The VST alignment: strategy and results

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ABSTRACT

In a wide-field telescope like the VST, the requirements for alignment are tighter than for traditional instruments. The same amount of misalignment can be negligible in traditional telescopes with fields of some arc minutes, but unacceptable when the field is one order of magnitude larger. We describe the alignment procedure implemented during the telescope commissioning on the Paranal ESO’s observatory, as well as the final results.

Keywords: Telescope, Alignment, Aberrations

1. INTRODUCTION

The existing medium and large ground-based telescopes are usually based on two mirrors with correcting power, complemented by a field corrector when a wide field is needed. Any deviation from the ideal alignment of the mirrors produces aberrations in terms of coma and off-axis astigmatism.

The inequality of the optical and instrument rotator axes is another error source: a defocus gradient appears on the images when there is an inclination between them, and the image is blurred with a pattern depending on the rotator angle.

The basics for correction of misalignment coma and astigmatism were given by Shack and Thompson [1] and then applied by McLeod [2] at Mt. Hopkins telescope. The alignment of ESO telescopes like NTT and VLT are described in [3]-[6]. The effect of misalignments is magnified in the wide-field survey telescopes, e.g. VISTA [7] and PAN-STARRS [8]. The knowledge of field aberrations for alignment discussed in [9] is also attractive for wide field telescopes, where the astigmatism due to misalignment is large on the edge of the field, and therefore easily measurable and comparable with theory.

We discuss here the alignment of the VST (VLT Survey Telescope) [10], a 2.6-m survey telescope operating in the ESO observatory of Cerro Paranal (Chile), currently the largest telescope in the world specifically designed for surveying the sky in visible light. VST (Figure 1) is a F/5.5 modified Ritchey-Chretien telescope with an alt-azimuth mount, designed with a field corrector in order to cover a wide field of view (1.47° diagonal), with a pixel scale of 0.21”/pixel and a pixel size of 15μm, operating in the optical bands. It is equipped with an active optics [11]-[22] system equipped with a Shack-Hartmann wavefront sensor. The 268 Mpix OmegaCAM camera [23] is its only focal plane instrument. It is composed by a mosaic of 32 2Kx4K scientific CCDs arranged in a 8x4 matrix. The camera provides an alternative curvature wavefront sensor and guiding system based on four additional CCDs at the outer edge of the mosaic, outside the scope of this paper.

2. THE OPTICAL SYSTEM

The telescope optics are designed in order to optimize the image quality on a large field of view; the field corrector is composed by three lenses, two hosted in the telescope and one within the OmegaCAM instrument. The primary mirror is a concave 2.6-m meniscus equipped with four rings of active axial supports and a lateral support system based on astatic...
levers [16]. It can be tilted for alignment purposes by modifying the positions of three 120° spaced axial fixed points. The secondary mirror can also be positioned by a hexapod in 5 degrees of freedom [17].

![Figure 1. The VST telescope at Paranal observatory: the primary mirror reflects the image of the spiders.](image)

A small amount of field aberrations is inherent in the VST optical design: these effects shall not be corrected by the active optics and must be subtracted from the wavefront measure. In traditional two mirror telescopes, the field aberrations are well known. For example, in a Cassegrain telescope, that is corrected for spherical, the relevant field aberrations are coma and astigmatism. Coma depends linearly on the field radius $\theta$; using the Zemax numbering of Zernike modes, it is:

$$Z_7 = K \theta \cos(\phi)$$

$$Z_8 = K \theta \sin(\phi)$$

while the astigmatism has a parabolic dependence on the field, that in the ideal case of perfect alignment can be expressed as:
On the contrary, in the other quite popular category of aplanatic Ritchey-Chretien telescopes, there is no field coma but just field astigmatism, according to Eq. (2).

Nevertheless, VST does not belong to these traditional categories, because the field corrector modifies the shape of the field aberrations and the Eq. (1) and Eq. (2) are not applicable. Thus, their radial shapes have been computed by interpolating ray-tracing data. The generic field aberrations with symmetry n>0 and order j can be described by a vector $u_{n,j}(\vartheta, \phi)$, whose x- and y-components are:

$$u^x_{n,j}(\vartheta, \phi) = f^x_{n,j}(\vartheta) \cos(n\phi)$$

$$u^y_{n,j}(\vartheta, \phi) = f^y_{n,j}(\vartheta) \sin(n\phi)$$

(3)

where the radial parts $f_{n,j}(\vartheta)$ are functions of the field radius $\vartheta$, and the azimuthal parts are functions of the angular position $\phi$ in the xy plane, scaled by the symmetry $n$ of the aberration mode. The Eq. (3) generalizes Eq. (1) and Eq. (2) and is applicable to any mode symmetry $n$.

The radial functions $f_{n,j}(\vartheta)$ have been calculated using an integrated modeling application based on a Data Dynamic Exchange (DDE) link between the ray tracing Zemax software and the Matlab scientific computing environment. Data have been collected with a 0.05 degree spacing, and afterward interpolated with polynomials.

The results for coma, astigmatism and defocus are superimposed in Figure 2: the field corrector reduces coma and astigmatism at the edge of the field, bending the diagrams that deviate from linear (coma) and parabolic (astigmatism) shapes. A focus curvature is also visible, corresponding to about $20\mu m$ in terms of peak to peak secondary mirror displacement. Curiously, the best focus in the center of the field is here not desired, because the borders of the image would be significantly blurred. The best compromise for a good image quality in such a wide field of view is achieved with a best focus at about mid-field, as in Figure 2.
3. ALIGNMENT OF MIRRORS

It is well known that a constant coma is present in the whole field when the secondary mirror is decentered or tilted with respect to the primary. It can be removed by a rotation of the secondary mirror around its center of curvature, that compensates for coma without changing the pointing of the telescope. After this correction, the coma coefficient is ideally zero.

Nevertheless, the absence of coma does not guarantee that the primary and secondary mirror axes are perfectly coincident, as it is desired for an ideal alignment. In the practical case, that condition is typically achieved with primary and secondary mirror axes intersecting at the coma-free point. Unfortunately, when this is the case, the telescope is still affected by undesired off-axis astigmatism: the larger the field, the worse the problem. At VST this effect is clearly visible and is shown quantitatively hereafter. The tilt of the secondary mirror around the coma-free point adds a
proportional tilt to the ideal shape of field astigmatism, which consequently increases on the edge of the field. This is shown in Figure 3 in the VST case, for a tilt of 180 arc seconds. The defocus diagram is also affected, losing the original symmetry of Figure 2. On the contrary, coma is unaffected by definition of coma-free point: decentering and tilt components of the rotation produce opposite coma vectors that cancel each other, when the axis of the rotation is in the xy plane of the coordinate system centered on the coma-free point.

Such misalignment condition would confuse any active optics system with a single wavefront sensor, like the VST Shack-Hartmann. If the star for the wavefront analysis would be in the center of the field, no coma and astigmatism would be measured, causing no corrections; if that star would be on the edge of the field, an astigmatism contribution caused by the misalignment would be measured, but it would be confused with astigmatism due to warping of the primary mirror and wrongly corrected modifying the shape of the primary. In both cases, after the active optics measurement and correction cycle, the coma and astigmatism would be ideally zero in the measurement point, but the images would be affected by astigmatism elsewhere. These misalignment problems can only be detected with more than one off-axis measurement points, i.e. with two wavefront sensors acting simultaneously or one wavefront sensor that can provide measurements in two different points in the field.

At VST, the initial opto-mechanical alignment was done as described in [24]. Afterward, the Shack-Hartmann wavefront sensor was used to fine tune the position of the secondary mirror. The coma coefficient, measured in the center of the field, was already reasonably low, and the next step was the verification of off-axis aberrations.

Ideally, the astigmatism vector angle (where modulus and angle of the vector are obtained from cosine and sine components of Zernike pairs) rotates according to the symmetry n=2 of the mode (Figure 4), while the modulus is known at any field radius θ from optical design. Also, the effect of the secondary mirror rotations around the x- and y- axes of the coordinate system centered on the coma-free point are known (Figure 5), in terms of astigmatism vectors.

The strategy implemented at VST has been the comparison between the ideal and real field astigmatism vectors in four 90° spaced points (0°, 90°, 180°, 270°), at a 40 arc minutes distance from the center of the field. Significant RMS coefficients up to 1000nm were initially measured, remarkably higher than expected from the optical design. Comparing the measured vectors with the ideal ones, it was possible to compute the correction vector and, consequently, the appropriate rotation around the coma-free point for the secondary mirror. The geometry is shown in Figure 6: at each measurement point, identified by the known angle φi, there is a measured vector mi, a desired vector ei and a misalignment vector vi generated by the secondary mirror rotation:

$$\vec{e}_i + \vec{v}_i = \vec{m}_i$$  \hspace{1cm} (4)

In Eq. (4), ei and mi are known; the correction vectors vi depend on three parameters:

$$\vec{v}_i = f (\varphi_i, A, \alpha)$$  \hspace{1cm} (5)

where the only unknowns are A and α, i.e. modulus and angle of the vectors:

$$x_{vi} = A \cos (\varphi_i + \alpha)$$

$$y_{vi} = A \sin (\varphi_i + \alpha)$$  \hspace{1cm} (6)

Also, the components of the expected vectors are:

$$x_{ei} = B \cos (2\varphi_i + \beta_i)$$

$$y_{ei} = B \sin (2\varphi_i + \beta_i)$$  \hspace{1cm} (7)

where the parameters B and βi are known from optical design. After a straightforward computation:
Fig. 6. Geometry for computation of the correction at generic point no. \(i\)

\[
A \cos \alpha \cos \varphi_i - A \sin \alpha \sin \varphi_i = x_m - B \cos \beta_i \cos 2\varphi_i + B \sin \beta_i \sin 2\varphi_i
\]

\[
A \cos \alpha \sin \varphi_i + A \sin \alpha \cos \varphi_i = y_m - B \cos \beta_i \sin 2\varphi_i - B \sin \beta_i \cos 2\varphi_i
\]

(8)

For \(i=1, \ldots, N\) points and \(N>2\) Eq. (8) represents an overdetermined linear system of \(2N\) equations for the 2 unknowns \(A \cos \alpha\) and \(A \sin \alpha\), which can be solved with least square methods.

Finally, in the coma-free point coordinate system, the rotations \(\delta\) and \(\epsilon\) around the x- and y- axes are:

\[
\delta = KA \sin \alpha
\]

\[
\epsilon = KA \cos \alpha
\]

(9)

where the scale factor \(K \approx 0.37\) arcsec/nm is known from optical design.

4. ALIGNMENT OF ROTATOR AXIS AND CAMERA

A wide field telescope can also suffer for serious problems due to a misalignment of the focal plane. A tilt of the focal plane produces defocus on the border of the images: again this effect is much more detrimental when the detector is physically large, as it is the case for the OmegaCAM square mosaic (side: 240mm). The focal plane tilt can be caused both by the misalignment of the camera focal plane with the rotator axis, and by the misalignment of the telescope optics with the rotator axis. Thus, it is essential to disentangle these two contributions, analyzing the situation at different angles of the rotator. If the tilt is due to the instrument (\(\theta_{\text{cam}}\) component), it always maintains the same orientation with respect to the CCDs; assuming there is one out of focus side of the mosaic, after a rotation the defocussed part of the mosaic shall be the same, invariant in pixel coordinates. On the contrary, in case the tilt is due to a misalignment between the optical and the rotator axes (\(\theta_{\text{tel}}\) component), after a rotation the blurred part of the mosaic shall change in pixel coordinates, being not invariant.

Following this conceptual idea, just two \(180^\circ\) spaced measurements of the tilts around x- and y-axes would be enough; combining them as in Eq. (10) and Eq. (11), the telescope and camera tilt components could be disentangled:
Nevertheless, in the real case four 90° spaced measurements were always collected, in order to have redundancy and a check for consistency. Also, the test was repeated many times to average out the measurement noise, taking data sets at four rotator absolute position angles (0°, 90°, 180°, 270°).

In Eq. (10) and Eq. (11), the \( \theta_{x,i} \) and \( \theta_{y,i} \) components of tilt were computed, for any image, through the best focus values of the 32 CCDs of the mosaic. These values have been measured using sequences of through focus exposures, that produce trails of charge shifted images of the same star, taken at different axial positions of the secondary mirror. Analyzing the trails, the best focus values have been found for any CCD in secondary mirror position units, and then used as the known values in a system of 32 equations in the \( \theta_{x,i} \) and \( \theta_{y,i} \) unknowns.

Despite all efforts during design and installation, both tilt components were measured during VST commissioning, with a dominance of the misalignment between the optical and rotator axes. The results for this larger effect were also independently checked through a second procedure, described hereafter. The defocus coefficient was measured with the Shack-Hartmann sensor, moving the guide probe to 40 arcminutes from the center of the field, in four 90° spaced points \( P_{\text{up}} \), \( P_{\text{down}} \), \( P_{\text{left}} \), \( P_{\text{right}} \). The differences in the defocus coefficient between the pairs of 180° spaced points (i.e. the two values \( \text{def}_{\text{up}} - \text{def}_{\text{down}} \) and \( \text{def}_{\text{left}} - \text{def}_{\text{right}} \) had a small variance in a set of tests performed at different altitude angles and repeated many times. Using the factor that converts the defocus coefficient to secondary mirror displacement, we ported the results of this second method to the same units adopted in the first procedure, verifying that the results were in good agreement, and therefore could be trusted.

The camera tilt component was removed by the OmegaCAM team by shimming the instrument at its flange. The planned correction for the tilt between optical and rotator axes should have been a modification of the optical axes, through movements of the primary mirror axial fixed points and of the secondary mirror by the hexapod. Unfortunately this strategy was not feasible, because the range of displacement of the mirrors was not sufficient. Therefore also this tilt component was removed by shims, fixing the rotator axis rather than the optical one.

The improvement after the removal of the two tilt components can be shown quantitatively. The ideal focus distribution along the mosaic should be symmetrical around the center (see Figure 2), with a peak to peak difference of about 20\( \mu \)m in terms of secondary mirror position. In the real case, immediately after the first light of the telescope, this peak to peak difference was significantly higher, up to 60-70\( \mu \)m. The consequence was a strong defocus constantly present on a side or a corner of the mosaic, compromising the image quality in about 30% of the field. Figure 7 shows an example for this situation, in good seeing conditions: in most of the image the FWHM is about 0.5 arc seconds, but on the upper side of the detector the stars are out of focus and the FWHM rises up to 1.5 arc seconds. The removal of both camera and telescope tilt components allowed to decrease the defocus differences in the image to the nominal values, obtaining a uniform image quality over the whole 1 square degree field, as it should be from optical design. Figure 8 clearly shows the improvement after the shimming, for an image taken in about the same seeing conditions of Figure 7 (FWHM \( \approx 0.7 \) arc seconds, measured by the Differential Image Motion Monitor of Paranal observatory).

5. CONCLUSIONS

We have presented the alignment strategy followed at VST. First a zero coma condition has been found, then the secondary mirror has been rotated around the coma-free point in order to remove the residual off-axis astigmatism.
Afterwards, the defocus gradients caused by tilts of the camera and of the rotator axis have been carefully removed by mechanical shims. The final result is a remarkably uniform image quality on the whole 1x1 deg$^2$ field.

![Graph 7](image1.png)

Figure 7. Misaligned optical and rotator axes: FWHM distribution along X- and Y-axes. One part of the image is blurred, especially along the negative side of Y-axis. The dashed lines represent the seeing measured by the DIMM at the beginning and the end of the exposure.

![Graph 8](image2.png)

Figure 8. After alignment of optical and rotator axes: FWHM distribution along X- and Y-axes. The dashed lines represent the seeing measured by the DIMM.

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