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VISTA Secondary Mirror Drive Performance and Test Results

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ABSTRACT

This paper summarizes the main aspects of the design and qualification test results of the secondary mirror mechanism for the VISTA Telescope. A design overview is presented, with detailed description of the main aspects of the system including the electromechanical part and the control system. Also a description of the test facilities and test methodologies is provided prior to the presentation and discussion of the performance test results.

Keywords: Alignment, Secondary Mirror, Hexapod, VISTA

1. INTRODUCTION

VISTA (Visible and Infrared Survey Telescope for Astronomy) will be a 4-m class wide field survey telescope for the southern hemisphere, equipped with a near infrared camera and located at ESO's Cerro Paranal Observatory in Chile, near the VLT and the VST. The site, telescope aperture, wide field, and high quantum efficiency detectors will make VISTA the world's outstanding ground based near-IR survey instrument [1].

The VISTA M2 Unit consists of an Hexapod made with 6 linear actuators in the conventional 3-3 arrangement and its function is the accurate positioning of the secondary mirror (approx. 1.2 meter diameter and 240 Kg weight). The geometry, in particular the M2 Unit ratio diameter to height is optimized for a maximum hexapod stiffness.
The main performance required for the VISTA M2 Unit is the active mirror position adjustment in 5 degrees of freedom to compensate the gravitational and thermal deformation of the Telescope structure and maintain the optical configuration. The adjustment motion of the M2 Assembly is defined along the *M2 Effective Axes*, whereby *centring* is defined as a rotation about a point 4018.8 mm above the M2 vertex and *tilt* is defined as a rotation about a point 1050 mm above the M2 vertex (see *Figure 1a*).

As system verification is made by means of instrumentation that provides position in cartesian coordinates, quantitive performance requirements are expressed in both Effective Axes and *Vertex* (cartesian) coordinates. The following table summarizes them:

Hexapod Performance	**Focus**	**Centring**		**Tilt**	
		Effective	**Vertex**	**Effective**	**Vertex**
Range	± 4 mm	± 3 arcmin	± 4.423 mm	± 3 arcmin	± 6 arcmin
Absolute Accuracy	10 µm rms	3 arcsec rms	58.5 µm rms	0.4 arcsec rms	0.4 arcsec rms
Differential accuracy	1 µm	0.2 arcsec rms	3.9 µm rms	0.1 arcsec rms	0.1 arcsec rms
Speed (≥)	0.05 mm/s	0.05 armin/s	58.6 mm/s	0.05 arcmin/s	0.05 arcmin/s
Step minimum amplitude	1.5 µm rms	0.5 arcsec	9.7 µm	0.15 asec	0.15 asec

Table 1: VISTA M2Unit requirements

Translation from M2 Effective Axes coordinates to M2 vertex coordinates is given by the following expressions:

$X_{M2} = -C_y * r_c - T_y * r_t;$
$Y_{M2} = C_x * r_c + T_x * r_t;$
$Z_{M2} = Z + r_c (1\text{-}\cos(|C|) + r_t (1\text{-}\cos(|T|)$
$A_{M2} = C_x + T_x$
$B_{M2} = C_Y + T_y$

where |C| and |T| are respectively the absolute center and tilt angles and r_c and r_t are respectively the centering and tilt radiuses as defined in the *Figure 1*.

Additional performance requirements are related to cross-talk, dynamic behaviour and stability. In case of *Cross-Talk* requirement, motion in any of the effective control axes of up to 20 times the minimum step size shall not cause the position of any other axes to change outside differential accuracy requirements. *Dynamic Behaviour* requirement makes reference system response to step demands:

-Step demands of up to 10 times the minimum step size shall be settled within 3 seconds.
-Steps demands greater than 10 times the minimum step size shall be Settled within a time equal to (3s+1.5*step size/max axis speed).
-All steps demands have a peak of <10% of the step amplitude.

Finally, it is required accuracy *Stability* to be maintained within absolute accuracies over the full range of operating conditions.

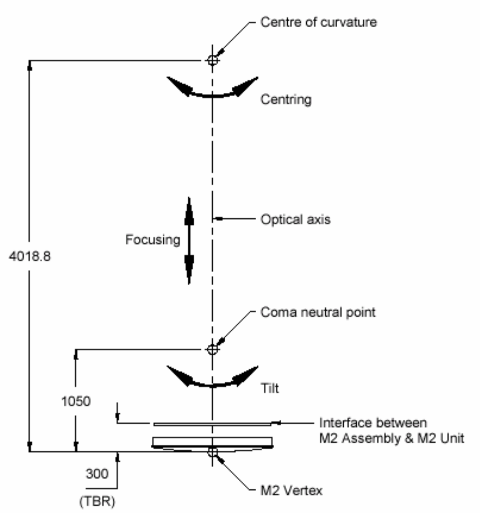


Figure 1a: Effective Axes Definition

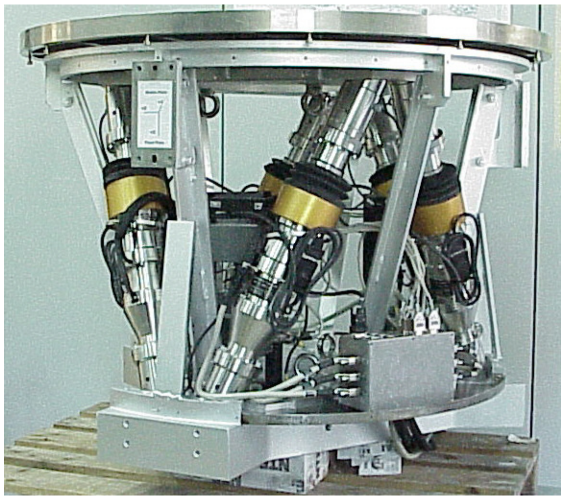


Figure 1b: VISTA M2 Unit Hexapod

2. VISTA M2 UNIT DESIGN OVERVIEW

The Vista M2 Unit consists of an active mechanism capable of 5 degree-of-freedom positioning. These degrees of freedom are combined to have effective motions for the VISTA Secondary Mirror in focus, centring and tilt. The M2 Unit is controlled by a dedicated electronics with embedded control software, installed in a special water cooled box, placed on the top of the telescope structure.

2.1. Alignment Hexapod

The alignment hexapod is composed by the following subsystems: fixed plate, linear actuators, mobile plate, hexapod joints, baffle support and protection cover.

2.1.1. Fixed Plate

The upper fixed plate of the hexapod is attached to the telescope spiders by means of 3 surface interfaces.
This part has been machined from a steel block and painted using low emissivity paint (LO/MIT paint from SOLEC has been used for external surfaces).

2.1.2. Hexapod actuators

Seven high precision Linear Actuator actuators have been manufactured and tested by ADS International s.r.l., reproducing the design implemented for GranTeCan M2 Drive System [3][4].
Each actuator consists of a closely integrated system, comprising a motor, an angular encoder, a screw with planetary rollers and a bearing. A linear encoder provides the detection of the absolute elongation of each actuator and a rotating encoder provides the feedback of the motor position. End-stops and limit switches in each actuator, limit the travel along hexapod focus. In addition, an electromagnetic brake prevents the reverse motion of the mechanism.

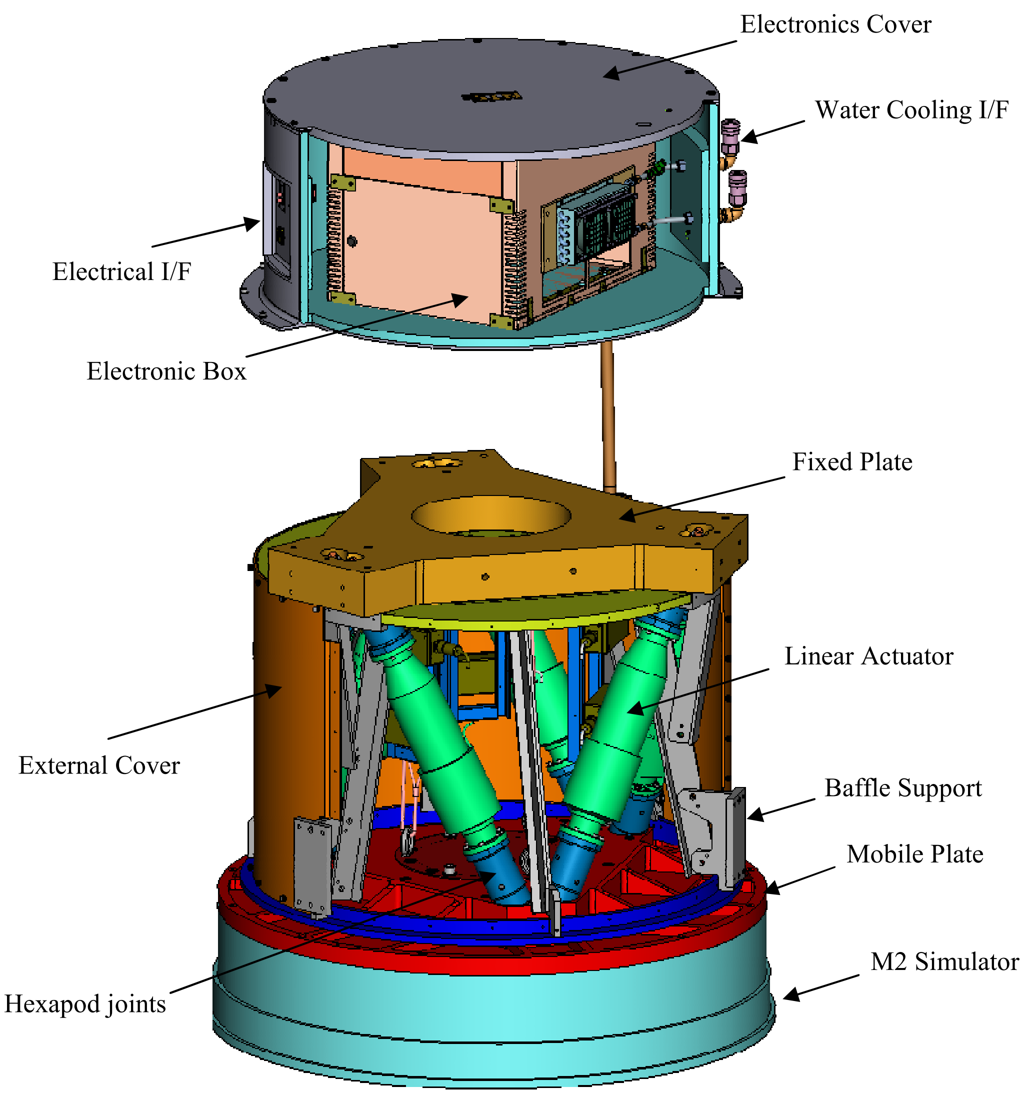


Figure 2: VISTA M2 Unit

2.1.3. Mobile plate

The mobile stage, consist of two parts: an aluminum triangular plate where the joints are attached and the mirror cell cover, also in aluminum alloy, that it is the interface with the secondary mirror by means of 12 M8 non-lose screws along a 1170 mm diameter.

2.1.4. Hexapod joints

The hexapod joints have been implemented using CuBe Flexure rods, preferred solution in front of gumball or spherical bearings, to assure the maximum linear behavior taking into account the system challenging accuracy requirements.
The lateral and tilt travel of the hexapod is limited by end-stops on each flexure joint: two concentric hard-steel cylinders with electrical limit switches that cut the linear actuator supply when the hexapod range is over passed.

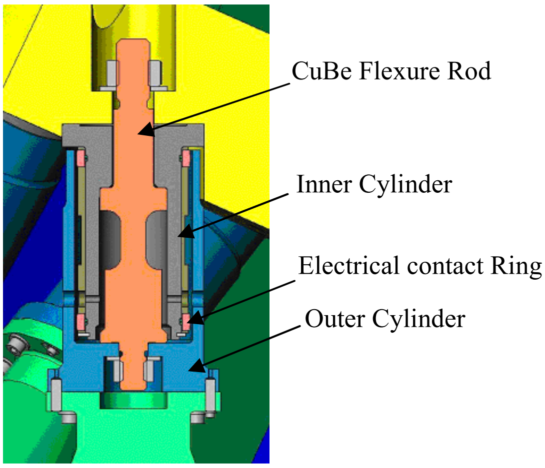


Figure 3: Hexapod Joint

2.1.5. Baffle Support

A ring structure is attached to the fixed plate by means of six bars, including auxiliary reinforcements. The ring and the bars are made in steel. This structure will support a reflective annular Baffle assembled to obstruct a region of the sky around the M2 Mirror.

2.1.6. External Cover

The hexapod is covered using three cylindrical covers, made in glass fibre laminate that contribute significantly to the stiffness of the baffle support structure. The covers are heated to have the external surfaces within ±1ºC the ambient temperature, using heaters and temperature sensors embedded inside the cover fiber.

2.2. Electronic Unit and Control System

The electronics and control software are installed inside a dedicated cylindrical fibre box. It is placed at the top of the telescope, 1.5m above the alignment hexapod and interconnected by signal and power cables.
In order to minimise electronics thermal radiation, the electronic box is water cooled and the air inside homogenised by means of fans. Special care has been taken in components selection, design and test of cooling circuit, to avoid any water leakage.

The M2 LCU (Local Control Unit) is based in a VME computer mounted in a 19'' cabinet. A simplified diagram is shown in *Figure 4*. Most of the parts used in the control system are electronic boards standardized by ESO, which eases the maintainability and ensures the availability of spare parts at the telescope site.

A Motorola MVME2604 based on the PowerPC 604e processor, is the CPU board in which the VxWorks real-time operating system and the control software run. This board implements the interface with the TCS (Telescope Control System) which sends commands to operate on the system and with the other parts of the LCU, in addition to the execution of monitoring and control tasks.

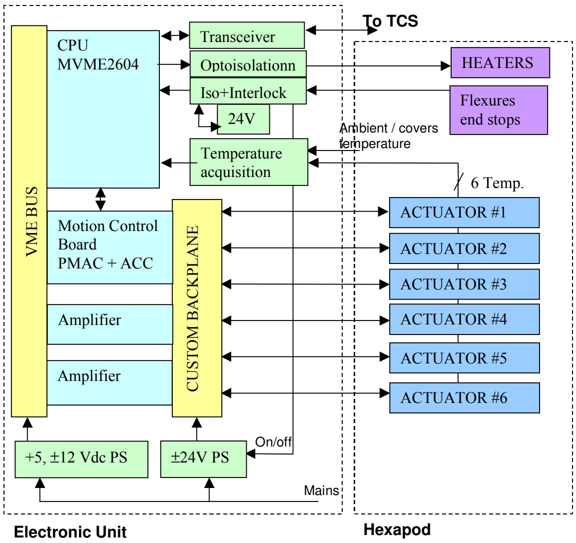


Figure 4: Simplified diagram of the LCU

The actuators motion is controlled by a PMAC VME motion board. This powerful controller implements a dual servo loop that ensures an accurate backlash-free positioning for each actuator. The feedback signals are issued by a Heidenhain rotary encoder mounted on the actuator shaft and a linear encoder (interpolated to improve accuracy and resolution) that provides the absolute elongation of the actuator. Based on this information, the board issues a control signal that after amplification is applied to the actuators motor. The PMAC and the amplifiers are connected through the P2 connectors using a custom-designed backplane. This device has built-in a versatile and powerful multi axis motion control. PMAC PLC's, Motion Programs and a user-written servo routine are the control system software components embedded that, together with the built-in PID servo motion algorithms, controls the motion of the secondary mirror in focus, centering and tilt.

The LCU is also in charge of the thermal control of the M2 Unit. This includes the acquisition of temperature readings and the control of the heaters located in the M2U covers. Thanks to this system, temperature homogeneity of +/- 1º with respect to ambient can be ensured.

The electronics include an interlock circuit that automatically stops motion and activates the actuator brakes when one of the hexapod flexures reaches its mechanical limit. This system ensures that no damage is made to the unit in case of unexpected out-of-range operation.

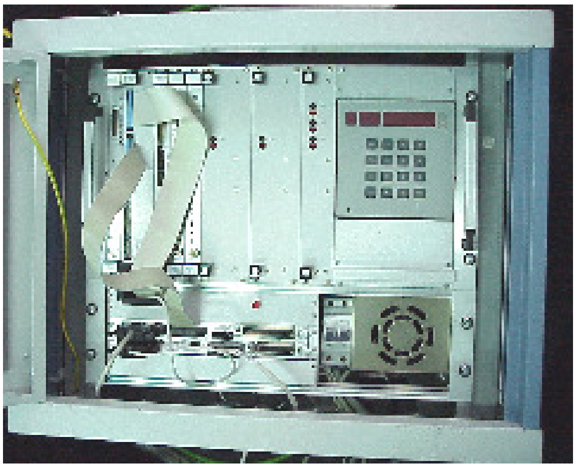


Figure 5: Snapshot of the Vista M2 Unit LCU

3. VISTA M2UNIT PERFORMANCE TEST AND RESULTS

3.1. TEST SET-UP

The test stand is very similar to the one used for GTC M2 Drive integration except for some minor modifications. The socket supports the M2 Drive during testing and can be dismounted for transportation. The bench allows the rotation in altitude of the socket to reproduce telescope elevation positions and is placed on a seismic isolation ground to minimize external perturbations during measurements.

Figure 7. Test Stand Picture

The lower part of the socket is adapted for the fixation of the metrology instrumentation used for calibration and verification of the system. An autocollimator and a set of three linear encoders were used for verification, with the help of several calibrated gadgets mounted in two different setups. An interferometer and a rectitude sensor with a corner cube were also used as additional instrumentation.

The first setup used two prisms glued to form a set of three orthogonal surfaces to be placed on the mirror vertex (See *Figure 8*). These surfaces were verified and used as a reference for calibration. The second setup consisted on a set of linear encoders placed in the usual triangular disposition used to measure focus and tilts. A special calibrated Y shaped gadget was used to ensure accurate positioning of the linear encoders.

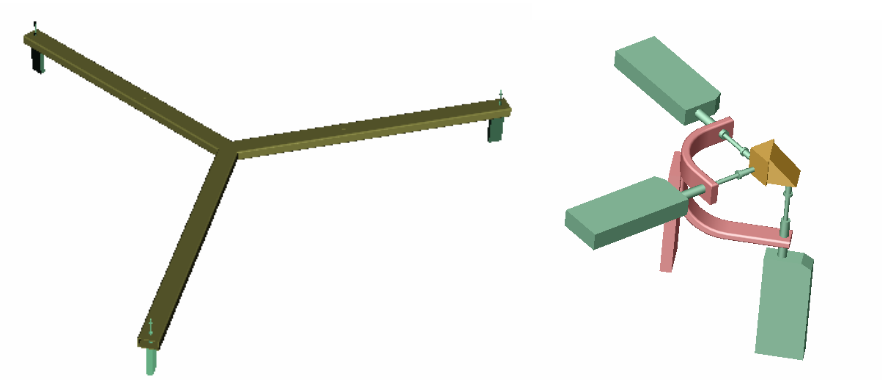


Figure 8: Metrology Tools used for calibration and verification. Left: Y-Shaped Gadget used to measure focus and tilts. Right : Two-Prism gadget and encoders support used to measure focus and lateral displacements.

All the external sensors were connected to a data gathering computer through a GPIB bus and through an encoder data interpolating card. Data from internal sensors was sent by TCP/IP over Ethernet at a rate of 60Hz and acquired and saved jointly with external readouts. The data acquisition and reduction system was built on LabView.

3.2. PERFORMANCES

3.2.1. Test procedures

Test procedures were divided mainly in two sections. The first devoted to absolute accuracy, speed and range of movement verification for each of the effective axes, and the second to differential accuracy, minimum step size, dynamic behaviour and cross-talk requirements.

Test procedures for absolute accuracy basically consisted in commanding the system to a position in a set of predetermined points across the range, gathering data and comparing internal sensors readings with external sensors,. The same procedure was repeated for a set of different elevation angles (see *Table 3*) of the test stand to check performance repeatability..

To verify differential accuracy, dynamic behaviour and minimum step size requirements, a set of step profiles were defined. As it shown in *Figure 9* there is a profile for each movement axis, and each profile contains a number of steps of different amplitude to verify different requirements. Each profile set was commanded at 20 different absolute positions in the movement range and for the six different elevation configurations to check performance stability.

Position	Elevation Angle
1	0º (Zenith)
2	30º moving from Zenith
3	30º moving from 50º
4	50º moving from 30º
5	50º moving from 70º
6	70º

Table 3 : Test Positions

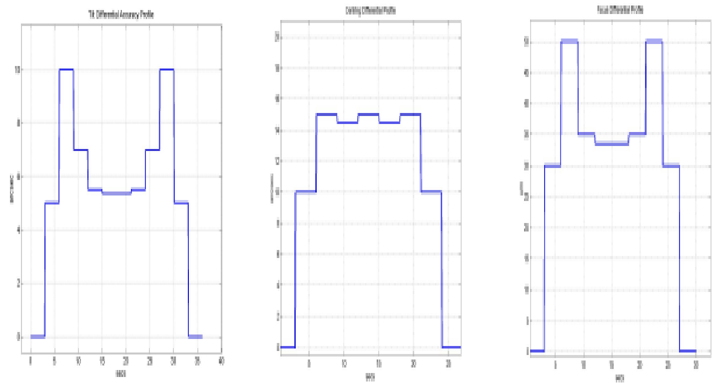


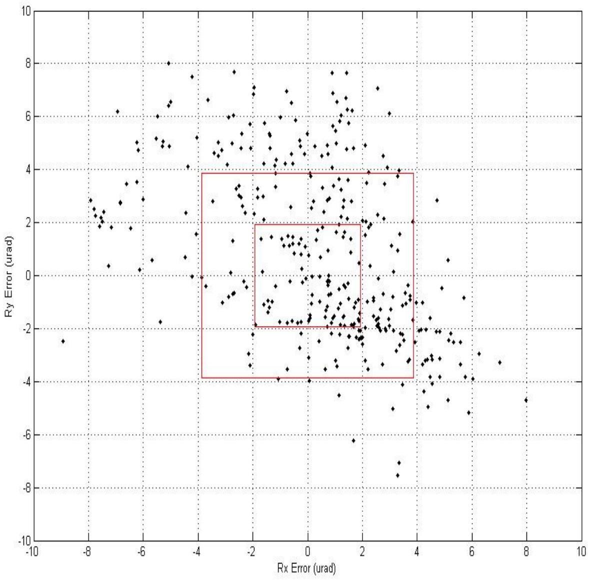
Figure 9: Differential Accuracy Test Profiles

3.2.2. Test results

It must be pointed out that while commanding was done in effective axes; external instrumentation allowed the acquisition of data only in Cartesian coordinates. That is the reason why requirements were translated to equivalent vertex coordinates in order to ease comparison with external instrumentation data. Following results then are shown in Cartesian coordinates.

Figure 10 shows absolute error for Centring and Tilt for each of the test points and for all six elevations. Boxes indicate the absolute value of the rms accuracy requirement. Even thought the number of points is not very high, as they are spread all along the range, the sample is representative enough to obtain a good estimate of the accuracy of the system.

It can be observed that, while centring accuracy seems to be far below requirement, Tilt accuracy is just below twice the requirement. This fact is in contradiction with the expected performance, as repeatability of the system has been measured to be about 1µrad. It is thought that this is the result of an underestimation of the effects of some environmental thermal instability during performance testing, that may have affected the performance of the system or the external instrumentation. Nevertheless, after consideration by VPO, the performance has been accepted.



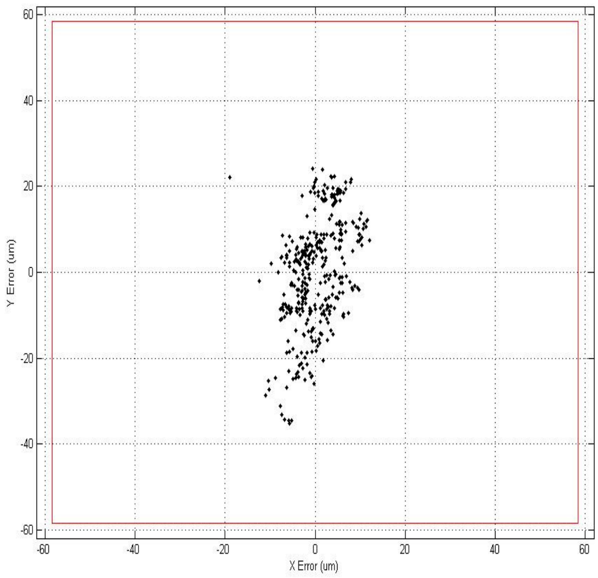


Figure 11 shows a sample of some differential accuracy step profiles and a detail of overshoot behaviour for tilts. Data was gathered at 60Hz using internal sensors, which had been previously correlated to external instrumentation. Performance results for step profiles, except for some minor deviations in cross-talk, are considered satisfactory. The differential tilt accuracy performance achieved of 0.1 arcsec rms is considered to be quite remarkable.

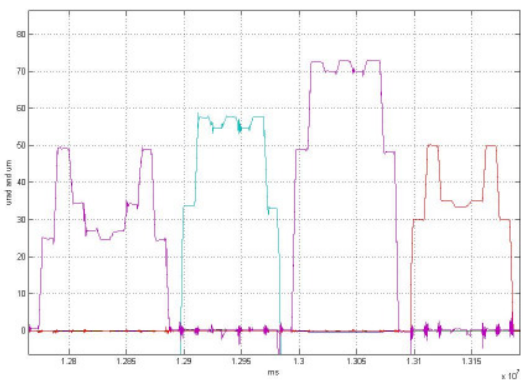


Figure 11.a. Sample of Step Profiles

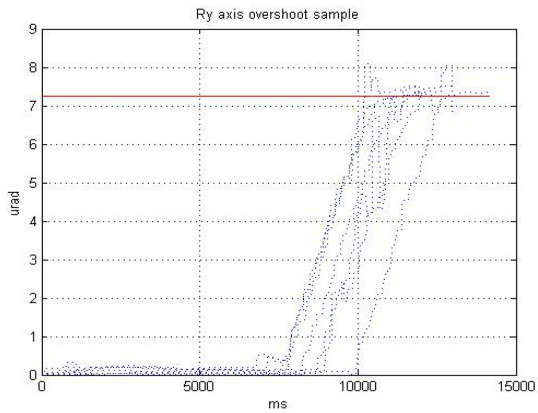


Figure 11.b. Step Overshoot Sample

On the other hand, no appreciable variations or trends in any of the performance parameters were observed for the different elevation configurations.

The following tables summarizes performances measured during test campaign:

Hexapod Performance	**Focus**	**Centring**		**Tilt**	
Ranges	± 4 mm	± 4.423 mm		± 6 arcmin	
		Cx	**Cy**	**Tx**	**Ty**
Absolute Accuracy (rms)	9.66 µm	16.2 µm	28.1 µm	0.73 arcsec	0.79 arcsec
Differential Acc. (rms)	0.3 µm	2.4 µm	2.6 µm	0.10 arcsec	0.11 arcsec
Speed	0.26 mm/s	0.26 mm/s	0.26 mm/s	0.41 arcmin/s	0.41 arcmin/s
Step minimum amplitude	1.5 µm	11.5 µm	11.6 µm	0.11 arcsec	0.11 arcsec

Crosstalk	*Crosstalk below requirement, except in the case of tilt cross-talk when performing focal displacements.*
Dynamic Behaviour	*System capable of 3 seconds settling in the required time.* *X Overshoot 0.49 um rms (Req 9.7 um)* *Y Overshoot 0.47 um rms (Req 9.7 um)* *Focus Overshoot 0.111 um rms (Req 1.5 um)* *Tx Overshoot 0.75 urad (Req 0.73 urad rms)* *Ty Overshoot 1.19 urad (Req 0.73 urad rms)*
Stability	*No performance variations for different elevation configurations.*

4. SUMMARY

The qualification tests carried out on the final system provide a clear report of system performances summarized in this paper. The main performances of the M2 Unit are better than specified except on tilt absolute accuracy and focus cross-talk. It is important to note the outstanding quality and precision of this mechanism taking into account the system dimensions, the mirror weight and the measured performances. The preliminary acceptance review of the system performances, inspections and safety tests were performed at NTE premises on December 2005. The M2 Unit preliminary acceptance was closed at beginning of 2006. The system is now ready to be packaged and transported to Chile for site acceptance and telescope integration. This is expected to be carried out after the summer of 2006.

At this stage in the project it is important to recount our experiences and list the following relevant lessons learned:

- First, and repeated in previous drive systems papers, the quality of the test equipment and test set-up shall be taken into account early in the project and preferably in the design stage in order to avoid repeating and having longer test campaigns.
- According to the experience obtained from GTC and VISTA M2 drive units, it can be confirmed that flexure elements have good performances as hexapod joints. Nevertheless, the precision of the end stops becomes critical when the hexapod range is reduced.
- Some non-conformances were raised during the mechanical subsystems manufacturing. Good quality management of these non-conformances and a working closely with the customer by means of manufacturing inspection points, minimized the impact to the project and avoided any consequences to the system performance.
- Temperature stability during calibration and verification are of clear importance, especially if temperature gradients appear in the laboratory environment.
- Finally, although previous experience in such systems should decrease the effort and time invested during the development of the project; this assumption has been proved to be valid only for the design phase. Control system, calibration and verification have shown that VISTA M2 Unit, although being similar to GTC M2 Drive in some aspects, is different enough so as to generate new problems. Small design variations may produce important system performance behavior variations and this fact should not be neglected during project planning.

5. ACKNOWLEDGEMENTS

The VISTA M2 Unit has been designed, manufactured and tested by NTE S.A under UK ATC contract, in collaboration with the Centre Suisse d'Electronique et de Microtechnique (CSEM) for the system design and analysis and ADS International s.rl. for the Linear Actuators procurement.

We would like to thank all the people involved in the project for the effort driven, necessary to complete such system with outstanding performances within a reasonable schedule and cost budget, and especially to VISTA Project Office for their exemplar project management and kind relation establish during all project phases.

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