The active optics system of the VST: concepts and results

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ABSTRACT

The active optics system of the VLT Survey Telescope (VST) adopts a positioning system for the secondary mirror, a system to support and modify the shape of the 2.6-m primary mirror, and a Shack-Hartmann wavefront sensor. This paper describes the concepts of the VST active optics and the commissioning of the whole system on the ESO’s Paranal Observatory.

Keywords: Telescope, Active Optics, Aberrations

1. INTRODUCTION

The active optics system of the VST (Figure 1 shows the telescope, in the background three of the four Unit Telescopes of the VLT array are also visible) has been deeply revisited in the last years of the project; consequently, there was a big expectation for the results of the telescope commissioning, in order to verify if the recently introduced concepts had the expected positive effects. The VST hardware implementation has some specific hardware features with respect to the other ESO telescopes, which in turn required specific solutions at control system level, discussed below.

2. SYSTEM OVERVIEW

The VST telescope is designed with an active optics system that monitors the optical quality of the image and controls the relative position and the shape of the optical elements. The active optics technology ([1]-[3]) was applied first to the ESO New Technology Telescope ([4]-[8]) and later to the ESO Very Large Telescope ([9], [10]) and to all the other large telescopes in the world. Periodically, an image analyzer calculates the deviation of the image from the best quality: the VST is equipped with both a Shack–Hartmann wavefront sensor in the probe system and a curvature sensor included in the OmegaCAM instrument [11] (outside the scope of this paper). The Telescope Control Software (TCS) decomposes the deviation into single optical contributions and calculates the force correction that each active element has to perform to achieve optimal quality. The set of correction forces, one for each axial actuator, is computed by the telescope workstation and transmitted to the local control unit (LCU) of the primary mirror system for execution. Also, the software computes the correction for the secondary mirror position and orientation in order to recover the alignment and optimize the focus position. Previous works reporting on various aspects of the VST active optics system are [12]-[24].

3. PRIMARY MIRROR SUPPORT

The most important element of the VST active optics is the primary mirror, with its active support system (Figure 2, Figure 3) located within the primary mirror cell structure. The mirror is a monolithic meniscus of 2.6-m diameter with a 60 cm central hole and 140 mm thickness (aspect ratio: 18.6), made of Astrositall. The mirror shape is actively controlled by varying the force pattern applied by its active supports. The support system consists of an axial and a lateral part, described in the following.

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The number of axial supports is higher than in comparably sized telescopes, giving an advantage in terms of the quality of generated aberration modes. The concentration of axial devices, i.e., the ratio between the number of axial supports and the mirror surface area is the highest: the VST is indeed a 2-m class telescope incorporating a 4-m class active optics system.

The support system is based on the following basic concepts: the lateral support is a highly reliable purely mechanical system; in the axial direction there is no passive astatic system (e.g., mechanical astatic levers or hydraulic or pneumatic systems), commonly used to redistribute automatically the load on each support when the altitude angle changes. The advantage is a high simplification of the axial support design: the supports are electromechanical push-only devices. The cost is a restriction of the telescope operating modes: it is not allowed to operate the telescope in passive mode, i.e., without using the active optics.

The weight of the mirror (1855 kg) is shared at zenith between 84 axial supports (81 electromechanical actuators and three axial fixed points) distributed in four rings of 12, 18, 24, 30 supports. The optical aberrations to be corrected by 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.

The three axial fixed points are controlled by motors and therefore can be regulated: this is done only for alignment purpose, while during normal operations they are never moved. They are provided with stiffer springs with respect to the active supports: their function is to define the axial position of the mirror, with respect to the cell. In the axial fixed supports case, the controlled variable is the position, while all the other 81 axial supports are force-controlled.
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 distributed using the Schwesinger’s theory. Three tangential lateral fixed points define the position of the mirror in the XY plane (XY is the mirror plane, Z is the optical axis).

A mirror safety system is also provided, with two essential functions: a safe restraint of the mirror in all directions during an earthquake event and, during normal operations, the axial restraint in the whole altitude maintenance range (0°; 95°), mandatory since the axial actuators are push-only type. During observations the safety pads are never in physical contact with the mirror: the contact is established during an earthquake. The safety pad surface is made by elastomers properly designed to absorb the earthquake energy. In its plane the mirror is protected by radially disposed lateral safety pads (radial safety devices). Along the optical axis the mirror is protected by pairs of axial safety pads (axial safety devices), positioned near the mirror front and back surfaces.

4. SECONDARY MIRROR POSITIONING

The positioning of the secondary mirror (Figure 4) has been implemented in VST through a hexapod (Figure 5): it has six degrees of freedom, including also the redundant rotation 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 a Stewart platform, was introduced by Gough [25] and then used by Stewart for a flight simulator [26] in 1965; afterward it has been used for many different applications, including telescope mounts [27]. The VST hexapod mechanics is based on the TNG implementation [28]; the motion control, the electronics, and the kinematics algorithms are totally new.

The secondary mirror is moved in VST for three different reasons:

- defocus correction
- coma correction
- off-axis astigmatism correction (alignment)
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 center of curvature. Thus, the periodic compensation during the exposures of both defocus and coma needs movements of the secondary mirror in five degrees of freedom ($x$, $y$, $z$, $\delta$, $\epsilon$) where $\delta$ and $\epsilon$ are the rotation angles around $x$ and $y$. Only positioners that can follow accurately trajectories in these five degrees of freedom, without moving the image on the focal plane, can be used during the exposures.

Nevertheless, the correction of coma does not guarantee the primary and secondary mirrors are perfectly aligned, but just ensures their axes intersect at the so-called coma-free point. The mirrors can still be significantly misaligned, producing an unacceptable level of off-axis astigmatism that would be confused by the wavefront sensor with astigmatism due to a deformation of the primary mirror, causing a wrong correction. This condition shall be prevented by an accurate alignment of the mirrors which requires the correction of the off-axis astigmatism. This is implemented rotating the secondary mirror through the coma-free point reference system.

Notably, the alignment in a wide-field telescope is much more critical than for traditional instruments. A negligible misalignment in telescopes with a field of view of some arc minutes can be significant in a telescope like VST. If this is the case, a strong contribution of misalignment induced astigmatism can appear; the Shack-Hartmann has no possibility to detect such situation with a single measurement, it would just confuse misalignment astigmatism with astigmatism due to primary mirror warping, leading to wrong corrections. Therefore, a special care was needed to align the telescope, taking measurements in different points of the field with the Shack-Hartmann [24].

5. SHACK-HARTMANN SENSOR

The VST Shack-Hartmann wavefront sensor is installed in the probe system, shown in Figure 6 (see also Figure 7 for the conceptual scheme). The Shack-Hartmann receives the light from the same star used for the autoguiding system: a pick-up mirror, that can positioned anywhere around the science object, deflects the light that is split in two orthogonal arms by a dichroic that feeds also the autoguider arm. The inclination of the pick-up mirror depends on the distance from the center, because of the field curvature. In the wavefront sensor arm the light is sent through a pin-hole to a collimator and then to a lenslet array which produces the array of spots on the technical CCD (Figure 8). The star light through the pin-
The computation of the aberration coefficients is done by the telescope control software. As the displacements of the spots from the reference positions are proportional to the wavefront slopes, two methods are available at software level to reconstruct the coefficients:

- fit of the wavefront slopes
- integration of the slopes followed by the fit of the wavefront

During the telescope commissioning we chose to fit the slopes directly, because the limited number of spots in our system would have caused inaccuracies in the integration of the slopes.

The wavefront sensor was affected by static aberrations, that were discovered during commissioning. The measurement of the aberrations was corrupted, therefore although we could see the active optics loop converging to small aberration coefficients in few iterations, the optical system was indeed affected by not negligible aberrations. Thus, a method was implemented to measure and remove them by software, without affecting the hardware [24].

### 6. OPERATIONS

The choice to live without a passive astatic system simplified the design of axial support, based just on electromechanical motor-spring actuators, but complicated the active optics operating model.

Whenever the telescope rotates around the altitude axis, the finite stiffness of the axial supports, combined with the absence of an astatic system, causes the displacement of the mirror from its nominal position defined by the fixed points. This happens during the slewing phase, when the forces are not continuously updated for safety reasons: since the control is local within the supports, in case of lost communication with the telescope control software, a wrong net force could be transmitted to the mirror. Therefore, during the slewing phase the supports just react passively and the load on the axial fixed points becomes different from the ideal one, much higher or lower, or even zero in case the mirror detaches from the fixed points.

A telescope whose primary mirror position is not constant and well defined during the observations would be unusable, therefore it is mandatory to move the mirror back to the plane defined by the three axial fixed points before the start of each observation. This is accomplished by performing a first correction of the mirror shape at the end of slewing, based on the altitude angle and a lookup table. Since the weight of the mirror is always higher than the sum of axial forces commanded to the 81 active supports, the missing weight is automatically taken by the fixed points and the mirror comes back to the right position. This mechanism is by default implemented within the calibrated correction performed after each preset.
Nevertheless, this preliminary correction is not enough: the altitude angle of the telescope changes continuously during the exposures, and in turn the axial component of the weight changes. Therefore the initial calibrated correction which has distributed the axial weight among the supports allowing the three axial fixed points to take the right weight, becomes inaccurate after a while. This happens rather quickly near the horizon, producing a considerable amount of trefoil, if no action is taken. Therefore, a background control task has been implemented in the telescope control software, which continuously slightly adjusts the weight on the axial active supports in order to avoid the load on the three fixed points becomes incorrect.

The active optics is operated at VST using a look-up table of calibrated corrections after the preset to a new sky target, followed by few closed loop corrections using the wavefront sensor feedback. As the exposure time is normally short with respect to the rate of variation of the aberration coefficients, usually the active optics loop is not closed during the exposures.

As the VST is a survey telescope, an observation block is frequently composed by sets of near targets. When the next target is very close to the current one, the previous active optics correction is likely still effective. In such cases the active optics loop is not repeated, reducing the global overhead. Nevertheless, even a small offset of the telescope in terms of altitude angle might produce an incorrect load on the three fixed points: therefore in such cases the correction of the background control task adjusting the weight on the fixed points is executed immediately, by-passing the scheduling of its timer.

Figure 9 shows the aberration coefficients after a very good active optics loop. The legend for types is: type=1 for elastic modes; type=2 for Zernike modes. Symmetry and order give the association with the corresponding optical aberration,
which is clarified in Table 1. The values of a single measurement are the recalculated values (second column in Figure 9), which take into account:

- the subtraction of the field aberrations
- the correction of wavefront sensor static aberrations
- the conversion from CCD coordinate system to the primary and secondary mirror coordinate systems.

The units are nm for moduli and degrees for the angles.

<table>
<thead>
<tr>
<th>Type</th>
<th>Symmetry</th>
<th>Order</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
<td>Defocus</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2</td>
<td>Spherical</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Coma</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>Astigmatism</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>Trefoil</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
<td>Tetrafoil</td>
</tr>
</tbody>
</table>

Table 1. Legend for aberration modes.

7. CONCLUSIONS

The active optics system of the VST has been successfully commissioned at Cerro Paranal. The amount of aberrations measured by the wavefront sensor can be normally reduced to a negligible level with a calibrated correction after the preset, followed by two closed loop iterations.

Long term statistics should in principle allow a further refinement of the calibrated corrections; this will give no advantage on the (already satisfactory) image quality, but will possibly reduce the overhead generated by the active optics loops.

REFERENCES


