



Exploring wind-induced plate scale vibrations at the Extremely Large Telescope

Pascal Jaufmann, Jörg-Uwe Pott, André Boné, Oliver Sawodny

► To cite this version:

Pascal Jaufmann, Jörg-Uwe Pott, André Boné, Oliver Sawodny. Exploring wind-induced plate scale vibrations at the Extremely Large Telescope. COAT2023, Mar 2023, Durham, United Kingdom. <10.34693/COAT2023-012>. <hal-04605009>

HAL Id: hal-04605009

<https://hal.science/hal-04605009v1>

Submitted on 13 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Exploring wind-induced plate scale vibrations at the Extremely Large Telescope

Pascal Jaufmann^{a,b}, Jörg-Uwe Pott^b, André Boné^b, and Oliver Sawodny^a

^aInstitute for System Dynamics, University of Stuttgart, Waldburgstr. 17/19, 70563 Stuttgart, Germany

^bMax Planck Institute for Astronomy, Königsstuhl 17, 69117 Heidelberg, Germany

ABSTRACT

As the size of telescopes increases, the performance of adaptive optics (AO) systems in extremely large observatories such as the ELT is dominated not only by atmospheric disturbances but also by structural vibrations. The SCAO control loop of MICADO provides optical correction for a single guide star, while the image magnification is variable. This leads to additional radial jitter, reducing the available Strehl ratio and therefore the usable field-of-view. Especially movements of M2 along the optical axis cause such plate scale variations in the focal plane. By analyzing the effect of M2 piston disturbance with optical ray-tracing software, we quantify its impact on image distortions and quality. The plate scale effect is then compared to residual tip-tilt jitter induced by atmospheric turbulence. Additionally, we investigate the surface figures required to compensate with the adaptive mirrors of ELT, M4 and M5.

Keywords: ELT, adaptive optics, telescope vibrations, plate scale, image magnification control

1. INTRODUCTION

The new generation of large-scale telescopes, such as the Extremely Large Telescope (ELT) currently under construction by European Southern Observatory (ESO) in Chile, promise to push the boundaries of ground-based astronomy. Achieving diffraction-limited imaging with ELT's first light instrument Multi-AO Imaging Camera for Deep Observations (MICADO) in the presence of atmospheric turbulence and structural vibrations is the main challenge for current AO. In the initial stage of operation, MICADO will use the single-conjugate adaptive optics (SCAO) mode as it is opto-mechanically simpler to design and implement. However, this limits the optical correction to a single guide star at the center of the detectors, leaving the image magnification variable and resulting in degraded image quality for stars near the edges. Compensating for these fast image magnification (also known as plate scale) variations greatly increases SCAO's usable field of view (FoV). This is especially significant for the ELT, since its aperture size is comparable to the outer scale of atmospheric phase turbulence. The point spread functions (PSFs) thus retain a diffraction-limited core even at larger radii ($\approx 25''$) beyond the typical isoplanatic angle of current 8 m class AO-supported telescopes [1]. A study by [2] shows that a piston shift of ELT's secondary mirror (M2) is one of the main contributors to plate scale variations. Hence, this paper aims to study the impact of wind-driven telescope vibrations on plate scale and image quality, and the methods for their compensation. At the ELT, the fourth mirror (M4) is a deformable mirror that provides the ability to perform small and fast image corrections, while the fifth mirror (M5) is a flat mirror that is mostly used for slower field stabilization but with a higher stroke. The main contribution of this work is to present our simulation setup for studying the aforementioned effects and to discuss the possibility and specifications to reduce the M2 piston-induced plate scale variations by ELT's adaptive mirrors.

The remainder of this paper is structured as follows: Section 2 presents the setup that we used to investigate the plate scale vibrations. Section 3 discusses the results obtained from our analysis. Finally, Section 4 gives a brief summary and outlook of the work.

Further author information (Send correspondence to P.J.):

Pascal Jaufmann, E-mail: pascal.jaufmann@isys.uni-stuttgart.de

Jörg-Uwe Pott, E-mail: jpott@mpia.de

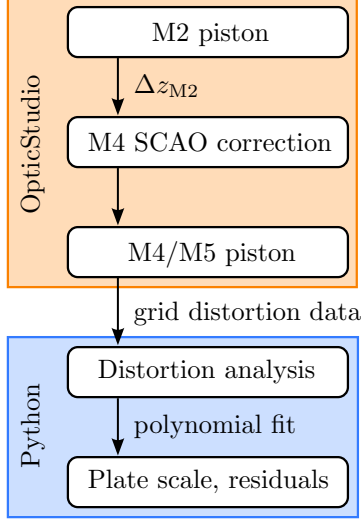


Figure 1: Workflow for analyzing the plate scale effect.

2. SIMULATION SETUP

To explore and quantify the mentioned plate scale effect, we use the optical ray-tracing software OpticStudio from Zemax [3], where we can design complex optical surfaces and subject them to various disturbances. The exact optical configuration for the ELT is provided by ESO [4]. Moreover, a simple python package is used to analyze the grid distortions output by OpticStudio.

The complete workflow is depicted in Figure 1. First, we subject ELT M2 to a piston offset Δz_{M2} , inducing a number of aberrations into the system. The Zernike defocus term is dominant because the M2 motion changes the effective focal length of the telescope. To refocus the beam and compensate for the other aberrations, we optimize the wavefront error (WFE) of the central field by adjusting the Zernike modes 3 to 36 (Noll notation) of M4, simulating a SCAO loop. Note that in reality, this loop would also be affected by a noisy wavefront sensor (WFS) measurement, the deformable mirror (DM) response function and other disturbances. The SCAO correction sharpens the image toward a guide star, but the plate scale is still variable. We therefore explore how a piston at M4 or M5 can restore the undisturbed plate scale value. This is optically possible even with flat mirrors, as a piston offset in a converging or expanding beam corresponds to a change in the focal plane position of the optical system. After applying the piston correction, the resulting grid distortion data is exported from OpticStudio and analyzed by a Python routine called MASCADO [5]. A detailed explanation of the package is also provided in [6]. By computing the difference between the reference grid x_{ref} and the affine transformation of the detector grid Ax_{det} , we obtain the drift $d = Ax_{\text{det}} - x_{\text{ref}}$. The distortion change is then given by the difference of the undisturbed ($\Delta z_{M2} = 0$) and disturbed ($\Delta z_{M2} \neq 0$) drifts:

$$\Delta d = d - d_0 = (Ax_{\text{det}} - x_{\text{ref}}) - (Ax_{\text{det}} - x_{\text{ref}})_0 \quad (1)$$

After normalization, a polynomial vector field is fitted onto the distortion drift by a least-squares algorithm, such that $P(x_{\text{norm}}) \approx \Delta d$. Finally, we extract the specific residual root mean square (RMS) of the polynomial fit for different distortion orders. As described, the affine transformation A is used to convert the grid from detector to sky coordinates. By applying the singular value decomposition (SVD) to A , we receive the rotation, scaling and reflection parts of A . The plate scale values are then the diagonal elements of the scale matrix, since plate scale is a measure of image magnification. However, we are not interested in the absolute value but in the plate scale change. It is calculated by

$$\Delta p = \frac{p}{p_0} - 1 \quad (2)$$

where p_0 is the plate scale value for a grid distortion with $\Delta z_{M2} = 0$.

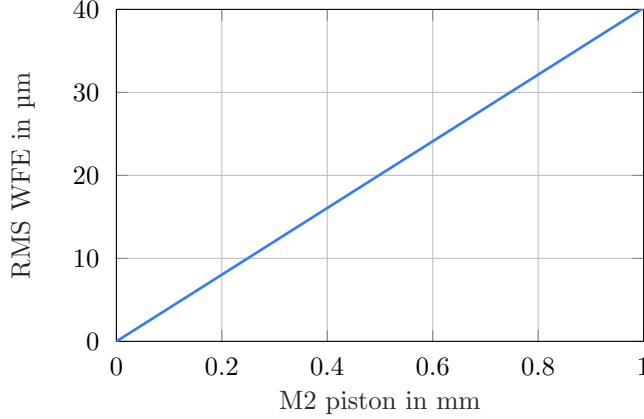


Figure 2: RMS WFE at ELT focal plane.

3. RESULTS

In our OpticStudio simulation, we assume a wavelength of $1\text{ }\mu\text{m}$ and a field with a maximum angle of $0.0106^\circ = 38.16''$ which corresponds to an off-axis star in the corner of the MICADO FoV. Based on [7] and [2], we estimate the M2 piston motion during a typical observation to be in the range of

$$\Delta z_{\text{M2}} = \pm 0.1\text{ mm.} \quad (3)$$

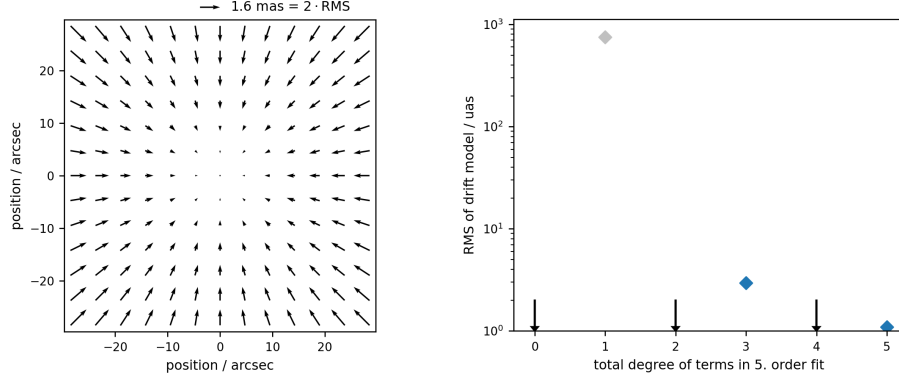
It should be noted, however, that the ELT has not yet been built, nor are details on the stability of the M2 piston publicly available. Therefore, a wider range of M2 piston drifts up to 1 mm are investigated below. Figure 2 displays the corresponding RMS WFE. In the following, we explore the impact and possible compensation of the M2 vibrations on plate scale and image quality.

3.1 Effect on plate scale

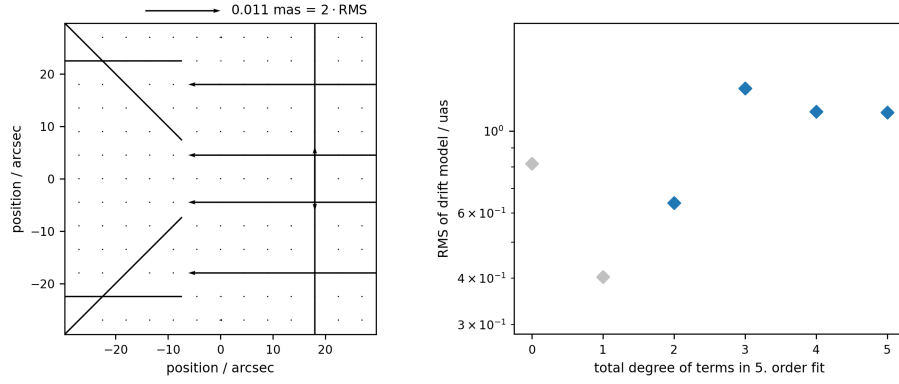
The simulation results are shown in Figure 3. Without a compensation for the plate scale change with M4, we see a drift pattern with significant image magnification toward the center (Figure 3a left). Accordingly, the first order distortion dominates with a residual RMS of $748\text{ }\mu\text{m}$ and the plate scale is changed by $4.75 \times 10^{-3}\%$. Now, M4 is moved $955\text{ }\mu\text{m}$ in piston to correct for the change in plate scale. The first order RMS is thereby reduced to under $1\text{ }\mu\text{m}$ (Figure 3b, right) and the drift pattern shows only minimal distortion compared to the undisturbed drift. In general, about 10 times the M4 piston is required to compensate for an M2 piston offset, i.e. $\Delta z_{\text{M4}} \approx 10\Delta z_{\text{M2}}$.

Overall, we can conclude that moving M4 in piston can compensate for the plate scale change caused by an M2 piston motion. However, the expected stroke limitation of M4 is just $\pm 50\text{ }\mu\text{m}$, which is too small for the predicted M2 piston amplitudes. Looking ahead, the plate scale vibrations can also be suppressed by a piston in M5 as illustrated in Figure 4. Analogous to the compensation with M4, the first order RMS is greatly reduced, which is also represented by the drift pattern with minimal distortions. This is achieved by a M5 piston correction of $-1186\text{ }\mu\text{m}$ yielding a sensitivity of $\Delta z_{\text{M5}} \approx -10\Delta z_{\text{M2}}$. The value is in the same order of magnitude as that for M4, since both M4 and M5 are located at similar positions in the optical assembly. However, unlike M4, M5 has a much larger stroke limitation of $\pm 5\text{ mm}$. Assuming that 10% of the M5 stroke is available for piston correction, M5 can compensate for up to roughly 0.5 mm M2 piston vibration. In practice, this can still be compromised by the frequency at which M2 vibrates in the wind. FE simulations in [8] suggest that M2 oscillations have a peak amplitude at 7 Hz, which is close to M5's specified bandwidth of 8–10 Hz.

Moreover, the previously calculated $4.75 \times 10^{-3}\%$ change in plate scale would correspond to an error of 1.8 mas when considering a $38''$ off-axis star. This error is comparable to the SCAO off-axis tip-tilt residuals for atmospheric turbulence with a seeing of $0.644''$ and a outer scale of 25 m as stated in [9]. Consequently, the



(a) Without M4 piston.



(b) With M4 piston of $955 \mu\text{m}$.

Figure 3: Results of MASCADO grid distortion analysis for plate scale compensation with a disturbance of $\Delta z_{M2} = 0.1 \text{ mm}$. *Left*: Change of drift pattern in compared to undisturbed grid. *Right*: Contribution of each polynomial fit order to the overall RMS.

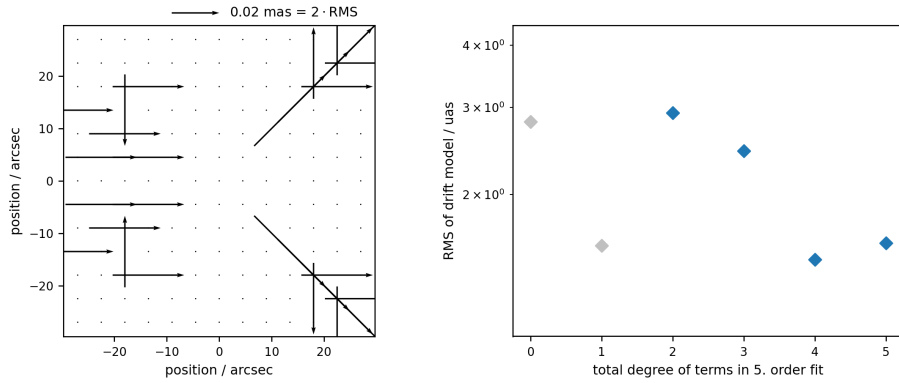


Figure 4: Results when compensating a disturbance of $\Delta z_{M2} = 0.1 \text{ mm}$ with an M5 piston of $-1186 \mu\text{m}$.

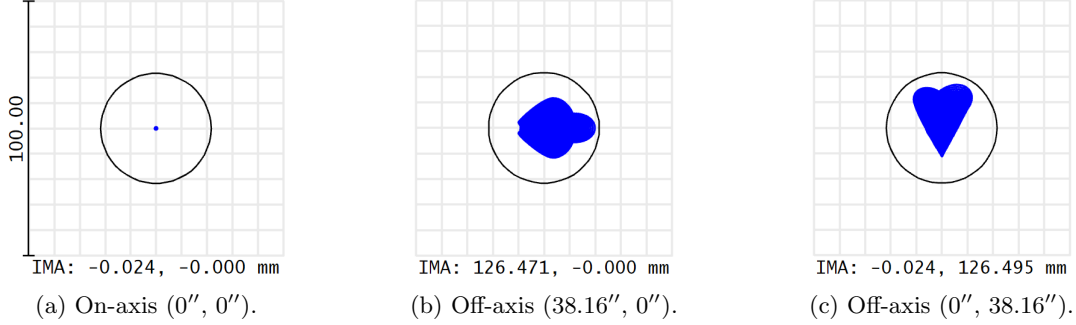


Figure 5: Spot diagrams for an on-axis and two off-axis stars at a disturbance of $\Delta z_{M2} = 1$ mm after SCAO correction using $81.2\mu\text{m}$ M4 PtV.

impact of the plate scale change on the Strehl ratio is acceptable in the H- and K-bands. For smaller wavelengths, the plate scale could be compensated with an M5 piston up to $\Delta z_{M2} = 0.1$ mm and about 10 Hz.

3.2 Effect on image quality

Apart from the impact on image magnification (plate scale), a piston disturbance at M2 also directly compromises the image quality due to a non-optimal PSF. Spot diagrams can be interpreted as geometric PSFs that fully sample the pupil of an optical system in a computationally efficient way. The point density determines how bright (high density) or dim (low density) certain parts of the image are lit [10]. Therefore, it is desirable for all points to be concentrated in a small spot. The respective spot diagrams can be seen in Figure 5. The results are obtained for an on-axis star and two off-axis stars at $38.16''$ and a piston disturbance of $\Delta z_{M2} = 1$ mm. The black circle represents the Airy disk with a radius of $21.65\mu\text{m}$. Before correcting with M4, the system has an RMS WFE of 40.18 waves $= 40.18\mu\text{m}$ (c.f. Figure 2). Figure 5a shows the spot diagram for an on-axis star, where we can see a perfect dot since the SCAO loop (here: Zemax Optimize-Tool) is reconfigured to correct only the on-axis star. In Figures 5b and 5c, two off-axis stars are depicted. The spots are not concentrated into a single spot but are still inside the Airy disk. Both off-axis fields have a Strehl ratio of 0.933, which is acceptable. For larger M2 piston disturbances, the image quality would be further degraded beyond the diffraction limit. Moreover, M4 would not be able to compensate for the induced aberrations, as for $\Delta z_{M2} = 1$ mm, the M4 uses already $81.2\mu\text{m}$ peak-to-valley (PtV) stroke (max. $100\mu\text{m}$ available).

4. CONCLUSION

In this work, we have derived the sensitivity with which piston oscillations at ELT M2 compromise the optical performance outside the SCAO-corrected star. Their optical impact is acceptable for near-infrared observations if the M2 piston vibration stays within a range of 0.1 mm around the nominal position. This level appears consistent with the quoted integral optical stability of the telescope interface. The M2 piston drift causes a respective plate scale change of 5×10^{-5} , which is comparable to the SCAO off-axis tip-tilt residuals. Furthermore, the induced variations are in the range of a few tenths of the ELT long-term plate scale stability of 10^{-4} given in the optical interface description for a period of 60 min [11].

However, the quoted stability describes the degree of alignment drift and telescope collimation precision rather than fast vibrations at individual mirrors. Since we do not currently have access to detailed FE simulations or structural details of the final design of the telescope mounting structure, much larger M2 piston disturbances are conceivable. If uncorrected, these disturbances would dominate the off-axis tip-tilt jitter beyond the atmospheric residuals, jeopardizing the achievable off-axis image quality. In principle, M4 can refocus the system up to 1 mm M2 piston, opening up the possibility of compensating for these larger M2 shifts without compromising on-axis SCAO performance. Corrective action is needed if either the fast M2 piston variations are greater than 0.1 mm, or if future AO systems aim for better off-axis performance at shorter wavelengths than MICADO in the astronomical HK-bands. The compensation can be achieved with additional actuators, such as an adaptive mirror in ELT's post-focal optical system. For MICADO, this is provided by the MCAO upgrade called MORFEO.

Future research should closely observe the amplitude of structural vibrations and explore new technologies for mitigating their effects on the optical performance.

ACKNOWLEDGMENTS

The authors would like to thank the German Federal Ministry of Education and Research (BMBF) for supporting this work under grant 05A20VS1 as well as the colleagues at ISYS and MPIA for their helpful suggestions and comments.

REFERENCES

- [1] Clénet, Y., Gendron, E., Gratadour, D., Rousset, G., and Vidal, F., “Anisoplanatism effect on the e-ELT SCAO point spread function. a preserved coherent core across the field,” *Astronomy & Astrophysics* **583**, A102 (2015).
- [2] Rodeghiero, G., Pott, J.-U., Arcidiacono, C., Massari, D., Glück, M., Riechert, H., and Gendron, E., “The impact of ELT distortions and instabilities on future astrometric observations,” *Monthly Notices of the Royal Astronomical Society* **479**(2), 1974–1985 (2018).
- [3] ZEMAX LLC., “OpticStudio.” <https://www.zemax.com/pages/opticstudio>. Accessed on 03/01/2023.
- [4] Schmid, C., *Common ICD between the E-ELT Nasmyth Instruments and the Rest of the E-ELT System* (2017). ESO-253082, v4.
- [5] Riechert, H. and Pott, J.-U., “MASCADO python package for analyzing geometric distortions.” <https://github.com/tychon/mascado> (2018). Max-Planck-Institute for Astronomy, Heidelberg.
- [6] Riechert, H., Garrel, V., Pott, J.-U., Sivo, G., and Marin, E., “GeMS/GSAOI: towards regular astrometric distortion correction,” in [*Ground-based and Airborne Instrumentation for Astronomy VII*], SPIE (2018).
- [7] Mueller, M., Cayrel, M., Bonnet, H., Ciattaglia, E., Esselborn, M., Koch, F., Kurlandczyk, H., Pettazzi, L., Rakich, A., and Sedghi, B., “The secondary mirror concept for the European Extremely Large Telescope,” in [*Ground-based and Airborne Telescopes V*], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., **9145**, International Society for Optics and Photonics, SPIE (2014).
- [8] Sedghi, B., Müller, M., Bonnet, H., Dimmler, M., and Bauvir, B., “Field stabilization (tip/tilt control) of E-ELT,” in [*Ground-based and Airborne Telescopes III*], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., **7733**, International Society for Optics and Photonics, SPIE (2010).
- [9] Carlà, G., Plantet, C., Busoni, L., and Agapito, G., “Temporal spectrum of multiconjugate adaptive optics residuals and impact of tip-tilt anisoplanatism on astrometric observations,” *Monthly Notices of the Royal Astronomical Society* **516**(3), 3837–3846 (2022).
- [10] Thibos, L. N., “Calculation of the geometrical point-spread function from wavefront aberrations,” *Ophthalmic and Physiological Optics* **39**(4), 232–244 (2019).
- [11] ESO, *E-ELT Interfaces for Scientific Instruments* (2010). E-TRE-ESO-586-0252, v3.