Removing static aberrations from the active optics system of a wide-field telescope

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The wavefront sensor in active and adaptive telescopes is usually not in the optical path toward the scientific detector. It may generate additional wavefront aberrations, which have to be separated from the errors due to the telescope optics. The aberrations that are not rotationally symmetric can be disentangled from the telescope aberrations by a series of measurements taken in the center of the field, with the wavefront sensor at different orientation angles with respect to the focal plane. This method has been applied at the VLT Survey Telescope on the ESO Paranal observatory. © 2012 Optical Society of America

1. INTRODUCTION

Active optics [12] is a technique to keep the optics of the telescope close to its prescription also during operation, which requires the correction of slowly varying wavefront errors that are generated by variations of the temperature and the inclination of the telescope tube, as well as temporally constant errors. The corrections can be done in closed-loop control, which requires a wavefront analyzer and correcting devices. The latter usually consist of actuators for modifying the shape of the primary mirror and for the positioning of the secondary mirror.

The first telescope with an integrated active optics system was the New Technology Telescope (NTT) of the European Southern Observatory (ESO) [3], a 3.5 m Ritchey–Chrétien telescope. Afterward, the same concept has been adopted for other telescopes with large mirrors. Depending on the type of the primary mirror, active optics requires different correction devices. The shape of thin, monolithic mirrors is controlled by modifying the support forces [4–8], whereas segmented mirrors are primarily controlled by changing the rigid-body positions of the segments [9,10].

An ideal telescope equipped with active optics can readily achieve a seeing limited performance, which requires that the wavefront errors generated by the telescope are negligible compared with the errors generated by the atmosphere. Quantitatively, this means the full width at half maximum (FWHM) of star spots in the images should be ideally the same as the one measured by seeing monitors (e.g. [11]). At the best sites for optical astronomy this so-called seeing can be well below 1 arcsec.

The wavefront sensor, which is most commonly a Shack–Hartmann device, is clearly a critical subsystem, because any feedback error directly affects the telescope performance. In most active telescopes, the light is directed to the wavefront sensor detectors by additional mirrors and lenses, which are not in the optical path toward the scientific detector. These additional optical devices can produce wavefront errors that are not affecting the wavefront at the scientific detector. Such static errors have been studied, for instance, in [12] or in [13] for adaptive optics systems.

The following sections present the application of a technique for the measurement of noncommon path aberrations at the VLT Survey Telescope (VST) [14], a 2.6 m survey telescope on the ESO observatory on Cerro Paranal (Chile), currently the largest operating telescope specially designed for surveying the sky in visible light.

This article is structured as follows. Section 2 provides an overview of the telescope. Section 3 discusses the field aberrations of its specific optical system. Section 4 describes the strategy that has been followed for the alignment. Section 5 proposes a method for the determination of static aberrations introduced by a wavefront sensor in an active optics system, based on measurements in the field center. Sections 6 and 7 present the results of the application of this method to the VST. Section 8 concludes the paper.

2. TELESCOPE OVERVIEW

The VST (Fig. 1) is an optical F/5.5 telescope with an altazimuth mount. Its optics includes a field corrector that is required to deliver a good optical quality over a wide field of view of 1° × 1°. The telescope is equipped with an active optics system using a Shack–Hartmann wavefront sensor.

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The field corrector is composed of three lenses, two hosted in the telescope and one within the camera; the overall optical layout is shown in Fig. 2. The primary mirror is a concave 2.6 m hyperbolic meniscus, axially supported by 84 active supports located on four rings and laterally supported by passive astatic levers [15]. It can be tilted for alignment purposes by modifying the positions of three fixed points on the third ring at angles of 120°. The rigid-body position of the convex hyperbolic secondary mirror can be controlled by a hexapod in 5 degrees of freedom [16]. Strictly speaking, the VST does not belong to any classical category of telescopes (e.g., Cassegrain, Ritchey–Chretien): the combination of mirrors and lenses has been designed in order to minimize the wavefront error across the whole field of view. One consequence is the unusual dependencies of the small field aberrations on the field radius (see Section 3).

The 268 Mpix OmegaCAM camera [17] with a pixel scale of 0.21′/pixel and a pixel size of 15 μm is the only focal plane instrument. It is composed of a mosaic of 32 2K × 4K scientific CCDs arranged in an 8 × 4 matrix. The camera provides an alternative curvature wavefront sensor and a guiding system based on four additional CCDs at the outer edge of the mosaic. Further details on VST subsystems are discussed in [18–26].

3. FIELD ABERRATIONS OF THE OPTICAL SYSTEM

A small amount of field aberrations is inherent in the VST optical design: these effects cannot be corrected by the active optics and have to be subtracted from the measured wavefront errors. In traditional two mirror telescopes, the lowest field aberrations have simple dependencies on the radial field coordinate θ and angular field coordinate φ. For example, in a perfectly aligned Cassegrain telescope, which is corrected for spherical aberration, the dominant field aberrations are field curvature, third-order coma, and third-order astigmatism. Using the Zemax TM numbering of Zernike standard modes, the dependencies on φ and, to the lowest order on θ, are given by

\[
Z_4 = c_{\text{curv}} \theta^2, \quad (1)
\]

\[
Z_7 = c_{\text{coma}} \theta \sin(\phi) \quad (2)
\]

\[
Z_8 = c_{\text{coma}} \theta \cos(\phi) \quad (3)
\]

\[
Z_5 = c_{\text{ast}} \theta^2 \sin(2\phi) \quad (4)
\]

\[
Z_6 = c_{\text{ast}} \theta^2 \cos(2\phi) \quad (5)
\]

The constants \(c_{\text{curv}}, c_{\text{coma}}, c_{\text{ast}}\) depend on the optical design.

In aplanatic Ritchey–Chretien telescopes, in addition, the field coma is corrected. Apart from field curvature, the dominant field aberration is then third-order astigmatism, described by Eq. (3).

However, the VST does not belong to these categories. Spherical aberration is corrected in the field, but the dependencies of the dominant field aberrations curvature, third-order coma and third-order astigmatism are more complicated. Thus, \(\theta\) and \(\theta^2\) in Eqs. (1)–(3) have to be replaced by general functions \(f(\theta)\). For the VST these have been computed by interpolating ray-tracing data and approximated as polynomials in \(\theta\).
Figure 3 shows the dependencies of defocus \( (Z_4) \) and the cosine components of third-order coma \( (Z_6) \) and third-order astigmatism \( (Z_8) \) on the radial field coordinate \( \theta \). They strongly deviate from the classical linear (coma) and quadratic (defocus, astigmatism) dependencies. As expected, the next order of field dependence is cubic for coma and quadratic for focus and astigmatism, i.e., the functions can be described by

\[
\begin{align*}
Z_4 &= c_{3\text{\text{curv}}} \theta^2 + c_{5\text{\text{curv}}} \theta^4, \\
Z_7 &= (c_{3\text{\text{coma}}} \theta + c_{5\text{\text{coma}}} \theta^3) \sin(\varphi), \\
Z_8 &= (c_{3\text{\text{coma}}} \theta + c_{5\text{\text{ coma}}} \theta^3) \cos(\varphi), \\
Z_5 &= (c_{3\text{\text{ast}}} \theta^2 + c_{5\text{\text{ast}}} \theta^4) \sin(2\varphi), \\
Z_6 &= (c_{3\text{\text{ast}}} \theta^2 + c_{5\text{\text{ast}}} \theta^4) \cos(2\varphi).
\end{align*}
\]

The variations in field curvature correspond to peak-to-peak secondary mirror displacement along the optical axis of about 20 \( \mu \)m. Focus is not designed to vanish in the center of the field, because the borders of the image would then 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 shown in Fig. 3.

4. ALIGNMENT

The survey telescopes have a wide field of view and consequently tighter requirements for the alignment: a certain amount of misalignment can be negligible in traditional instruments with fields of few arc minutes but unacceptable when the field is one order of magnitude larger. A basic theory for field aberrations in misaligned systems has been developed by Shack and Thompson [27] and applied to the alignment of the Mt. Hopkins 1.2m telescope by McLeod [28]. The theory and practice of the alignment for ESO telescopes with normal field of views like the NTT and the VLT is described in [29–32]. The knowledge of field aberrations for alignment discussed in [33] 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, e.g., in VISTA [34]. The differences between astigmatic figure errors and astigmatism induced by misalignment are also extensively discussed in [35–37]. The essential concepts and the strategy that has been followed for the VST are summarized below.

A. Coma

Constant coma is usually present in the whole field when the axes of the optical elements are misaligned with respect to each other. However, since a rotation and a lateral shift of an optical element can generate coma with opposite signs, the constant coma can be eliminated by an appropriate rotation of one of the elements around a specific point. In two-mirror telescopes this is done by a rotation of the secondary mirror around its center of curvature, since this does not change the pointing of the telescope. After the correction of coma, the axes of the primary and secondary mirror intersect in the so-called coma-free point.

B. Off-Axis Astigmatism

Nevertheless, the absence of coma in two-mirror telescopes does not guarantee that the primary and secondary mirror axes are perfectly coincident, as it is desired for an ideal alignment. If the axes are not congruent, the telescope is still affected by additional field astigmatism with a linear dependence on the field radius \( \theta \). A comparison of Fig. 4 with Fig. 3 (note the different scales in the two figures) shows the computed changes of the field dependences for defocus and third-order astigmatism for a 255 arc sec tilt of the secondary mirror of the VST around the coma-free point. Since this tilt is about the same as the largest tilt around the coma-free point corrected during the telescope alignment, Fig. 4 represents the field aberrations prior to the alignment. Contrary to defocus and astigmatism, third-order coma is, as expected, not affected by a rotation around the coma-free point. The effect of a misalignment-induced astigmatism on the image is well described by Fig. 5: the orientation of the image ellipticity follows a \( \theta/2 \) dependence.

Such misalignment conditions cannot be detected by a single measurement with a single wavefront sensor in some cases.
location in the field, since the wavefront sensor cannot distinguish between a contribution to third-order astigmatism generated by a misalignment and a contribution generated by a deformation of the primary mirror. Disentangling the contributions is only possible with either simultaneous measurements by at least two wavefront sensors in different field locations or at least two measurements with one wavefront sensor at different field locations. For more details on this subject see [36].

C. Alignment Driven by Field Astigmatism Data

After the preliminary optomechanical alignment of the VST [38], the Shack–Hartmann wavefront sensor was used to fine-tune the position of the secondary mirror. The coma, measured in the center of the field, was already reasonably low and could be easily removed by a rotation of the secondary mirror around its center of curvature. Thus, the next step was the measurement of off-axis aberrations, for the reasons described in the previous section.

The field aberrations introduced by a misalignment of the corrector optics are small for the expected errors in the alignment. For example, even a strong decentering of the corrector optics of 1 mm would generate a coefficient of Zernike astigmatism of less than 70 nm at a field radius of 40 arcmin. Therefore, from the point of view of alignment, the telescope could be regarded as a two mirror telescope, which requires primarily an alignment of the secondary mirror with respect to the primary mirror.

In the following, the aberrations with symmetries other than 0 are described in terms of vectors, whose \(x\)- and \(y\)-components are the cosine and sine terms of orthonormal Zernike mode pairs, adopting the Zemax TM set of Zernike standard polynomials. Figure 6 shows the angles of the nominal field astigmatism, which rotate with twice the field angle,
and Fig. 7 the angles of the linear field astigmatism, which rotate with the field angle. The linear field astigmatism is generated by rotations of the secondary mirror around the \(x\)- and \(y\)-axes through the coma-free point. The values in Fig. 6 are calculated for a field radius of \(\theta = 40\) arcmin and for a plane in front of the last lens of the corrector. This explains why the modulus of nominal astigmatism (160 nm) is larger than the one in the focal plane, shown in Fig. 3.

The alignment of the VST was based on the comparison between the ideal astigmatism vectors and the ones measured at four field locations at a distance of 40 arcmin. from the center of the field and separated by 90° (0°, 90°, 180°, 270°). In Fig. 8, the dashed lines show the measured vectors of astigmatism before the rotation of the secondary mirror around the coma-free point. These initial coefficients were much larger than expected from the optical design.

Without measurement noise, the difference vectors between the measured vectors and the ones expected for the fully aligned system should be a sum of the vectors shown in Fig. 7. These vectors, which are generated by rotations around the coma-free point, are linear functions of the rotation angles \(\delta\) and \(\epsilon\) around the coma-free point. One measurement point would therefore be sufficient to determine the two unknowns \(\delta\) and \(\epsilon\). With four measurement points one has an overdetermined linear system of eight equations for two unknowns, which can be solved by a least square fit. For the measured pattern of Fig. 8, which is also affected by noise introduced by the wavefront sensor and the atmosphere, the best fit was achieved with \(\delta = -255''\) and \(\epsilon = 18''\).

After the correction by rotations of the secondary mirror around the coma-free point, the measured residual vectors, shown also in Fig. 7 by the solid lines, are very similar to the vectors expected for a fully aligned system (see Fig. 6). This indicates that, after the corrections, the telescope was nearly perfectly aligned.

5. WAVEFRONT SENSOR STATIC ABERRATIONS

In the framework of the alt-azimuthal telescopes terminology, the adapter-rotator is an interface between telescope and instrument, which compensates the effects of the rotation of the field and contains devices for the autoguiding and active optics wavefront sensing (see Section 6 for the VST implementation).

It is assumed the wavefront sensor is composed of several optical elements and a detector, which are all located inside the adapter-rotator of an alt-azimuthal telescope. This is the case for most of the active optics systems. For each aberration mode, the measure \(a_m\) done by the wavefront sensor in the adapter-rotator is the sum of a contribution \(a_{tel}\) due to the telescope and a contribution \(a_{ws}\) due to the wavefront sensor itself:

\[
\vec{a}_{ws} + \vec{a}_{tel} = \vec{a}_m. \tag{7}
\]

The contribution \(a_{ws}\) has to be removed from \(a_m\) to only apply those actuator commands that are required to correct the telescope aberrations described by \(a_{tel}\).

The two contributions can be disentangled by a set of \(N\) measurements with the adapter-rotator at different angles. The measurements are done in the center of the field, where they are not affected by field aberrations. Since the sensor rotates together with the rotator, the contribution \(a_{ws}\) can safely be assumed to be independent of the rotator angle. On the other hand, the measured angle of the contribution \(a_{tel}\) does depend on the rotator angle.

This technique can only be applied if the true telescope aberrations \(a_{tel}\) are largely constant during the time required for the \(N\) measurements. Therefore the choice of \(N\) should be the result of a trade-off between two contradictory requirements: collecting a large number of data for statistical averaging and completing the experiment in a short time to avoid the occurrence of significant variations of the telescope aberrations.

At different rotator angles \(\phi_i\) with \(i = 1, \ldots, N\) the wavefront sensor measures \(N\) coefficients \(a_{m;i}\) of a specific aberration. The cosine and sine components of a specific telescope aberration mode of symmetry \(n\) are given by

\[
x_{tel;i} = a_{tel,0} \cos(n \phi_i - \phi_0),
\]

\[
y_{tel;i} = a_{tel,0} \sin(n \phi_i - \phi_0), \tag{8}
\]

where \(a_{tel,0}\) is the modulus and \(\phi_0\) the angle of the coefficient of the mode. Hence, using Eqs. (7) and (8),

\[
x_{ws} + \cos n \phi_i a_{tel} \cos \phi_0 + \sin n \phi_i a_{tel} \sin \phi_0 = x_{m;i},
\]

\[
y_{ws} + \sin n \phi_i a_{tel} \cos \phi_0 - \cos n \phi_i a_{tel} \sin \phi_0 = y_{m;i}, \tag{9}
\]

where \(x_{ws}\) and \(y_{ws}\) are the constant components of the aberrations introduced by the wavefront sensor itself. With \(N\) measurements, Eq. (9) represents a linear system of \(2N\) equations for the \(4\) unknowns \(x_{ws}\), \(y_{ws}\), \(a_{tel} \cos \phi_0\) and \(a_{tel} \sin \phi_0\). For \(N > 2\) the system is overdetermined and an solution can be found with least square methods. Thus, the cosine and sine component of the noncommon path aberrations can be estimated and removed from the total aberrations measured by the wavefront sensor.

The analysis presented in Section 6 is restricted to astigmatism, trefoil, and tetrafoil, which are the only significant static aberrations measured at the VST. However, it could also be
applied to any other mode with a rotational symmetry larger than 0.

6. CASE STUDY

During the commissioning the dependence of the telescope aberrations on the zenith angle was tested by continuously measuring the wavefront errors while the telescope followed the meridian without the application of any active optics corrections. For a well aligned and corrected VST as described at the end of Section 4 the changes in the low-order coefficients were slow far away from zenith, but surprisingly strong close to the zenith. However, with large errors introduced into the telescope optics the fast changes near the zenith disappeared.

Since the measurements were done in the center of the field and the telescope was well aligned, the most reasonable explanation was that the fast changes near zenith were caused by noncommon path aberrations generated by the wavefront sensor. In the reference system of the telescope tube, to which all aberrations are finally referred at the end of the wavefront analysis, these errors would rotate with the rotator. Strong changes due to noncommon path aberrations could then be expected near the zenith, where these rotations are fast.

The VST adapter-rotator is shown in Fig. 9. The camera, not shown in the figure, is attached to the rotator bearing at the gray inner circular interface. During the observations, the probe system (black assembly in the figure) is rigidly rotated together with the scientific instrument. However, since it can also be rotated independently and the pick-up mirror between the second lens of the corrector and the filter (Fig. 2) can be moved in radial direction, any star in the field can be used as a guide star. The light is split and directed to both the Shack–Hartmann and the autoguiding units by a dichroic (Fig. 10). The Shack–Hartmann itself is composed of a collimator, a lenslet array, and a CCD detector, which records the Shack–Hartmann spots.

Although, the probe can be moved to any field location, it has been positioned at the center of the field for the whole process of measuring the static aberrations.

The primary mirror with a diameter of 2.6 m has a moderate thickness of 140 mm. The structure of the comparatively compact telescope is also rather rigid. Both characteristics should assure that the shape of the mirrors and the alignment of the optics are rather stable over time periods of 15 min.

The hypothesis that the strong changes of the coefficients of the low-order modes are due to a rotation of the adapter-rotator was checked by the sets of measurements described at the end of Section 5. One set of measurements consisted of 13 measurements with steps of 30° of the rotator angle between two consecutive measurements. This gave a sufficiently large number of samples, which could be collected within a reasonably short time of about 15 to 20 min. The first and the last measurements were done at the same rotator angle. Significant differences between these two measurements could only be due to strong variations of the telescope aberrations during the measurements. Therefore, sets of measurements with large differences between the first and last measurements were not taken into account.

7. TEST RESULTS

Figures 11, 12, and 13 show a graphical representation of the measurements; the x- and y-axes correspond to the cosine and sine components, in units of nanometers, of orthonormal Zernike mode pairs (Zernike standard polynomials in Zemax TM terminology) with symmetries $n$ other than 0. Using Zemax TM numbering, Fig. 11 shows the Zernike pair $(5,6)$.
for astigmatism, Fig. 12 shows the Zernike pair (9,10) for trefoil, and Fig. 13 shows the Zernike pair (14,15) for tetrafoil.

The points in the plane represent the $x$- and $y$-components of the measured coefficients $a_{m,i}$. The constant sensor components, which do not rotate with the rotator angle, should give points at a fixed location $(x_{ws}, y_{ws})$ in the plane. The variable telescope components, which do rotate with the rotator angle, should give points that lie on circles around $(x_{ws}, y_{ws})$. The radius of a circle is proportional to the modulus of coefficient of the mode. Each mode with a rotational symmetry $n$ should describe $n$ circles around the origin. Thus, the coefficients of astigmatism, trefoil, and tetrafoil should rotate around the origin two, three and four times, respectively. The rotations are clearly visible in the figures.

The deviations from perfect circles are caused predominantly by atmospheric disturbances. The RMS values of the noise are shown in Table 1: as in the case of the VLT [2], the relative ratios between the modes are in good agreement with the ones expected from Kolmogorov turbulence theory [39]. The expected ratios between the values measured at the VLT and the VST are also in good agreement with the expected scale factor $(2.6/8.2)^{5/6}$ due to the different diameters of the primary mirrors.

The data in the figures were collected after active optics corrections before the first measurement. However, the static aberrations had not yet been identified and taken into account for the correction. The figures show that the amount of static aberrations, represented by the distance of the centers of the circles from the origin, was comparable to the amount of telescope aberrations, represented by the radii of the circles. For instance, in Fig. 11 the center of the circle shows a 245 nm astigmatism coefficient in the Shack–Hartmann (at an angle of 98°), while the radius of the circle is 315 nm and represents the astigmatism generated by the telescope in the center of the field. This latter value is unusually large for VST standards: the reason is that the active optics correction just before the measurements was based on corrupted data and had incorrectly introduced additional 245 nm of astigmatism into the telescope optics. Identical considerations apply for Fig. 12 and Fig. 13.

With the knowledge of the static aberrations, the telescope aberrations can be corrected. A subsequent set of measurements would again show circles around the same center, but with smaller radii.

Within the scope of this paper, which deals primarily with the measurement method, the cause of the aberrations produced by the wavefront sensor is of no importance. In the specific VST case, they might be introduced by incorrect manufacturing or support of some optical elements. The latter is most likely the case for the pickup mirror.

8. CONCLUSIONS

Noncommon path aberrations were measured in the VST wavefront sensor by taking measurements in the center of the field at different rotator angles. This facilitated the removal of these errors from the active optics correction process and improved significantly the performance of the telescope. Noncommon path aberrations in wavefront sensors are present in any active telescope. Measurement of such error is always useful, even if they only confirm that the errors are negligible. The technique described above does not require any additional instrumentation. All measurements are done with the telescope in its normal configuration. The method is intuitive and easily applicable to most of the active telescopes with characteristics similar to the ones of the VST.

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