MAVIS: Astrometric and NCPA Calibration Plan

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ABSTRACT

The adaptive optics module of MAVIS will feed an imager and spectrograph with an MCAO corrected wavefront, producing near-diffraction-limited science in the visible spectrum over a wide field of view. To capitalise on this performance, non-common path aberrations between the wavefront sensors and science instruments must be measured and corrected over the field. Additionally, there will always be a small amount of undesirable distortions over the field of view induced by optical surfaces and imperfections, which must be characterised to deliver the required astrometric performance in MAVIS. We describe the methods proposed for both the NCPA and astrometric calibrations, as well as the status of their early development.

Keywords: MAVIS, adaptive optics, calibrations, astrometry, NCPA

1. INTRODUCTION

Multi-conjugate Adaptive Optics (MCAO) allows for wide-field high-order correction of atmospheric turbulence for ground-based telescopes. MAVIS, the MCAO-Assisted Visible Imager and Spectrograph for the ESO VLT, aims to deliver a 30 arc-second Field-of-View (FoV) with at least 10% Strehl-ratio in V-band under median seeing conditions [7]. This requirement for MAVIS translates into a tight wavefront error budget, a total of approximately 130 nm, over the FoV.

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Non-Common Path Aberrations (NCPAs) arise in optical systems if wavefront sensors and science devices do not completely share the same optical path. For example, when a beam-splitter divides incoming light to a separate wavefront sensing channel and a science channel, such that all optics (and any aberrations they introduce) after the splitter are not on the common path. In the family of wavefront error sources, NCPAs are particularly burdensome, as they cannot be unambiguously measured by the WFS alone. We consider all NCPAs as either:

- in the WFS path only, in which case the AO system will try to inject the negative aberration into the common science path by some compensation mechanism (e.g., deformable mirror). We refer to this as a *false NCPA*. Or,
- the NCPA can be in the science path only, in which case there will be no measurement by the WFS, and thus no effort from the AO system to correct for it. We refer to this as a *true NCPA*.

Both classes of NCPAs are damaging to the quality of the science Point Spread Function (PSF) when the AO loop is closed. For a nice discussion on NCPAs in AO, see Hénault (2019) and Skaf *et al.* (2021) [5, 8].

In MAVIS, if left uncorrected, NCPAs would contribute an estimated 100 nm RMS WFE based on ray-tracing simulations. This is unacceptable, as it would reduce the remaining error budget to less than 85 nm RMS (a value that is currently extremely difficult to realise even on a narrow-field instrument). We aim to identify and correct the MAVIS NCPAs, with a target residual error of less than 20 nm RMS.

Apart from the NCPA challenge, optical aberrations must also be precisely characterised to satisfy the demanding level of astrometric accuracy required of MAVIS. *Astrometry* here means: the extraction of positional information of objects in the sky. For MAVIS, the astrometric performance is specified only when at least three GAIA objects are available, allowing for the precise removal of plate scale and world-coordinate-system (WCS) errors. MAVIS is required to achieve astrometric precision:

- better than 150 microarcsec (goal of 50 microarcsec) for any objects separated by less than 1 arcsec (i.e., *relative astrometric accuracy*), and
- better than 2 milliarcsec (0.4 milliarcsec goal) for any object in the field (i.e., *absolute astrometric accuracy*).

Preliminary work has been done developing an astrometric calibration method for MAVIS, and can be found in [2].

In this brief communication, we summarise the key concepts involved in both the NCPA and Astrometric calibration methods proposed for MAVIS. We outline the principles and assumptions involved in each, and the plan for prototyping these methods before MAVIS goes on-sky. Due to the relative immaturity of the methods proposed within, we openly invite feedback from the community in the form of criticisms, concerns, and constructive suggestions for improvement. Please email any such correspondence to the first author.

2. NON-COMMON PATH ABERRATIONS

The NCPA calibration strategy is based on the Tomographic Phase-Diversity (TPD) approach, proposed by Gratadour *et al.* designed and used for GeMS [4]. TPD allows the reconstruction of several *layers* of NCPA sources optically conjugated to physical altitudes $h \in (-\infty, \infty)$. Upon reconstructing these layers, an optimised set of Deformable Mirror (DM) and WFS references can be produced, and the AO system can be configured to operate around these references - rather than simply trying to produce a flat wavefront on the WFS. Figure 1 describes the conceptual process of determining these references.

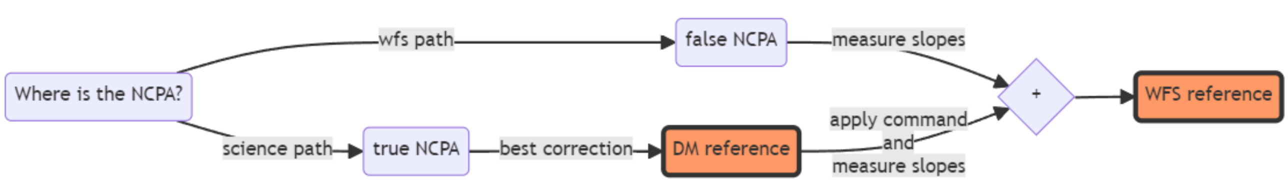

Figure 1. Reference calculation conceptual diagram.

2.1 Sources of aberrations in MAVIS

While it is not possible to know the exact values of the NCPAs in MAVIS until it is fully integrated, it is possible to use ray-tracing optics software and surface quality statistics to estimate the contribution of NCPAs at various altitudes in MAVIS, given the optical design alone. Figure 2 shows the distribution of optical non-common path surfaces in MAVIS.

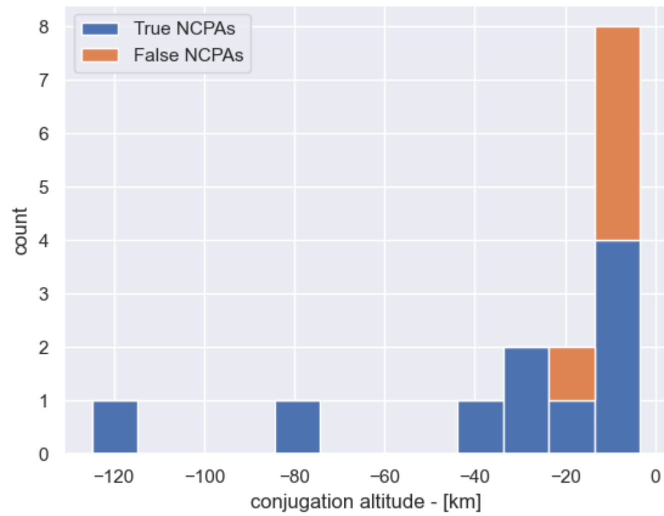

Figure 2. Conjugation altitudes of non-common path surfaces in MAVIS (excludes two science filters < -400 km).

Most notably, all of these surfaces are conjugated to negative altitudes. This is an outcome of optical engineering trade-offs, and the deliberately minimalist design of MAVIS. The three DMs of MAVIS are conjugated to 0 km, 6 km, and 13.5 km, which means that they have a limited ability to correct for these NCPAs, but most of these sources are within [-20,0] km, so will be at least partially correctable by the Deformable Secondary Mirror (DSM) of the VLT. The ability to compensate for *true NCPAs* depends on this generalised fitting error, but the level of compensation for *false NCPAs* depends only on our abiliy to measure them. That is, false NCPAs are only required to be known to the AO controller in the form of WFS references, and are not to be actively corrected (see Figure 1).

Even in conjugation altitudes where we cannot correct for NCPAs, we are still able to measure them. As such, it may prove beneficial to feed those NCPAs which are measurebale but uncorrectable into the point-spread function reconstruction pipeline used in MAVIS, which will in turn pass estimated PSFs to the VLT operators and the science data products. This will not affect the baseline performance of MAVIS, but will allow astronomers to improve the accuracy of the astrometric and photometric science extracted from MAVIS data.

2.2 Tomographic Phase Diversity in MAVIS

As stated above, the TPD approach follows the methodology of [4], though in the MAVIS case, there are some key differences which will drive the software solution.

Firstly, in [4], the only conjugation altitudes were those of the physical DMs. Since our conjugation layers are negative, we will reconstruct the NCPAs on the altitudes of their sources, and then optimise their compensation over the science field*. This requires reconstruction onto many more layers than we have DMs, and increases the computational complexity of the algorithm, as well as introducing an extra task.

*To be convinced that this additional complexity is justified, consider that for a narrower field, we could correct for a larger range of altitudes with the same set of DMs, and that the optimisation field is defined only in software.

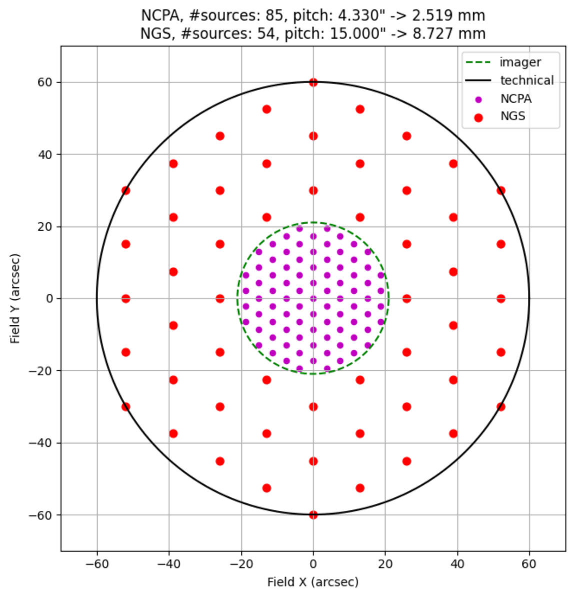

Figure 3. NCPA and NGS calibration mask, pinhole distribution in MAVIS.

Additionally, since the MAVIS error budget is much tighter than GeMS, many more sources are required to fully probe the NCPAs to a satisfactory level. In the current design, the MAVIS calibration unit is equipped with 85 point-like visible sources distributed over the field (compared to 24 in GeMS) to act as reference objects to probe the NCPAs. This also increases the computational complexity. The proposed distribution of sources is shown in Figure 3.

Finally, MAVIS contains three different rotating coordinate systems at any given time:

- The rotating Nasmyth focus coordinate system, defined by an elevation-based rotation, driven by the telescope pointing. This is the coordinate system of the common-path post-focal optics, as well optics between the LGS dichroic and K-mirror.
- The pupil coordinate system, defined by the DSM of the VLT, which is also the coordinate system of the Laser Guide Stars (LGS) due to the laser launch telescopes being fixed with respect to the VLT Alt/Az mount. Derotation of the LGS to their WFS is performed by the LGS WFS carousel.
- The science + Natural Guide Star (NGS) coordinate system, which has been derotated by a K-mirror to simultaneously balance the effects of: Alt/Az telescope pointing for the science target location (hour-angle and declination), sidereal vs non-sidereal source motion, and desired position angle of the observation, set by the observer.

In order to fully capture the NCPAs, it will be necessary to extract the NCPA sources separately in their corresponding coordinate system. That is, many batches of TPD will be run at different configurations of MAVIS so that one can determine the rotation-dependent NCPA functions. Then, when determining the DM and WFS references to apply over a period of observing, one can use the average configuration of MAVIS during this period to perform the optimal NCPA compensation.

All of these factors suggest that we will have a much more demanding computational load than in GeMS, which we will address by optimising the TPD algorithms and modifying it to be suitable for modern high-performance computing hardware.

2.3 Prototyping Plan for NCPAs in MAVIS

A prototyping plan for the NCPA process in MAVIS is being established. Early work has been done in simulation to assess the capacity of TPD in the context of MAVIS. An early bench prototype was also developed but the results were largely inconclusive, owed in part to the lacking of a suitable pinhole mask. From the results of simulations and the insights from the first prototype, a new prototype is being considered which will include an as-specified replica of the MAVIS NCPA pinhole mask.

As can be seen in Figure 3, it has been determined that the NCPA pinhole mask will be part of the same pinhole mask used to calibrate the NGSs. In order to accurately replicate the input focal plane of MAVIS (as a good calibration mask should do), this mask is required to curve with the curved focal plane of the VLT. This limits the possibilities for manufacturing the mask, though we are currently investigating the possibility to etch a pinhole mask onto a suitably curved transparent optic, which is then back illuminated by a grid of NIR and visible LEDs. Results from this prototype, including the suitability of this calibration mask manufacturing method, will feature in a future publication.

3. ASTROMETRIC DISTORTIONS

While NCPAs affect the image by means of degrading the PSF, astrometric distortions affect the image by changing the positions of objects in the science field without necessarily degrading the PSF quality. The source of both of these errors (imperfect optics) are typically stronger at lower spatial frequencies, which results in the fact that NCPAs have the strongest effect on the PSF when they are caused by optics near the pupil plane (typically where the beam footbrint is largest). Conversely, when optical surfaces are placed nearer to the focal planes of a system, they are more likely to introduce distortions, and typically have little effect on the PSF.

The astrometric distortion calibration is different to the NCPA calibration in that the distortions are not actively corrected in the AO loop. Instead, it is proposed that a distortion map is passed to the data reduction pipeline with the science data, and this map can be used to improve the astrometry for arbitrary objects in the data.

As in the NCPA process, the sources of astrometric error rotate as the VLT and MAVIS track objects in the sky. As such, the distortion maps will be calibrated over many different configurations of MAVIS, and the observer will receive distortion maps based on the *average* configuration during their exposure.

In previous work, we described in-depth the *differential* astrometric calibration technique proposed for MAVIS [2]. Here we briefly summarise the key points, but refer the reader to that work for more details.

3.1 Differential Astrometric Calibration Technique

For illustrative purposes, first consider an *absolute* astrometric calibration technique. In that regime, a calibration source with precisely known coordinates is presented at the input focal-plane of the optical system. Its position at the output focal-plane of the system (i.e., the science imager) is measured, and the difference between these two quantities describes the distortion induced by the optical system. Extending this source to a grid of sources, one can probe the distortions over the field and build knowledge on the overall *distortion field*.

This absolute method is straightforward and effective, but relies on precise knowledge of input source positions. In the case of MAVIS, the tolerance for those positions is in the order of nanometres. Due to this overly sensitive constraint, we developed the aforementioned differential method, which is insensitive to absolute position errors of pinholes, at the cost of becoming insensitive to tip-tilt and plate-scale distortions. These are not significant costs in MAVIS, since the astrometric performance requirements are specified only when a sufficient number of GAIA reference sources are in the field to calibrate the WCS and plate-scale directly from the image.

The differential method works by offsetting the calibration mask (see Figure 4) in x and y, in order to estimate the Jacobian of the distortion field. This estimated Jacobian is used to fit to the distortions with a set of distortion basis functions (e.g., bivariate polynomials), which have analytically derived Jacobians. In other words, we measure the partial derivatives of the distortion functions and integrate those to determine the distortion functions themselves. The *integral* is accurate up to a constant in each dimension (i.e., constant tip/tilt across the field).

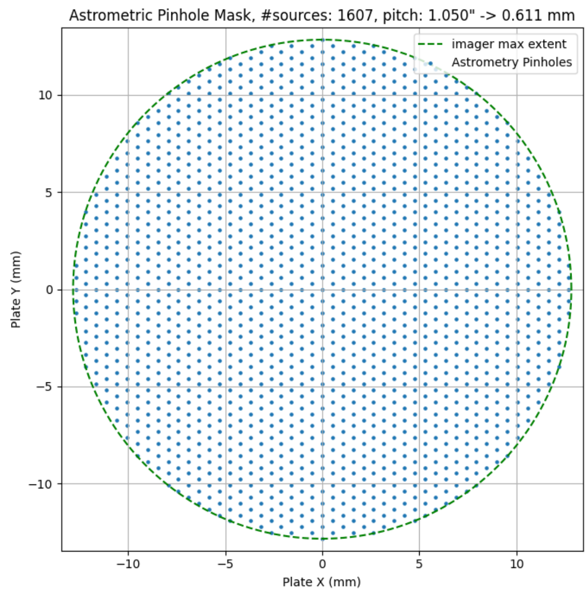

Figure 4. Astrometric calibration mask, pinhole distribution in MAVIS.

Since the last work, we have made minor improvements to the differential technique, namely that we now use a hexagonal lattice of pinholes rather than a square one, and that the software pipeline (available in `mavisim` [6, 3]) can handle an arbitrary set of translations when estimating the distortion Jacobian from calibration data (previously translations were only in the x and y axes).

3.2 Prototyping Plan for Astrometric Distortions in MAVIS

The prototyping of the astrometric calibration process for MAVIS is relatively simple (at least opto-mechanically) compared to that of the NCPAs. However, the differential method is completely untested in existing AO systems and is a critical element of MAVIS, so it requires careful consideration and conclusive verification.

A prior iteration of this experiment was conducted by our team using the OLED display of a Samsung S20 phone, inspired by the work of Walk *et al.* [9, 1]. With this method, a grid of very bright "pinholes" can be reconfigured at will. This type of technique is particularly convenient in the early stages of prototyping when considering design parameters such as grid densities, brightness, and grid geometry.

Regrettably, this first experiment was ultimately inconclusive. The flaw in the experiment was a lack of precise *a priori* knowledge of the input distortion field, meaning that while we were able to estimate a reasonable distortion field using the differential method, we were unable to verify if this was in fact the distortion field of the optical system (and to what level of accuracy had the method performed); that is, we lacked knowledge on the *ground-truth* distortions.

In the coming months, we will further develop the prototype of the astrometric calibration technique, using either the OLED source or a replica of the proposed MAVIS astrometric cailibration pinhole mask. In the new method, we propose to apply an optical aberration with a precisely known distortion effect, as to quantitatively assess the differential method.

4. CONCLUSIONS

In MAVIS, the NCPA calibration process is built around the Tomographic Phase Diversity method used in GeMS. To be suitable for MAVIS, many more point-sources are required than in GeMS, and the NCPAs will be tomographically reconstructed onto many layers – based on the optical design – rather than directly onto the DMs. The key aspect which is yet to be demonstrated is simply the level of performance of TPD compared to MAVIS's tight error budget.

Astrometric distortions induced by MAVIS are to be compensated to an acceptable level using the differential astrometric calibration technique. This technique has shown promise in simulation, but also requires prototyping on the bench. It is yet to be shown on the bench or on sky if the technique can achieve the required low levels of astrometric error. This method has the additional risk that it has never been fully validated in any capacity (beyond end-to-end simulations), so the ongoing testing of this method is a crucial risk mitigation measure for MAVIS.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Leo Neat and Aiden Walk for developing and sharing their source code, used for addressing individual OLED pixels on an Android Smartphone, which we continue to use as an astrometric calibration source in our developing prototypes.

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