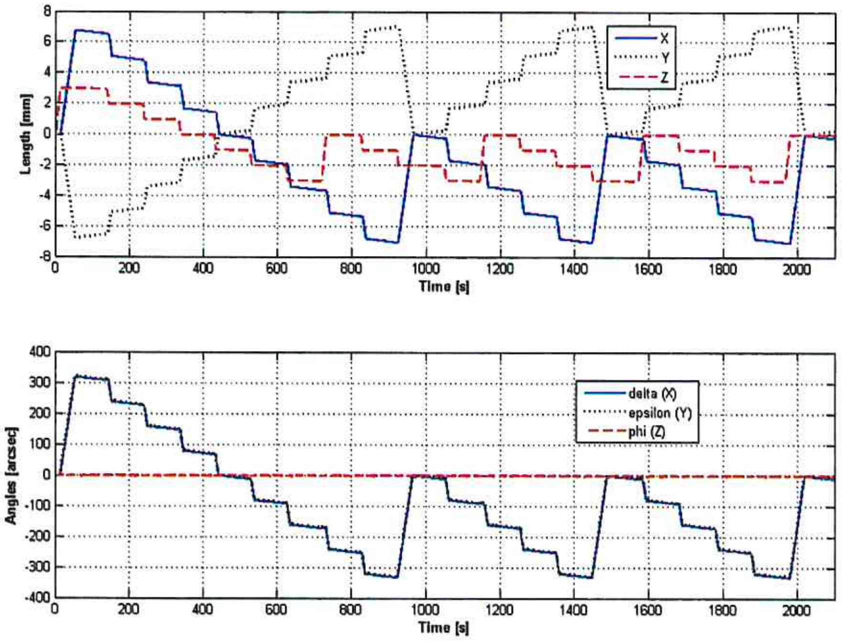


Fig. 8 – Performance tests: sequence of large absolute corrections followed by small relative adjustments.

The hexapod performance has been tested in laboratory with sequences of large absolute and small relative corrections, simulating the real active optics operation. The relative corrections in the sequences corresponded to about 80 nm of defocus and coma (2 μm displacements along Z, 1 arcsec rotations around the centre of curvature). As expected after the results obtained in the tests of individual actuators, the hexapod performance were within the budget. The hexapod has been connected to the mirror support interface based on astatic levers (Fig. 4), in turn connected to a metallic dummy of the mirror. The overall chain of hexapod, astatic levers support system and dummy was installed on a tilting device simulating the rotation of the telescope in laboratory (Fig. 5), and the test sequences were repeated intensively in the whole altitude range (0°-70° in terms of zenith angles). Further, reliability tests were performed from zenith to horizon, so even outside the operational range, in order to stress the system in a worse condition than any real case. The reliability tests were based on random motion commands in the whole hexapod operational envelope, with a much higher duty cycle than in normal operations.

Both performance and reliability tests were performed again at the telescope in Chile, where the secondary mirror support system has been installed in 2009 (Fig. 6, Fig. 7).

Fig. 8 shows a test of operating conditions simulation: large absolute corrections are followed by several small relative corrections, simulating the first correction (look-up table based) after the telescope slewing phase and the next periodic corrections driven by the wavefront sensor.

Fig. 9 is a magnification of small defocus and coma corrections; the motions along the optical axis in 2 μm steps are visible in the top, the rotations around x and y (superimposed) in 1 arcsec steps are shown in the bottom: the control errors are noticeably very small, sometimes with negligible (for their little amount and short duration) overshoots in the correction of defocus.

Fig. 10 shows some 21 μm lateral decentering steps along x and y, associated to a 1 arcsec rotation around the mirror centre of curvature.

Fig. 11 presents one session of reliability tests, based on random movements with the telescope pointing to horizon, i.e. in a worse load condition than in the real case: the linear degrees of freedom (top) change of some millimeters, the rotations around x and y (bottom) are up to 2000 arcsec.

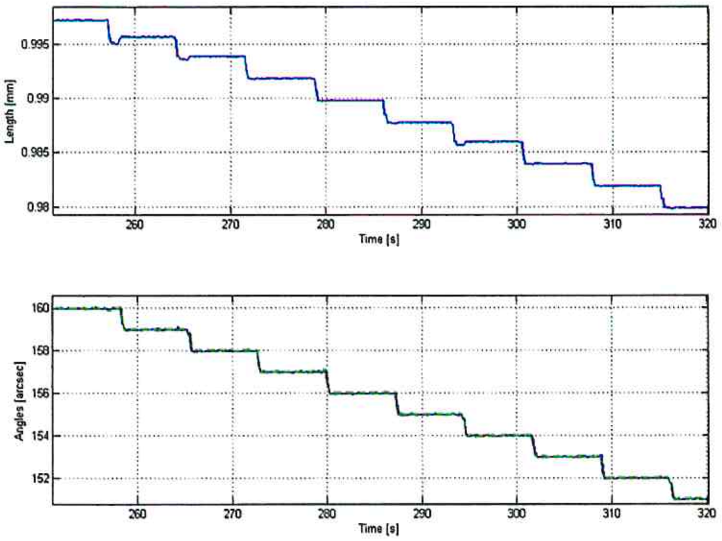


Fig. 9 – Magnification of 2 μm defocus corrections (motions along the optical axis), and 1 arcsec rotations around the secondary mirror center of curvature to compensate for coma.

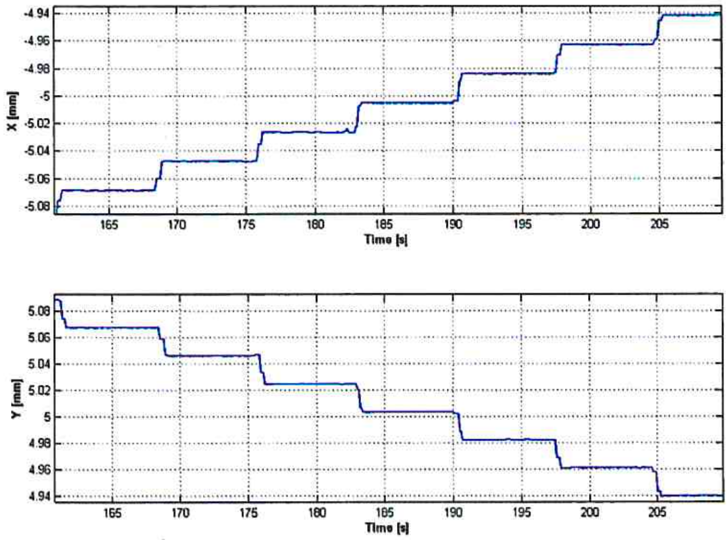


Fig. 10 – Magnification of 21 μm lateral displacement corrections, associated to 1 arcsec rotations around the secondary mirror center of curvature, to compensate for coma.

6. CONCLUSIONS

The secondary mirror support system of VST has been tested in laboratory and then installed at the telescope. The positioning unit is based on a stiff 6 degrees of freedom parallel robot. The control system embeds real time kinematics computations, using in practice no approximation in the translation from joint space to work space and vice-versa. The results of performance and reliability tests have been shown. Optical tests with the real mirror, replacing the metallic dummy, are upcoming.

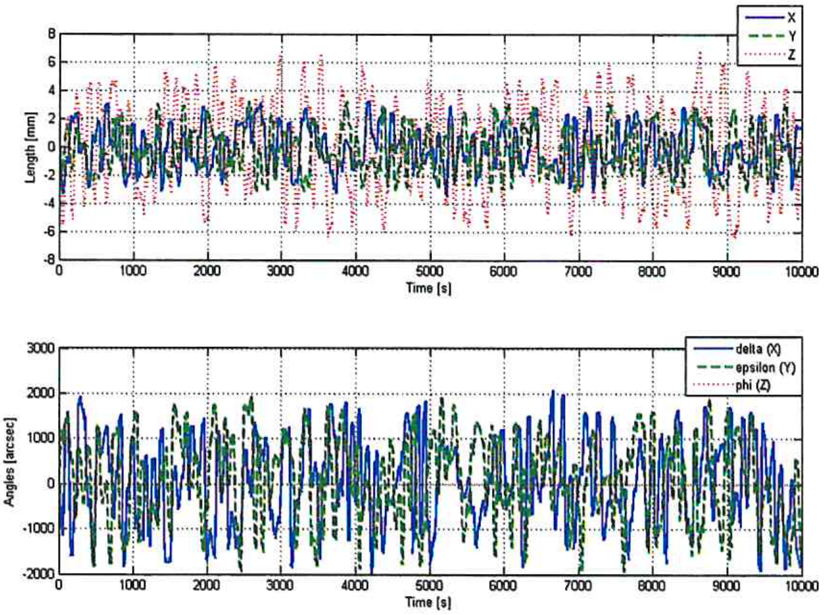


Fig. 11 – Reliability tests: random motions within the operating envelope.

7. ACKNOWLEDGEMENTS

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