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ABSTRACT

The 2.6-m primary mirror of the VST telescope is equipped with an active optics system in order to correct low-order aberrations, constantly monitoring the optical quality of the image and controlling the relative position and the shape of the optical elements. Periodically an image analyser calculates the deviation of the image from the best quality. VST is equipped with both a Shack-Hartmann in the probe system and a curvature sensor embedded in the OmegaCAM instrument. The telescope control software decomposes the deviation into single optical contributions and calculates the force correction that each active element has to perform to achieve the optimal quality. The set of correction forces, one for each axial actuator, is computed by the telescope central computer and transmitted to the local control unit of the primary mirror system for execution. The most important element of the VST active optics is the primary mirror, with its active support system located within the primary mirror cell structure. The primary mirror support system is composed by an axial and a lateral independent systems and includes an earthquake safety system. The system is described and the results of the qualification test campaign are discussed.

Keywords: Active Optics, Telescope, Actuators

1. INTRODUCTION

Starting from mid-2007, after a Critical Design Review of the primary and secondary mirror systems that revealed several weak points in the design, with the exception of some parts, major changes were triggered in the project. The primary mirror support and safety system was deeply reviewed at a system engineering level by INAF, but within time and budget constraints that pushed to recycle as much as possible the existing parts. The telescope error budget was revisited [1] and the concept of the primary mirror support and safety system was redesigned [2], considering both performance and maintenance operations. A similar work was done on the secondary mirror support system [3].The support system conceptual design, the control software and electronics were updated by INAF while the new mechanical parts were designed by Tomelleri srl under INAF requirements and commitment. The earthquake safety system has been designed in a common effort coordinated by INAF that performed the analysis jointly with BCV srl and with a support from ESO, while the mechanical design was committed to Tomelleri srl. In early 2009 the system was considered ready to be shipped, but unfortunately a serious damage during the transportation caused a supplementary year of work in Italy, which has positively terminated with successful system tests on April, 2010. The support system was tested in Italy with a metallic dummy of the mirror, as the mirror was already in Chile.

2. AXIAL SUPPORT SYSTEM

The axial support system is designed to support the component of mirror weight along the optical axis (passive force) and to correct the low order aberrations tuning the optical surface (active force). The primary mirror is a monolithic meniscus of 2.6 m diameter with a 60 cm central hole and 140 mm thickness, made of Astro-Sitall. The concentration of axial devices, i.e. the ratio between the number of axial supports and the mirror surface area, is higher than in comparable size telescopes: VST is indeed a 2 m class telescope incorporating a 4 m class active optics system.

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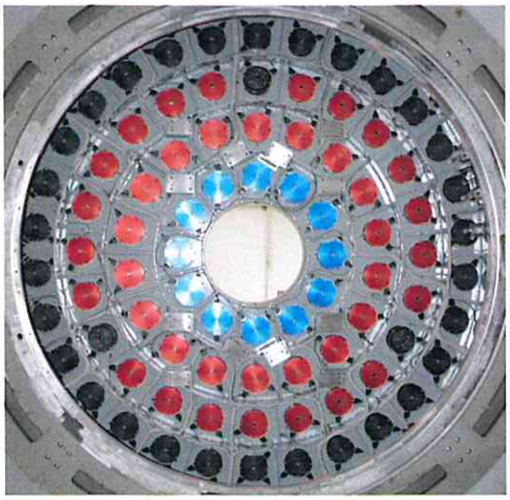

Fig. 1 – The four rings of axial supports from the cell back side. The three black supports in the 3rd ring are the axial fixed points.

Fig. 2 – The axial and lateral supports before the installation of the mirror (top view).

The active forces deform the mirror to remove the amount of aberrations measured by the image analyzer. The axial system corrects at configurable time intervals the shape of the mirror by applying controlled forces on its back surface; the force delivered by the supports is transmitted to the mirror by means of a push-only connection, highly simplifying the mirror removal procedure necessary for the periodic coating. The weight of the mirror is shared between 84 supports (81 electro-mechanical actuators and 3 axial fixed points) distributed in 4 rings of 12, 18, 24, 30 supports (Fig. 1, Fig. 2). The number of supports in each ring is a multiple of 3 in order to place three fixed points at 120° in a threefold symmetry.

The optical aberrations to be corrected changing the shape of the primary are described by the primary mirror natural vibration modes, rather than by the widely used Zernike modes. They form an orthonormal basis with analytic expressions depending on the mirror material and geometry and with shapes analogous to the Zernike modes. For the theory and justification of the use of minimum energy modes see Noethe [4]. Following the Noethe work the mirror aberration modes are computed starting from the equations describing the minimum energy modes of a thin shallow shell. The solutions are characterized by a radial and an azimuthal component. For each rotational symmetry n, the infinite solutions of the problem are found imposing the free edge boundary conditions. The results of the computation are the radial parts of the mirror elastic modes $u_{n,m}(r)$, depending on the symmetry n and the order m; the elastic modes considered for VST are shown in Fig. 3. Further details for the analytical expression of elastic modes and the computation of the calibration forces for VST are discussed in [5].

2.1 Axial Actuators

The axial actuators are electro-mechanical push-only devices. A motorized screw moves axially a piston on which there are six helical springs in parallel; they transmit the load to the mirror through a pusher, acting on a load cell and then on a rotating sphere in contact with the mirror (Fig. 4).

The supports are equipped with local control boards based on microcontrollers, organized in a distributed control architecture based on a CAN bus network [6] whose master node is the VME based Local Control Unit (LCU) that controls both the primary and the secondary mirrors. The LCU communicates with the Telescope Control Software [7] workstation, that implements the coordination of the active optics activities and the computation of the correction forces.

The actuators have a force control capability, up to the 500N limit set by the load cells full scale, with a firmware [8] programmed in C language.

The power to the supports comes from a distribution system based again on microcontroller boards, providing protection, diagnostic and control capabilities. Seven Power Distribution Boards (Fig. 5) supply power to the 84 supports; they are fed by commercial power supplies and are also nodes of the CAN Bus network.

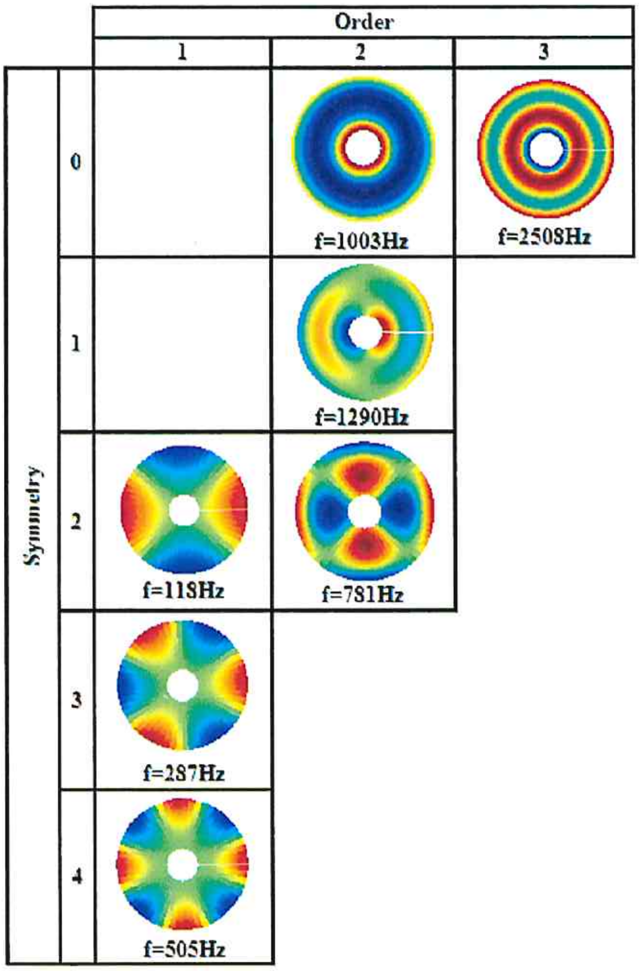

Fig. 3 – The primary mirror elastic modes

2.2 Axial Fixed Points

In the third ring of supports there are 3 axial fixed points delivering just a passive reaction force, interfaced to the mirror by three 120° spaced axial pads. The fixed points define within a predetermined accuracy the axial position of the mirror with respect to the cell. Further, they carry the force unbalance coming from inaccuracies in the force settings of the 81 active supports; in case all the 84 forces would be actively controlled the resultant of these errors would produce an unbalanced net force.

The fixed supports have a much higher spring constant than the active ones, because during operations the loads on the fixed points change producing tilt and this effect is minimized by a high stiffness, of about 12000 N/mm. Their mechanics is derived from the axial actuators with small differences. They are not allowed to take the whole mirror weight, by design: it is forbidden to sustain the mirror in only three points for safety reasons. Hence, the stiffness of the fixed points indeed is not linear by design, and decrease suddenly after a threshold of about 70Kg, becoming identical to the one of active axial supports.

Like the force actuators, the axial fixed points are equipped with local control boards based on microcontrollers, are nodes of the CAN bus network and are equipped with load cells to monitor the reaction forces; unlike them the fixed points have no force control capabilities. They have instead a position control capability: their heights are adjustable by DC motors allowing the alignment of the mirror, with a position feedback system based on two averaged LVDTs.

Fig. 4 – The axial supports in the primary mirror cell.

3. LATERAL SUPPORT SYSTEM

The lateral system supports the weight component of the mirror perpendicular to the optical and altitude axes. It is based on 24 passive lateral supports and three lateral fixed points defining the position of the mirror in the XY plane (XY is the mirror plane, Z is the optical axis).

3.1 Lateral Supports

The mirror is laterally supported by 24 supports based on astatic levers distributed around the external edge (Fig. 6, Fig. 7, Fig. 8). The choice to avoid active controls in the lateral support simplifies the control system and improves the reliability. The implemented solution is a Schwesinger [9] distribution where each of the 24 lateral supports produces a force described by X-Y-Z components; the additional axial forces applied along Z by each lateral support balance the moment produced by the fact that the mirror is laterally not supported under its centre of gravity. The force components and their resultants are derived analytically for each support. The astatic levers are designed to allow the installation of load cells to check the load during the tuning phase.

3.2 Lateral Fixed Points

The lateral fixed points define the mirror position in the XY plane, compensating the small force unbalance caused by force errors in the 24 lateral supports. In the ideal case of perfect astatic levers, null forces should be measured at the lateral fixed points. The fixed points are three, arranged tangentially to the outer edge (Fig. 6, Fig. 7) in order to preserve the mirror from stresses due to free thermal deformations of its cell, with load cells monitoring the delivered forces. They are connected to amplifiers sending the signals to the analogue input channels of three axial actuator boards. The reading of the lateral fixed points forces is implemented within the local control unit monitoring loop of the axial actuators and is available at the Telescope Control Software workstation.

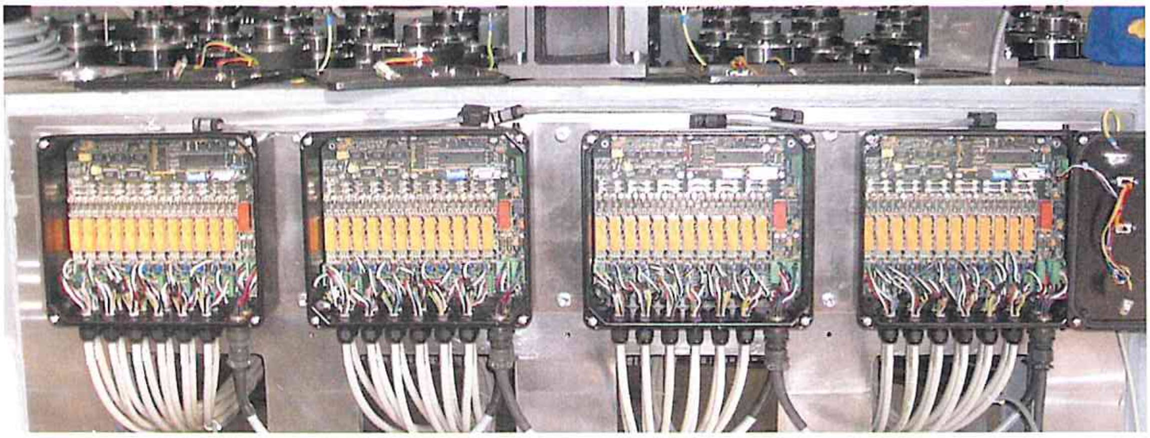

Fig. 5 – Some power distribution boards for the axial supports.

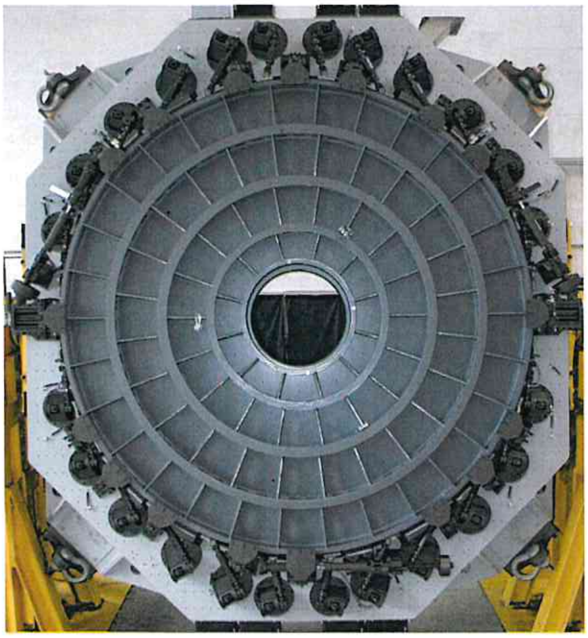

Fig. 6 – The front-side of the support and safety system, with a metallic dummy of the mirror.

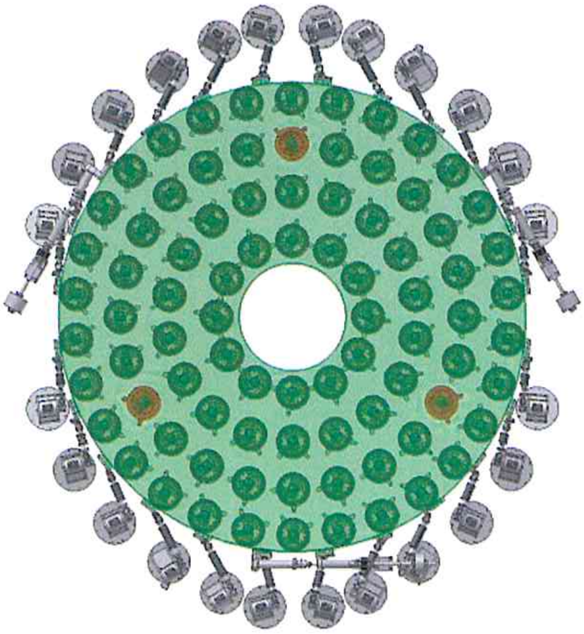

Fig. 7 – Schematic of the axial and lateral support systems. The red supports are the axial fixed points.

4. SAFETY SYSTEM

The safety system has two essential functions:

- a safe restraint of the mirror in all directions during an earthquake event;
- the axial restraint in the whole altitude maintenance range during normal operations, mandatory since the axial actuators are push-only type.

The safety system ensures the safety of the primary mirror under seismic loads, at any position of the telescope tube from zenith to horizon. During observations the safety pads are never in physical contact with the mirror: the contact is established during an earthquake event. The safety pads surface is made by elastomers properly designed to absorb the earthquake energy. In its plane the mirror is protected by lateral safety pads, positioned at 1 mm distance from the mirror outer edge (Fig. 6). Along the optical axis the mirror is protected by pairs of axial safety pads, positioned at 0.5 mm distance from the mirror front and back surfaces.

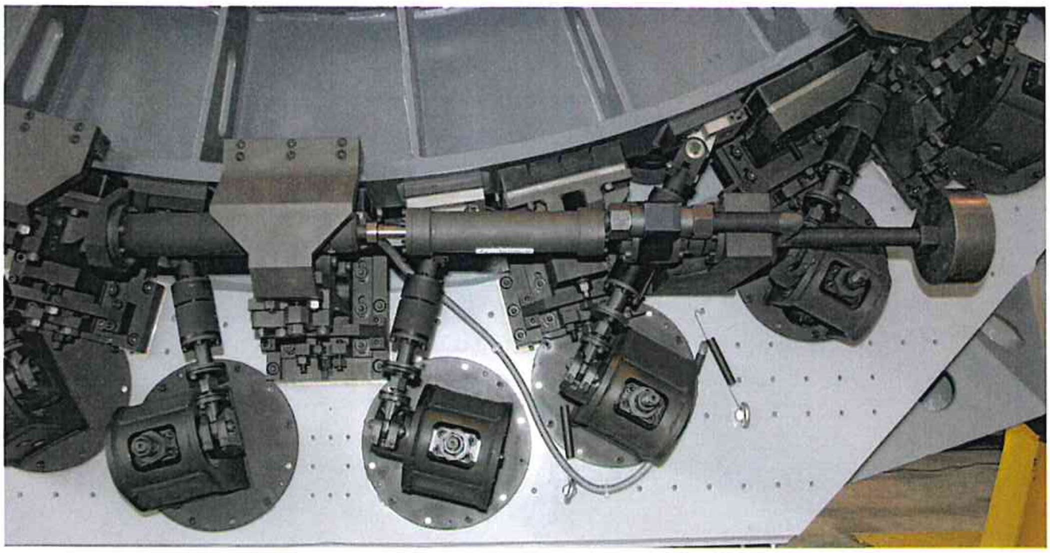

Fig. 8 – Lateral support system: one of the lateral fixed points and some astatic levers.

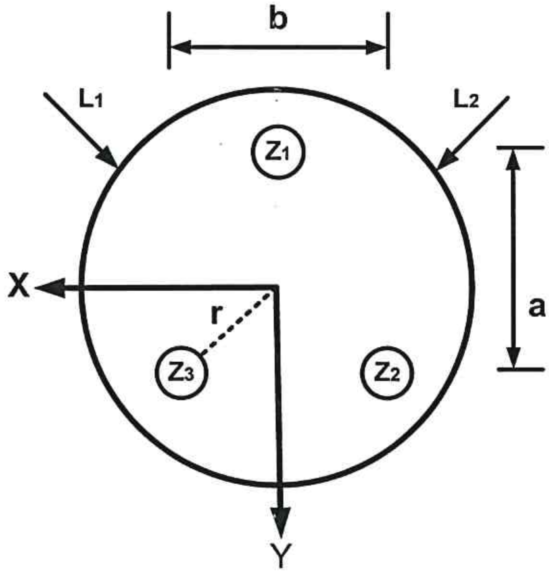

Fig. 9 – Position reading system geometry.

5. POSITION READING SYSTEM

The mirror position and orientation are measured with two different sets of sensors. The three axial fixed points are equipped with high precision LVDTs, providing three 120° spaced readings along Z axis which are used to compute Z, θx, θy. Five additional linear position sensors are also installed, three are 120° spaced under the mirror to compute Z, θx, θy and the other two are disposed symmetrically on the outer edge of the mirror to compute X and Y (Fig. 9); they are connected to the analogue input channels of five axial support boards. The reason for the duplication of the sensors along the Z axis comes from two opposite necessities:

- a high precision reading during normal operation: this is achieved by the axial fixed points LVDTs, but they have a small measuring range and give a meaningless reading when the mirror is not in touch with them (e.g. during the lowering phase of the mirror installation);
- to know the mirror position even during the installation or whenever it detaches from the axial fixed points, a possible situation due to spring-type actuators in not-observing conditions: this task is accomplished by the linear position sensors, less accurate than the axial fixed points LVDTs, but with a much higher measuring range.

The reading of the axial and lateral positions is implemented within the local control unit monitoring loop that computes the five degrees of freedom X, Y, Z, θx, θy and makes them available at the Telescope Control Software workstation.

Fig. 10 – The Hydra-Set load positioner

Fig. 11 – Primary mirror handling procedure (1/4): the mirror is lifted by its handling device, connected to a load positioner and the crane.

6. MIRROR HANDLING

The mirror handling is performed by a handling device which sustains the mirror by 6 external and 3 internal (in the central hole) legs. Despite the impressive (with respect to the mirror size) number of devices surrounding the cell, the primary can be installed and removed with minimum maintenance activities, because the location of lateral safety pads has been optimized with the criterium to allow the insertion and removal of the mirror in the cell with its handling device, without the necessity to dismount them. Before the installation and removal, the safety devices just need to be moved back.

Fig. 12 – Primary mirror handling procedure (2/4): lowering the mirror on the axial supports.

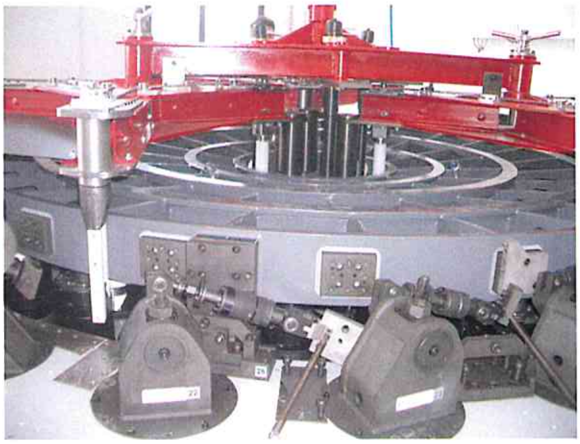

Fig. 13 – Primary mirror handling procedure (3/4): the mirror rests on the axial supports, lateral fixed points and supports are connected.

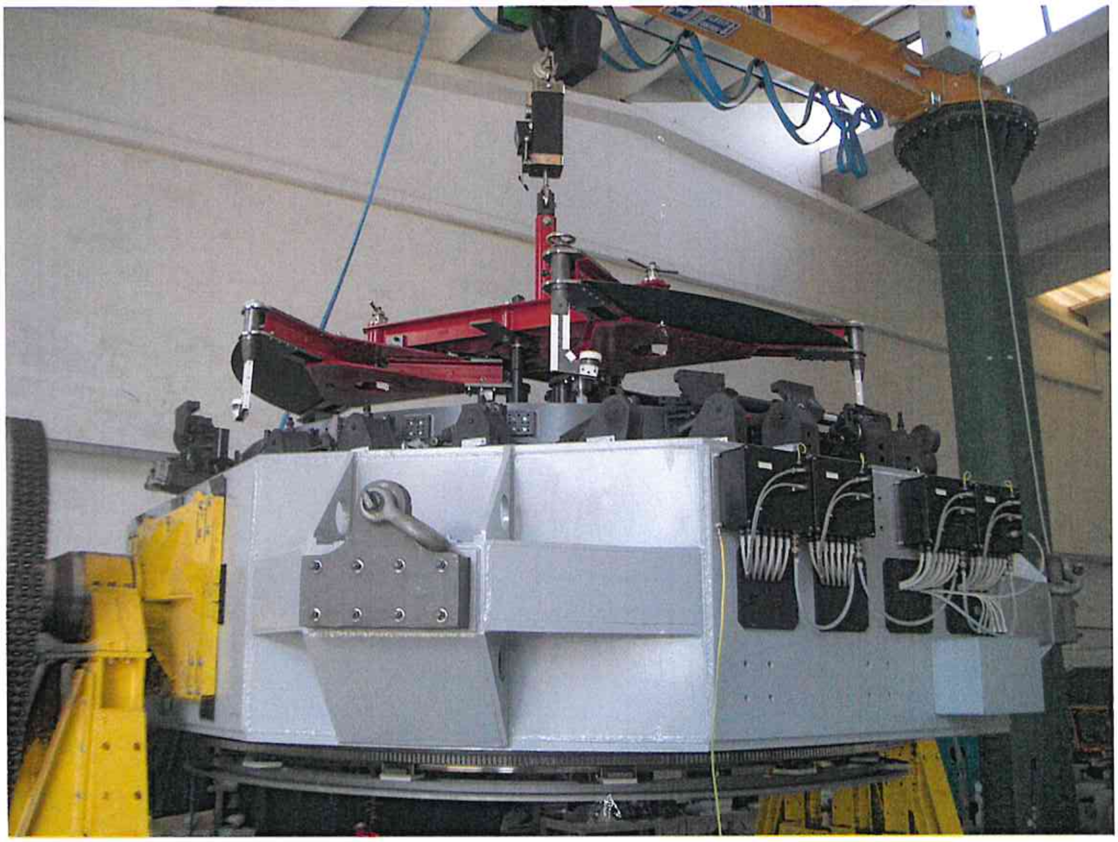

Fig. 14 – Primary mirror handling procedure (4/4): the handling device is removed

In the handling procedure (Fig. 11, Fig. 12, Fig. 13, Fig. 14) a Del Mar Avionics Hydra-Set precision load positioner (Fig. 10), used in between the crane and the handling device, allows to perform the lowering phase very smoothly. The installation of the mirror is relatively straightforward, with a procedure which is here summarized:

Fig. 15 – The mirror cell during tests on a motorized tilting device at Tomelleri s.r.l. premises.

- the mirror cell is prepared, moving back all the mechanical devices which could interfere
- the active axial supports are sent to their lower limits
- the axial fixed points are sent to their nominal position
- the mirror is lowered, until it touches the axial linear position sensors
- the mirror is further lowered, after some millimiters the lateral fixed points are connected
- the mirror is further lowered, until it touches the axial fixed points, but still it is mainly sustained by the crane
- the mirror is further lowered, the axial fixed points stiffness threshold is overcome and they are compressed down by the mirror weight
- the mirror is further lowered, until it rests on all the axial supports and the crane sustains only the weight of the handling device
- the handling device is removed
- the mirror is pushed up by the active supports to its nominal position
- the lateral supports are connected
- the earthquake protection safety devices are moved to their nominal position

Each step of the procedure is monitored by the crane operator in coordination with a workstation operator. The procedure was tested several times with the mirror dummy, taking a reasonably short time.

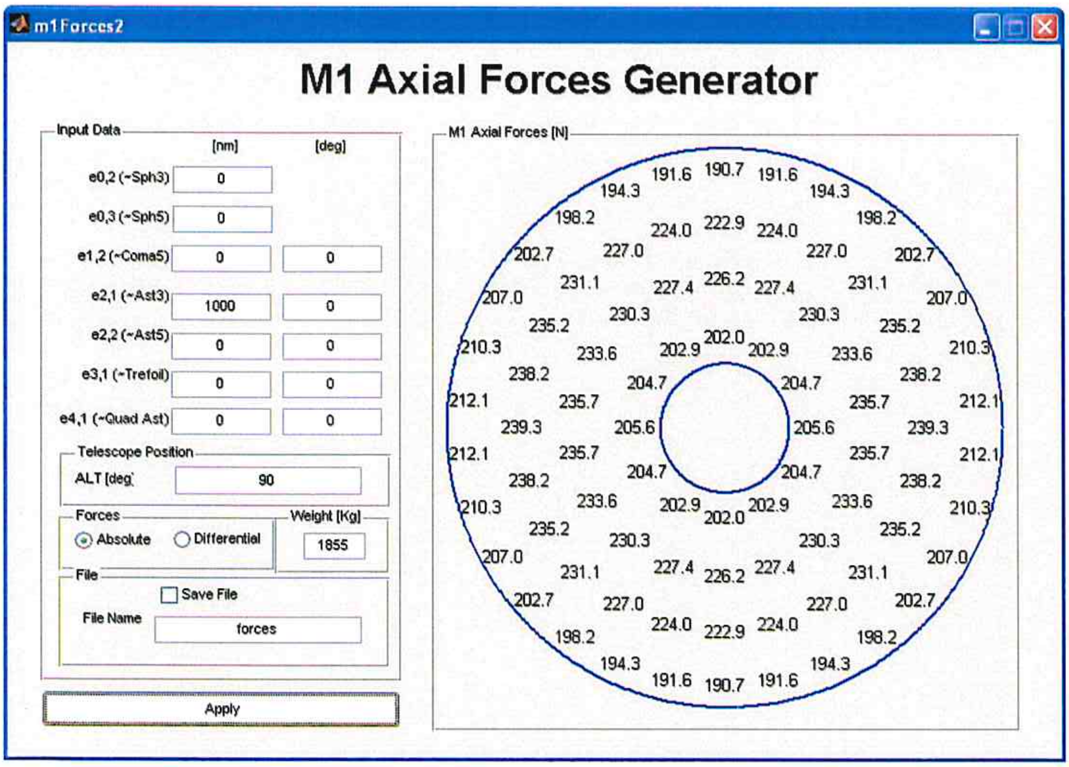

Fig. 16 – Matlab tool to compute axial support forces.

7. TESTS OF THE SYSTEM

Many tests have been performed to validate the system in the factory with all the subsystems integrated, the mirror dummy installed in the cell, the cell mounted on a rotating device to simulate the altitude angle variations (Fig. 15). The tests have been performed at the extreme positions of the telescope operating range and in some intermediate positions.

They were based on sets of forces to be applied to the mirror through the 81 active supports, stored in text files. A Matlab application (Fig. 16) was created to generate easily and quickly force files in the Telescope Control Software format, allowing to select mirror weight, altitude angle, aberration mode coefficients and angles, correction type (absolute or relative).

Also, the complete chain of active optics software was tested, starting from Shack-Hartmann images (both fictitious and produced in laboratory with the real wavefront sensor), computing aberration coefficients, producing and applying active forces to the back of the mirror dummy.

During the tests all the information available at the control system (loads, positions, tilt angles) were continuously collected and then post-processed. As shown by the results the system behaves reasonably as expected in terms of axial and lateral support. The axial actuators force error is in most of the cases not greater than ±0.2N. These values are better than the ±0.5N threshold considered in the error budget, corresponding to less than 20 nm r.m.s. of $e_{2,1}$ elastic mode (similar to third order astigmatism) according to the results of a random analysis.

The tuning of axial fixed point heights has been tested after the mirror installation, simulating mirror alignment sessions.

Further, the load assigned to fixed points has been analyzed: considering the measured active force inaccuracies, the overall error for the 3 fixed points should be limited within ±20N regardless of the altitude position, thus with a higher error percentage towards the horizon. Due to a non perfectly homogeneous mirror dummy the check was partially postponed.

The lateral support system quality is reasonably good as shown by the low residual forces measured at the lateral fixed points: they should be ideally null, but in the real case the measured net force along X and Y was at most 200-300N, within 1-2% of the mirror weight. Since the equivalent stiffness of the lateral fixed points along X and Y is 40N/μm, the mirror displacement from zenith to the lowest operating angle is just several μm, corresponding to a negligible amount of r.m.s coma coefficient, and anyway well within the correction range of the secondary mirror hexapod.

Fig. 17 shows a simulation of operating conditions: a sequence of force patterns was applied, both just passive and passive + active (simulating the correction of predetermined aberrations); the mirror cell was rotated repeating the same sequence at different angles (order: 90°-60°-30°-15°-30°-60°-90°). Fig. 17(a) presents the axial support forces superimposed: the "straight" lines correspond to identical forces for all the supports in each ring, after the application of ideal passive forces. Fig. 17(b) shows the force setting errors superimposed: the little spikes represent the arrival of next force setting commands, the "trapezoidal" zones correspond to the rotations of the cell simulating the telescope slewing. Fig. 17(c) is the magnification of force setting errors in ±0.5N: between the not significant spikes and slewing phases, the errors are mostly bounded in ±0.2N.

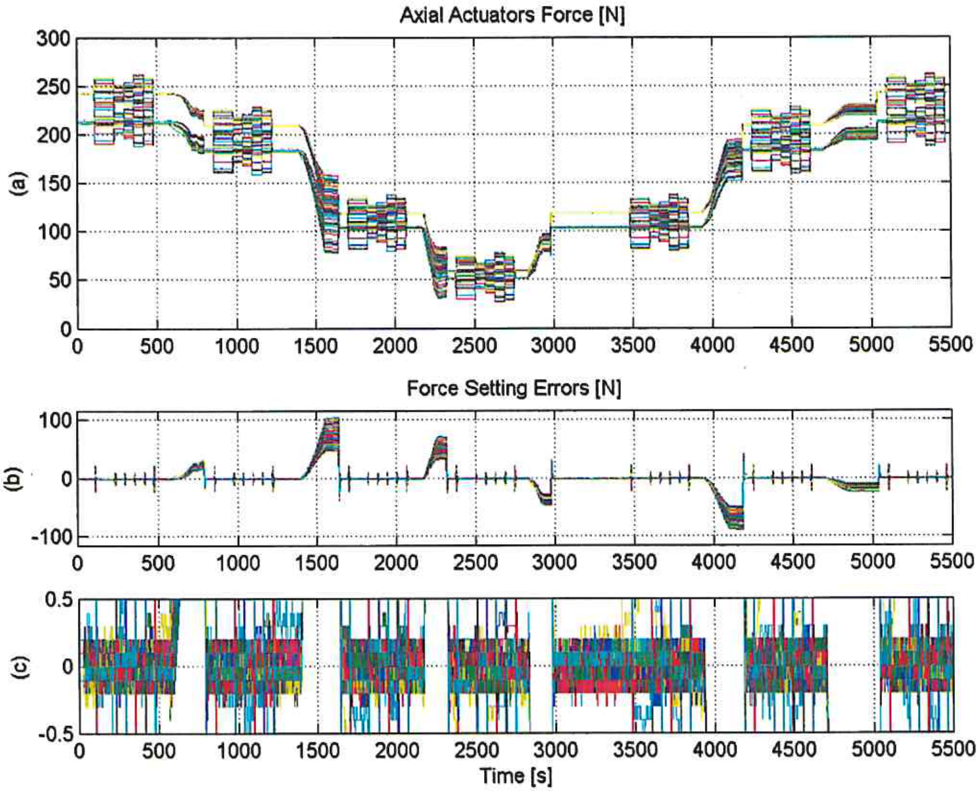

Fig. 17 – Results from a system test session.

8. CONCLUSIONS

The primary mirror support system of 2.6 m VST telescope has been presented; it is characterized by a concentration of supports greater than the other active telescopes, and is based on relatively simple support devices, with an axial system realized with electromechanical motor-screw supports and a purely mechanical lateral system. The system has been tested and shipped to Chile, where work with the real mirror is upcoming.

9. ACKNOWLEDGEMENTS

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