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**Design and development of MCAO systems for
the next generation of astronomical instruments:
MAVIS case**

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To my mum.

Abstract

Originating in the late 1980s, the concept of multi-conjugate adaptive optics (MCAO) as a technique to correct atmospheric turbulence underwent two decades of development before achieving practical implementation on the Gemini telescope. The GeMS system demonstrated the remarkable potential of MCAO, and only recently has this technology begun to see broader adoption. The success of GeMS became a driving force for the development of new MCAO instruments and the next generation of adaptive telescopes. The facilities currently under development for the next few years include, for instance, MORFEO on the ELT, NFIRAOS on the TMT and MAVIS on the VLT.

The work presented in this thesis is dedicated to the MAVIS instrument, which will soon operate on the VLT. My primary focus has been the finalisation of the optical design for the parts of the Adaptive Optics Module of MAVIS, along with the verification of its optical performance. The analyses conducted as part of this effort include Mid-Spatial Frequency (MSF) figure error and differential distortions analyses, plate-scale variation, and image uniformity analyses. Additionally, in-field scattering and ghost analyses are presented. These studies aim to ensure the AO module meets stringent performance requirements for scientific observations, particularly astrometric studies.

Another significant aspect of this thesis concerns the optical design of the Verification Test Bench (VTB). The VTB serves as a critical internal tool during the MAIT phase. Its purpose is to validate and test the performance of MAVIS prior to its deployment for on-sky operations, ensuring seamless integration with the VLT.

The methodologies and analyses presented here are not only essential for MAVIS but are also broadly applicable to the development and optimisation of other adaptive optics systems. By contributing to the refinement of AO technologies, this work supports advancements in astronomical instrumentation and observational capabilities.

Riassunto

Originato alla fine degli anni '80, il concetto di multi-conjugate adaptive optics (MCAO) come tecnica per correggere la turbolenza atmosferica ha attraversato due decenni di sviluppo prima di raggiungere un'implementazione pratica sul telescopio Gemini. Il sistema GeMS ha dimostrato il notevole potenziale della MCAO e solo recentemente questa tecnologia ha iniziato a vedere una più ampia adozione. Il successo di GeMS è diventato una forza trainante per lo sviluppo di nuovi strumenti MCAO e della prossima generazione di telescopi adattivi. Tra le strutture attualmente in fase di sviluppo per i prossimi anni si includono, ad esempio, MORFEO sull'ELT, NFIRAOS sul TMT e MAVIS sul VLT.

Il lavoro presentato in questa tesi è dedicato allo strumento MAVIS, che presto sarà operativo sul VLT. Il mio principale obiettivo è stato la finalizzazione del disegno ottico delle parti dell'Adaptive Optics Module di MAVIS, insieme alla verifica delle sue prestazioni ottiche. Le analisi condotte come parte di questo lavoro includono le distorsioni dovute agli errori di figura delle superfici ottiche nelle medie frequenze spaziali (MSF) e le distorsioni differenziali, le variazioni della scala e le analisi dell'uniformità dell'immagine. Inoltre, sono presentate analisi sulla luce diffusa da oggetti in campo e sui ghosts. Questi studi mirano a garantire che il modulo AO soddisfi i rigorosi requisiti di prestazione per le osservazioni scientifiche, in particolare per studi astrometrici.

Un altro aspetto significativo di questa tesi riguarda il design ottico del Verification Test Bench (VTB). Il VTB serve come strumento interno fondamentale durante la fase MAIT. Il suo scopo è convalidare e testare le prestazioni di MAVIS prima della sua messa in funzione in cielo, garantendone una corretta integrazione con il VLT.

Le metodologie e le analisi presentate qui non sono essenziali solo per MAVIS, ma sono anche ampiamente applicabili allo sviluppo e all'ottimizzazione di altri sistemi di ottica adattiva. Contribuendo al perfezionamento delle tecnologie AO, questo lavoro supporta i progressi nella strumentazione astronomica e nelle capacità osservative.

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List of Acronyms

AO	Adaptive Optics
AOM	Adaptive Optics Module
AOF	Adaptive Optics Facility
ACM	Astrometric Calibration Module
ADC	Atmospheric Dispersion Corrector
AIT	Assembly, Integration and Testing
AOI	Angle of Incidence
BBAR	Broad-Band Anti-Reflection
BSDF	Bi-directional Scatter Distribution Function
CU	Calibration Unit
CCM	Calibration Control Module
DM	Deformable Mirror
DSM	Deformable Secondary Mirror
DNU	Diagnostic and NCPA Unit
FWHM	Full Width at Half Maximum
FoV	Field of View
FDR	Final Design Review
GC	Globular Cluster
IMBH	Intermediate Mass Black Hole
IFS	Integral Field Spectrograph
LGS	Laser Guide Star
LSM	Light Source Module
MCAO	Multi-Conjugate Adaptive Optics
MAVIS	MCAO-Assisted Visible Imager and Spectrograph
MAIT	Manufacturing, Assembly, Integration, and Testing
MC	Monte-Carlo
MCM	Main Calibration Module
MSFE	Mid-Spatial Frequency figure Error
NA	Numerical Aperture
NGS	Natural Guide Star
NIR	Near-InfraRed
NCPA	Non-Common Path Aberration
OMS	Overall mechanical system

OOP Object-Oriented Programming
OPD Optical Path Difference
PAC Percentage of Area Coverage
PFR Post-Focal Relay
PDR Preliminary Design Review
PSD Power Spectral Density
PSF Point Spread Function
PtV Peak-to-Valley
RMS Root-Mean Square
RTC Real-Time Computer
SCAO Single-Conjugate Adaptive Optics
SHWFS Shack-Hartmann WaveFront Sensor
SR Strehl Ratio
TIS Total Integrated Scatter
TT Tip-Tilt
VLT Very Large Telescope
VTB Verification Test Bench
WFE WaveFront Error
WFS WaveFront Sensor
ZA Zenith Angle

Introduction

The rapid development of technologies ushers in a new era of astronomical instrumentation. Current instruments on both small and large telescopes face many limitations when studying deep space or dense regions such as globular clusters. Although space missions, such as Cheops^[1], James Webb Space Telescope (JWST)^[2], Euclid^[3] have revolutionised our exploration of the Universe, they come with crucial constraints. These constraints are not due to atmospheric interference, as with ground-based instruments, but rather related to factors such as size, budget, and the complexity of making repairs once a mission is launched. Consequently, there is a strong need to develop better instruments that can be operated from ground-based telescopes.

Significant progress in ground-based instrumentation was made in the late 20th and early 21st centuries. Modern imagers and spectrographs now cover a wide wavelength range—from the ultraviolet (UV) to parts of the radio spectrum. However, this coverage is not continuous; it is constrained by atmospheric transmission windows. The Earth’s atmosphere absorbs light at many wavelengths, particularly in the UV, infrared (IR), and some radio bands, creating observational gaps from the ground. In addition to these spectral limitations, atmospheric turbulence distorts incoming light, degrading image quality. These limitations highlight the need for advanced techniques to enhance the performance of ground-based telescopes.

These decades offer numerous possibilities for the future of astronomy. Adaptive optics (AO) technology, first developed in the late 1980s, has proved to be an effective tool for correcting atmospheric turbulence. First AO systems were relatively simple single-conjugate setups, consisting of only one deformable mirror (DM), one wavefront sensor (WFS), and the Real-Time Computer (RTC). The examples of such systems include COME-ON^[4] or its successor COME-ON+^[5].

The first multi-conjugate adaptive optics (MCAO) system was the Multi-conjugate Adaptive optics Demonstrator (MAD), which main goal was to demonstrate RTC and reconstruction techniques for complex MCAO systems. The MAD bench supports two different reconstruction approaches: the star-oriented MCAO mode using multi Shack-Hartmann WFSs, and the layer-oriented MCAO mode, which uses multiple Pyramid WFSs^[6].

Ongoing developments in adaptive optics have since paved the way for a new generation of instruments planned for both existing and upcoming large telescopes.

Examples include the Multi-AO Imaging Camera for Deep Observations with Multi-Conjugate Adaptive Optics Relay For ELT Observations (MICADO-MORFEO system)^{[7],[8]} on the Extremely Large Telescope (ELT), the Narrow Field InfraRed Adaptive Optics System (NFIRAOS)^[9] on the Thirty Meter Telescope (TMT), the MCAO-Assisted Visible Imager and Spectrograph (MAVIS)^[10] on the Very Large Telescope (VLT), among others.

All these instruments will provide significant improvement to the astronomical observations, possibly pushing beyond the current limits of resolution and precision. The most evident advantage lies in photometry studies^{[11],[12]}. The integration of adaptive optics systems on the instruments will enable an increase in the Strehl ratio, resulting in higher flux concentration and better contrast with the background. This is particularly critical for the crowded fields, as it will reduce flux blending and allow for the clear separation of close sources. The latter also holds great importance for astrometry^{[13]–[15]}. For instance, the main science case of MAVIS is the search for intermediate mass black holes (IMBH) in globular clusters which relies heavily on the astrometric measurements^{[16],[17]}.

The work presented in this thesis focuses on the finalisation of the optical design and performance verification of the MAVIS instrument, serving as a practical case study of a complex MCAO system. The structure of the thesis is as follows: Chapter 1 provides a comprehensive overview of MCAO techniques and a detailed description of the MAVIS instrument. Chapter 2 discusses the optical design of the adaptive optics module (AOM) of MAVIS and the modifications made during Phase B of the instrument development and outlines the design and purpose of the Verification Test Bench. In Chapter 3, I present instrument-related analyses, including distortion, plate-scale, uniformity evaluations, scattering and ghost analyses. The last Chapter 4 is dedicated to the design of the Verification Test Bench.

Chapter 1

Scientific background and instrument context

1.1 Imaging through atmosphere

Ground-based astronomical observations are inherently constrained by the Earth's atmosphere, which distorts the wavefront of incoming light from stars and other celestial objects. These distortions arise due to atmospheric turbulence, a complex phenomenon influenced by various environmental factors such as wind speed, temperature gradients, and pressure variations. Although the atmospheric turbulence is generally neither isotropic or homogeneous, Kolmogorov proposed that in fully developed turbulence, energy cascades from large-scale motions to progressively smaller eddies until reaching a dissipation scale where viscosity dominates^[18]. At these smaller scales, turbulence is thought to reach statistical equilibrium, resulting in locally isotropic conditions^[19].

Nevertheless, it would not be an issue for the observation from Earth, if those instabilities in the atmosphere were not causing temporal and spatial fluctuations of the refractive index. According to turbulence theory, these fluctuation can be described using the index structure function:

$$D_n(\vec{\xi}) = \left\langle \left| n(\vec{x} + \vec{\xi}) - n(\vec{x}) \right|^2 \right\rangle = C_n^2 \xi^{2/3}, \quad (1.1)$$

where n is the refractive index and angle brackets define a spatial average. C_n^2 , which is the structure constant of refractive index, can be considered as a descriptive quantity of the strength of small-scale turbulence.

Generally, the refractive index of air depends on temperature and relative humidity. Although the latter plays a negligible role in optical propagation. Taking that into account, we can write the formula for the refractive index structure constant including only temperature dependence^{[20],[21]}:

$$C_n^2(z) = \left(\frac{80 \cdot 10^{-6} P}{T^2} \right)^2 \cdot C_T^2(z), \quad (1.2)$$

where P is the atmospheric pressure expressed in millibars, T is the temperature in Kelvins, C_T^2 is the temperature structure constant.

Similarly to the spatial description, the structure function can be written for the temporal evolution of the refractive index:

$$D_N(\tau) = C_n^2 |\vec{v}\tau|^{2/3}, \quad (1.3)$$

where $\vec{v}$ is the wind velocity.

Generally, the structure constant of the refractive index depends on the altitude. This dependence defines the vertical profile of atmospheric turbulence. Because atmospheric turbulence is inherently non-stationary – changing both in time and space – obtaining accurate, high-resolution turbulence profiles is a challenging task^{[22],[23]}. Typical measurements of turbulence profiles are based on a direct balloon micro-thermal sounding or a remote optical sounding, such as those using scintillation measurements of binary stars. However, none of these methods can continuously track the temporal evolution of turbulence with sufficient resolution. As a result, some statistical database is required for the observational sites.

Despite the temporal variability, there are a few altitude layers that have a peak in the overall turbulence energy, which allows to have an estimate while deciding the conjugation of the deformable mirrors in the adaptive optics systems described below. One of the most significant contributors is the ground layer, typically extending several hundred meters above the surface. This layer accounts for a large portion of the total turbulence energy and is primarily driven by surface-atmosphere interactions, such as thermal gradients and terrain-induced wind shears^[24]. Other major turbulence contributors are located at higher altitudes, particularly around the boundary layers between the troposphere and tropopause, and between the upper troposphere and lower stratosphere. These layers often exhibit enhanced turbulence due to the presence of jet streams, which are fast-moving air currents that generate strong shear instabilities^[25]. An example of the vertical turbulence profile for the Paranal observatory is shown in Fig. 1.1, where the stratification and energy peaks of atmospheric layers are clearly illustrated^[26].

While observing through the atmosphere, all the turbulent layers have an integrated effect on the incoming wavefront from a source. Light going through the regions with higher refractive index will experience a delay with respect to the light propagating through other regions. These optical path fluctuations are considered achromatic, although the air is slightly dispersive. However, the wavefront phase is strongly dependent on the wavelength as shown in Equation (1.4)^[27].

$$\varphi = k \int n(z) dz = \frac{2\pi}{\lambda} \int n(z) dz, \quad (1.4)$$

where $n(z)$ is the refractive index fluctuation along the light beam.

To describe random fluctuations of the wavefront phase, we can use the structure

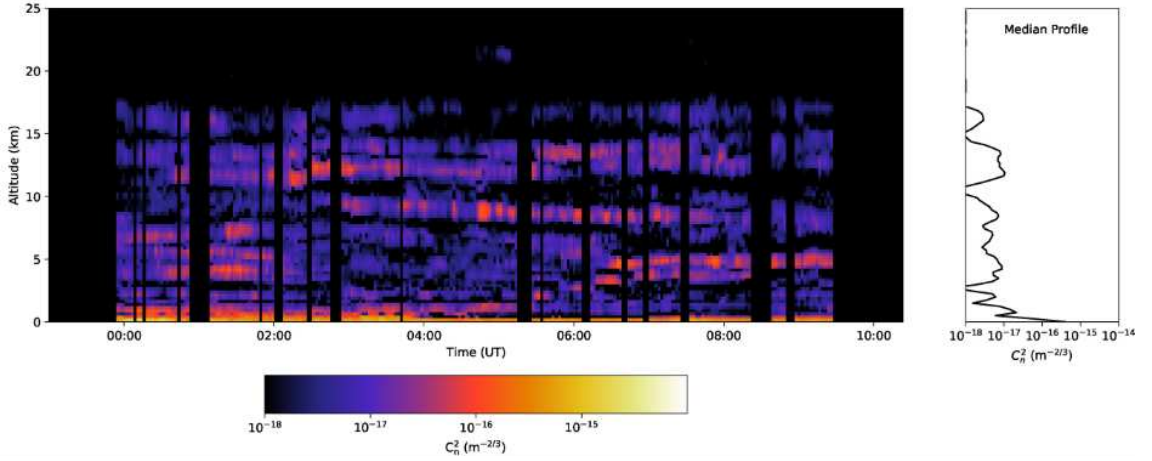


Figure 1.1: An example of the vertical turbulence profile at ESO Paranal. Credits: Stereo-SCIDAR.

function as in the case of the refractive index:

$$D_\varphi(\vec{\xi}) = \left\langle \left| \varphi(\vec{x}) - \varphi(\vec{x} + \vec{\xi}) \right|^2 \right\rangle \quad (1.5)$$

Substituting Equation (1.4) into Equation (1.5) and calculating the integral of an ensemble average, we can rewrite the phase structure function in a different way:

$$D_\varphi(\vec{\xi}) = 6.88 \left(\frac{\xi}{r_0} \right)^{5/3}, \quad (1.6)$$

where

$$r_0^{-5/3} = 0.423 \left(\frac{2\pi}{\lambda} \right)^2 \sec(z) \int_0^{H_{max}} C_N^2(h) dh \quad (1.7)$$

is an atmospheric coherence radius, or the so-called Fried parameter^[28]. It can sometimes be considered as the characteristic scale of the perturbations introduced by the atmosphere. While it provides a useful metric for describing the effects of atmospheric turbulence, this interpretation is most accurate in the context of long-exposure imaging, where phase fluctuations average out over time. For spatial scales smaller than r_0 , or spatial frequencies larger than r_0^{-1} , the optical transfer function of the atmosphere tends to zero, indicating a loss of image contrast at high spatial frequencies. In the Equation (1.7), h is the altitude, z is the zenith distance and the quantity $\sec(z)$ is the air mass – a dimensionless quantity that defines the relative amount of air along the line of sight between an observer and a celestial object. Its value is equal to 1 at the zenith. As the zenith angle increases, the airmass increases, meaning the light traverses a longer atmospheric path. This results in more scattering and absorption, which not only affects photometric measurements but also amplifies turbulence-induced image degradation. Hence, the airmass factor plays a direct role in modulating the value of the Fried parameter.

The Fried parameter is an important characteristic for astronomical imaging, as it defines the seeing and the Strehl ratio. Astronomical seeing characterises the

degradation of the image of an object observed through the atmosphere, typically called blurring^[29]. It can be measured as the full width at half maximum (FWHM) of the point spread function (PSF) and is connected with the Fried parameter by the relation:

$$\beta = 0.98 \frac{\lambda}{r_0} \quad (1.8)$$

The Strehl ratio is a fundamental metric for assessing the optical quality of an image after propagation through the atmosphere and, more generally, through an optical system. Analytically, the Strehl ratio is measured as the ratio of the central intensity of the PSF to that of the diffraction-limited Airy function, or aberration-free PSF^[30]:

$$S = \frac{P(0)}{P_0(0)} \quad (1.9)$$

If we instead consider the wavefront propagated from the source over a circular area of diameter d , the Strehl ratio can be well approximated (for $S \gtrsim 0.15$) by

$$S \approx e^{-\sigma^2}, \quad (1.10)$$

where σ^2 is the variance of the wavefront distortion.

An alternative interpretation of the Strehl ratio can be derived by considering an ideal telescope with a diameter equal to the Fried parameter. In such a scenario, the telescope's performance would be minimally affected by atmospheric turbulence. For a telescope with a diameter $D > r_0$, the Strehl ratio can be approximated as the square of the ratio between the Fried parameter and the telescope aperture:

$$S = \left(\frac{r_0}{D} \right)^2 \quad (1.11)$$

Since the Fried parameter depends on wavelength as $r_0 \propto \lambda^{6/5}$, it follows that achieving a high Strehl ratio—and consequently better image resolution—is more feasible at longer wavelengths. This wavelength dependence is particularly important for adaptive optics systems, as it directly impacts their ability to correct atmospheric distortions and improve image quality in different observational regimes.

1.2 Multi-conjugate Adaptive Optics

Over many decades, scientists have explored various techniques to enhance the imaging capabilities of ground-based observatories. The introduction of adaptive optics revolutionised the field, providing a powerful solution to correct atmospheric turbulence in real time^[31].

The aforementioned Multi-Conjugate Adaptive Optics, or MCAO, is a state-of-the-art technology that allows to correct for turbulence effects from different atmospheric layers on a relatively wide area of the sky^[32]. Modern adaptive optics (AO) systems, both existing and in development, can generally be classified into five main

categories: Single-Conjugate AO (SCAO)^[33], Ground-Layer AO (GLAO)^[34], Laser Tomography AO (LTAO)^[35], Multi-Object AO (MOAO)^[36], and MCAO. While all these systems significantly enhance observational astronomy by mitigating atmospheric aberrations, each comes with its own set of limitations.

For instance, one of the primary challenges of SCAO is anisoplanatism^[37]. An SCAO system uses one natural guide star (NGS) to sense the aberrations introduced by the atmosphere, and the corresponding correction is applied to the observed target. However, this approach assumes that the wavefront distortions experienced by the guide star are representative of those affecting the science target. In practice, this assumption breaks down when the line of sight to the guide star passes through a different turbulence volume than that of the object of interest. As a result, the correction becomes less accurate with increasing angular distance from the guide star, leading to a degradation in image quality across the field. This effect imposes constraints on the compensated field of view (FoV). The angular distance from a guide star where the anisoplanatism error is acceptable (typically less than 1 radian root-mean-square (RMS)) is called the isoplanatic angle and can be defined as

$$\theta_0 = 0.314 \frac{r_0 \cos z}{\bar{h}} \quad (1.12)$$

Here, $\bar{h}$ is the weighted average altitude of turbulence layers.

The dependence of the isoplanatic angle on the Fried parameter also implies a wavelength dependence $\theta_0 \propto \lambda^{6/5}$, which highlights that achieving a larger isoplanatic angle – and thus a wider corrected FoV – is more favourable at longer wavelengths, making infrared observations less affected by anisoplanatism compared to visible wavelengths.

MCAO tries to overcome these issues by using multiple sources to obtain corrections, both natural guide stars (NGS) and laser guide stars (LGS). This approach significantly extends the corrected FoV. A notable example demonstrating the effectiveness of MCAO is the Gemini Multi-Conjugate Adaptive Optics System (GeMs), which achieved a corrected FoV of 2 square arcminutes^[38]. This capability is particularly crucial for the study of extended astronomical objects, such as solar system bodies and extragalactic sources.

The structure of an MCAO system is inherently more complex than that of an SCAO system. There are two main types of MCAO: layer-oriented and star-oriented. In layer-oriented MCAO, WFSs are conjugated to a specific atmospheric layer, sensing the turbulence and providing commands to the DMs conjugated to the same altitude^[39]. This approach uses light from multiple stars simultaneously. In star-oriented MCAO, a separate WFS is required for each guide star, whether natural or laser-generated. These WFSs operate in a coordinated manner within a common control system, generating signals that are processed by the RTC to convert them into control commands for the DMs, ensuring precise compensation for atmospheric turbulence. A schematic representation of a star-oriented MCAO

system is shown in Fig. 1.2.

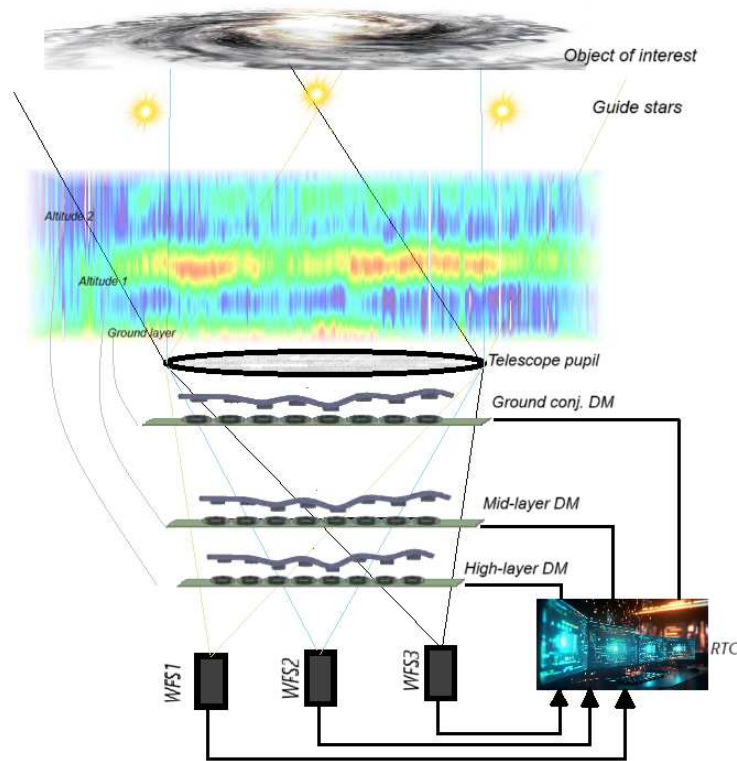


Figure 1.2: Schematic view of the MCAO work principle.

As mentioned above, an MCAO system tries to correct not only on a wider area but also to compensate for turbulence at different atmospheric layers. This requires the use of at least two DMs, conjugated to a specific altitude. Typically, one DM is conjugated to the ground layer, where the majority of atmospheric turbulence is concentrated, while the others are conjugated to high-altitude turbulent layers.

The use of LGSs in such systems is primarily due to the fact that NGSs might not be bright enough in the region of scientific interest or may be absent altogether. Artificial laser stars enable reasonable AO correction even in such cases. However, LGSs come with several limitations.

To create an artificial laser star, a laser excites sodium atoms in the sodium layer, which is located at a finite altitude in the atmosphere, typically 90 to 100 km above sea level. This leads to the so-called cone effect, meaning that the light from the LGS does not perfectly overlap with the light cylinder from an astronomical source at infinity. As a result, it senses slightly different turbulent volumes, introducing wavefront sensing errors^[40]. A schematic explanation of the cone effect is shown in Fig. 1.3. The way to mitigate this effect is to use multiple LGSs, thereby increasing the overlap with the light from a target source across different turbulence layers.

Another issue is related to the shape of the LGS, which is affected by the finite thickness of the sodium layer, as well as instabilities within the layer itself. For

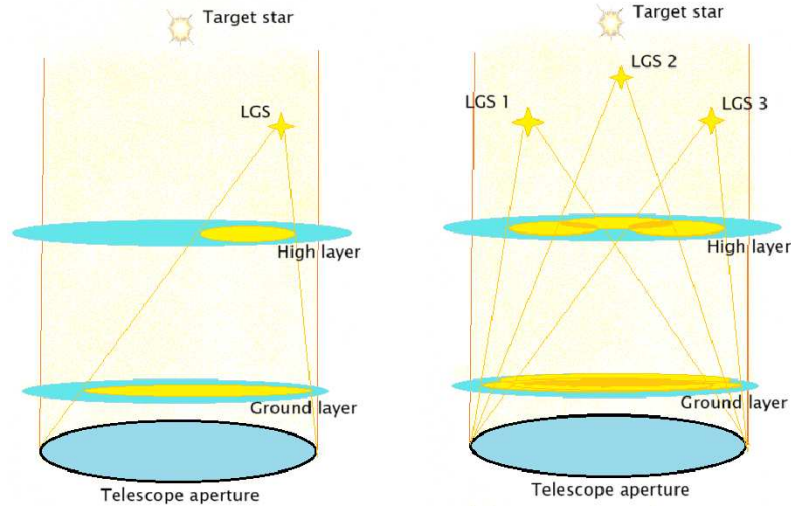


Figure 1.3: LGS cone effect that leads into the mismatch between the atmospheric volume corrected for a target and the one sensed by the LGS. It is partially compensated by utilising multiple LGSs as shown on the right figure.

example, in case of the Shack-Hartmann WFS (SHWFS), it translates into a spot elongation, which differs for each sub-aperture^[41]. Although there are techniques that partially address this issue, such as range gating or dynamic defocus, they are in general technologically demanding.

Moreover, it is practically impossible to measure tip-tilt (TT) or other low-order aberrations with LGSs. This is because during uplink propagation, the LGS already experiences tip and tilt, which then corrupts this information during downlink propagation^[42]. Therefore, there remains a strong need for NGSs, but now they can be much fainter, since less photons are required to sense global low-order aberrations. Nevertheless, several projects are actively working on solutions to these LGS-related issues^{[43]–[45]}. A prominent example is the INGOT WFS^[46], designed to cope with the 3D nature of laser stars.

1.3 MAVIS at the VLT

1.3.1 Design and technical characteristics

The majority of the current and upcoming AO-supported instruments work in the infrared (IR) wavelength range, as the wavelength dependence of atmospheric turbulence makes it easier to design and implement adaptive optics systems in this regime. At longer wavelengths, the effects of atmospheric distortions are less pronounced, allowing for more effective wavefront correction. MAVIS, MCAO-Assisted Visible Imager and Spectrograph, pushes the limits of the AO correction at shorter wavelengths^[47]. The working range of this cutting-edge instrument spans from 370 to 935 nm, covering the ultraviolet (U) to part of the near-infrared (NIR) wavebands.

MAVIS is a new generation instrument that is being developed by a large consortium consisting of prominent research institutes from Italy, Australia, and France. This instrument is planned to be installed on one of the VLT Unit telescopes (UT), UT4 Yepun. The choice was driven by the presence of the Adaptive Optics Facility (AOF) on UT4^{[48],[49]}. The centre of the AOF is the M2 unit, called Deformable Secondary Mirror (DSM). The mirror is 1120 mm in diameter and offers 1170 actuators for the correction of the wavefront. In addition to the DSM, the AOF provides the capability to generate four laser guide stars to obtain high-order aberration correction for astronomical instruments. MAVIS will benefit from this facility. However, given the wavelength range of MAVIS, four LGSs are not enough to provide an optimal correction. Therefore, it was decided to split each of the artificial stars into two, resulting in eight LGSs symmetrically positioned within the circular FoV^[50].

The instrument itself consists of four main subsystems and the overall mechanical system (OMS). They are the adaptive optics module (AOM), the imager, the spectrograph, and the calibration unit (CU). The optical layout of MAVIS is shown in Fig. 1.4.

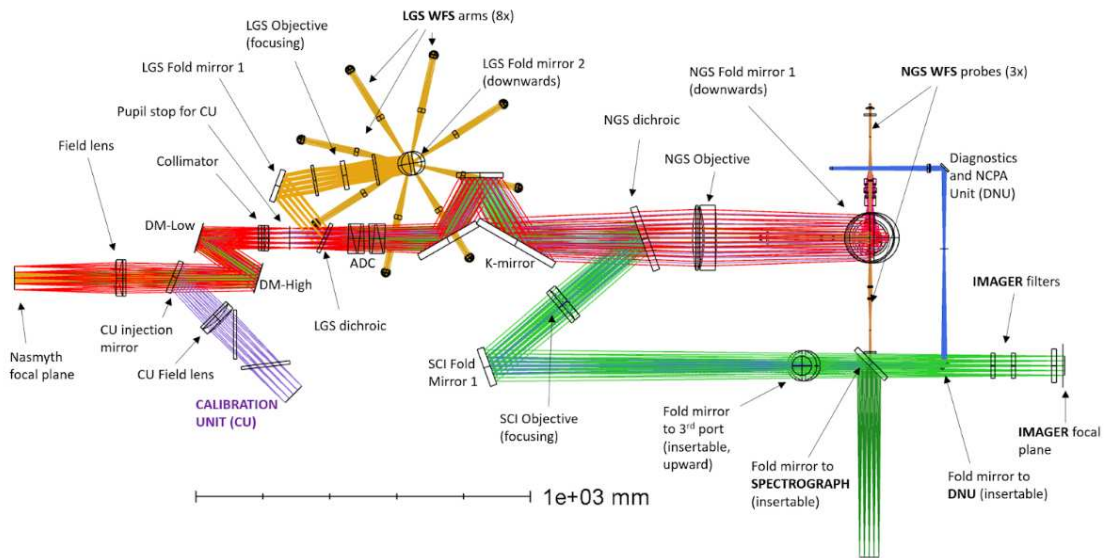


Figure 1.4: Optical design layout of MAVIS

Adaptive optics module

MAVIS will be positioned on the Nasmyth platform. The AOM subsystem, located immediately after the Nasmyth focal plane, is designed to collect the incoming light from the telescope, provide AO correction, and direct the corrected light to the scientific instrumentation. The module consists of three modules: the Post-Focal Relay (PFR), the NGS WFS and the LGS WFS, together with the RTC^[51].

The PFR is designed with all on-axis refractive components to make the design more flexible and minimise field distortions. It provides two post-focal DMs for

the adaptive correction of the wavefront. The Atmospheric Dispersion Corrector (ADC), made of two Amici prisms, compensates for chromatic effects caused by wavelength-dependent atmospheric refraction, while the K-mirror acts as a sky de-rotator.

The NGS channel, operating in the NIR (960 - 1740 nm), includes three WFSs and an acquisition camera. The NGS probes can move to acquire natural guide stars within an unobscured 2 arcmin FoV^[52]. The LGS channel includes a refocusing objective and a splitting pyramid feeding eight WFSs to measure high-order aberrations.

A more detailed description of the AOM design and its performance is provided in Chapter 2.

Science instruments

The current design of MAVIS includes both an imager and a spectrograph^[53], along with a dedicated port for a visitor instrument. The science channel receives an F/35 focal plane from the AOM. The Imager includes filters and cryogenic window without any reimaging optics, as illustrated in Fig. 1.4. The CCD camera is positioned immediately after. The FoV of the Imager is 30.2x30.2 arcsec, however the AO corrected FoV is slightly smaller, with a diameter of 30 arcsec. The plate scale of the imager is 0.737 arcsec/mm, or 7.5 mas/px, and the FWHM expected in V band is around 18 mas. According to the science case, MAVIS offers a selection of five broadband, three medium-band, and sixteen narrowband filters. The sensitivity of the imager is more than 29 mag in V band within one hour of integration at 5σ confidence level.

An additional fold mirror can be inserted after the SCI fold mirror, as shown in Fig. 1.4, allowing light to be redirected to the Integral Field Spectrograph (IFS). The optical design layout of the spectrograph is demonstrated in Fig. 1.5.

The IFS features two spatial and four spectral modes. The fine spatial mode provides 25 mas spaxels and 3.6"x2.5" FoV, while the coarse mode provides 50 mas spaxels and 7.2"x5.0" FoV. The spectral modes include:

- Low Resolution - Blue (LR-Blue): Covering 370–695 nm, with a median resolving power of 5900.
- Low Resolution - Red (LR-Red): Covering 490–935 nm, with a median resolving power of 5900.
- High Resolution - Blue (HR-Blue): Covering 425–550 nm, with a median resolving power of 14,700.
- High Resolution - Red (HR-Red): Covering 630–880 nm, with a median resolving power of 11,500.

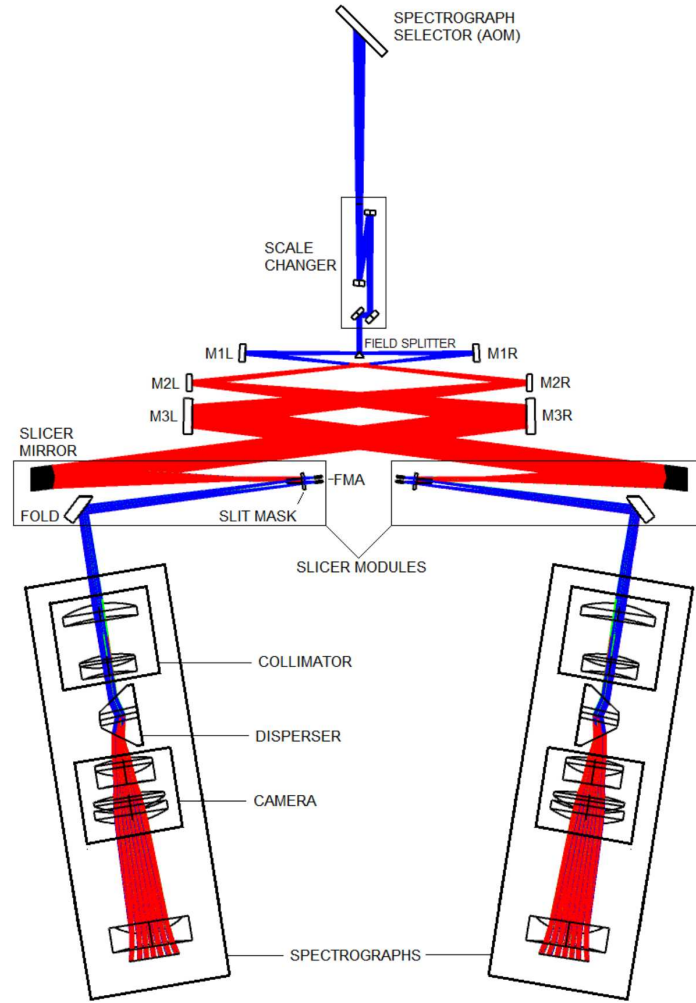


Figure 1.5: Optical design layout of the spectrograph.

Calibration unit

The light from the calibration unit (CU) can be injected into MAVIS through an insertable flat mirror positioned immediately after the field lens. The CU is composed of five modules: the Main Calibration Module (MCM), the Light Source Module (LSM), the Astrometric Calibration Module (ACM), the Calibration Control Module (CCM) and the Calibration Unit Instrument Control System Software (CU ICSS). The MCM, whose optical design layout is depicted in Fig. 1.6, provides calibration means for flat fields, NGS, LGS and Non-Common Path Aberration (NCPA), slicer alignment, PSF characterisation etc. The LSM, located outside of the thermal enclosure, supplies continuum light sources, the LGS light source and absolute spectral calibration sources. The ACM is a self-contained module that contains the astrometric calibration mask and a dedicated light source for back-illumination^[54]. Differently from the rest of the CU, the ACM is positioned at the entrance Nasmyth focal plane to avoid differential distortions arising from the CU optical elements.

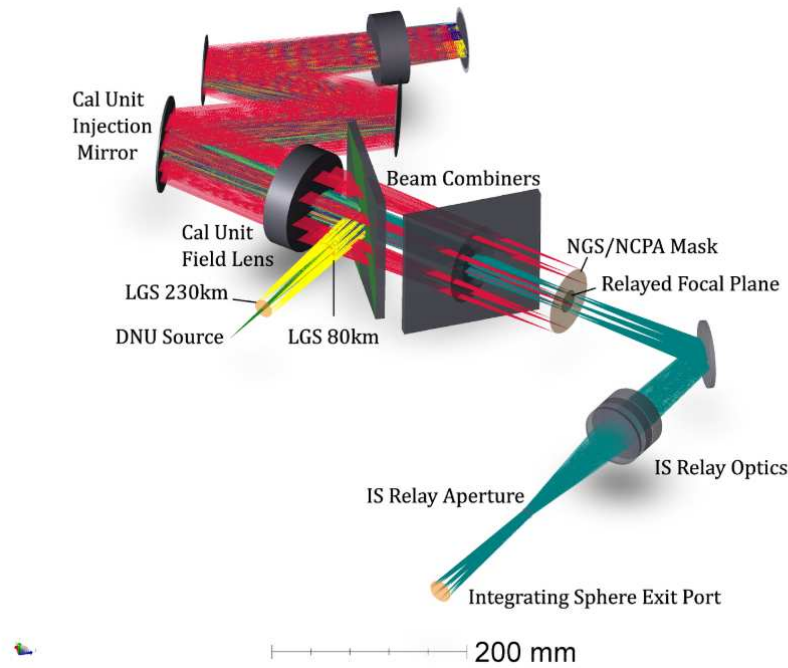


Figure 1.6: Optical design layout of the Main Calibration Module (MCM).

1.3.2 Science with MAVIS

MAVIS will enable in-depth studies of a wide range of astronomical topics by providing high angular resolution and high sensitivity across a relatively large area of the observable sky. Its imaging sensitivity on point sources exceeds that of the Hubble Space Telescope (HST)^[55] by close to one magnitude. Moreover, given the wavelength range in which MAVIS will operate, it is expected to become a significant complement to the infrared instrumentation of the ELT. In particular, this capability will facilitate deeper investigations of the low-redshift Universe at $z < 0.5$.

The science cases for MAVIS span from Solar System studies, including planets and small bodies, to galactic and extragalactic objects. One of its key scientific goals is the search for intermediate-mass black holes (IMBHs), which are believed to be located in the centres of globular clusters (GCs)^[56]. One possible formation mechanism for these black holes is stellar mergers within the dense cores of GCs^[57]. The direct detection of black holes, including IMBHs, remains exceptionally challenging. However, their presence can be inferred by analysing spatial and kinematical signatures in the distribution of stars. While such signatures may also be explained by other factors, differences in central dynamics can help distinguish the presence of an IMBH from alternative scenarios.

The IMBH search in GCs sets very demanding requirements on the astrometric performance of MAVIS. The relative astrometric error should be less than $150\mu\text{as}$. Using simulation tools developed for MAVIS, the feasibility of detecting IMBHs through velocity dispersion profiles has been demonstrated by the astrometric group of MAVIS (see Fig. 1.7)^{[16],[17]}. The IMBH of a mass of $1500M_{\odot}$ was planted in the

centre of GC NGC 3201. By simulating observations with MAVIS, it was possible to recover kinematics of the cluster and calculate its velocity dispersion profile. A clear difference can be observed in the inner ≈ 7 arcsec region, where the velocity dispersion in case of the presence of the IMBH increases with respect to the case without it.

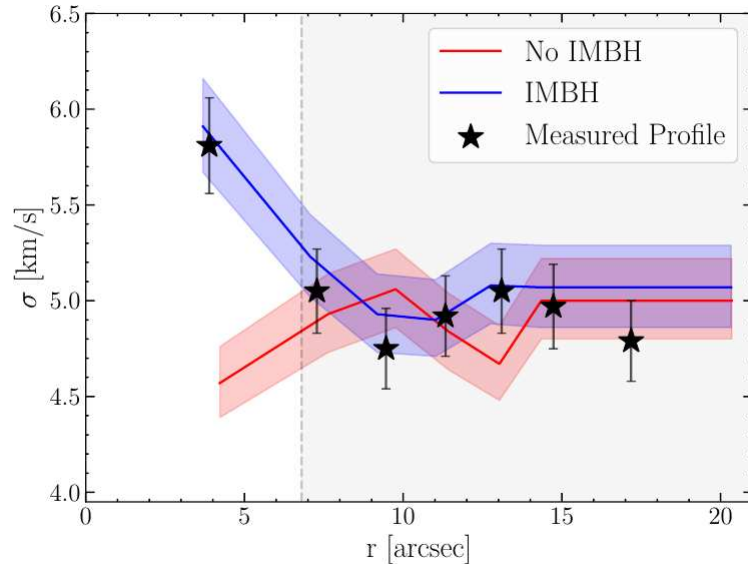


Figure 1.7: Velocity dispersion profile of the GC recovered from simulated images over a ten year epoch. Credit: S. Monty

Although simulation results are very promising, it is crucial to account for all potential sources that may contribute to the astrometric error to ensure proper calibration of the raw data. Major contributors include optical distortions within the system, TT residual errors, plate scale variations, and PSF field variability. Equally important are detector-related errors, that may introduce photon and read-out noise. The effects of many of these errors, along with their corresponding calibration strategies, are incorporated into the MAVIS Simulation Tool (MAVISIM), available at <https://github.com/smnty93/MAVISIM>. The calibration of optical distortions using this module is detailed in the following section.

Another key science case for MAVIS is the study of deep fields, which will provide insights into the morphological structure of the first galaxies at redshifts $z > 3$. The study of high-redshift galaxies has seen significant progress through observational programs with HST and JWST, which have provided unprecedented views of the early universe^[58]. However, the high spatial resolution and sensitivity of MAVIS make it the most powerful optical instrument for studying UV galaxy morphology, surpassing existing ground-based optical facilities in this regard. While the detection of high-redshift galaxies will primarily rely on the red end of MAVIS' wavelength range, the full spectral coverage will be essential for detailed morphological mapping. A detailed discussion of the galaxy science cases enabled by MAVIS can be found

in the MAVIS White book or in featured papers by F. Mannucci, M. Gullieuszik, P. Rosati and collaborators^[59]. Here, I provide a brief overview of the main aspects relevant to this work.

Since high- z galaxies are typically compact, achieving extremely high spatial resolution is crucial for resolving their internal structures. With the FWHM of up to 30 mas, MAVIS is expected to resolve star-forming clumps within these galaxies, enabling detailed studies of their substructures. Simulations, based on the model of the $z = 5$ "Althæa" galaxy developed by Pallottini et al.^[60], demonstrate exceptional capabilities of MAVIS compared to other instruments, as illustrated in Fig. 1.8. The clumpy regions present in the simulated galaxy model were successfully detected with MAVIS at a signal-to-noise ratio (SNR) of 5, with the faintest regions reaching an AB magnitude of 29. Optical imaging from MAVIS combined with IR imaging from MICADO will provide insights into the phenomena that drive morphological assembly and therefore set constraints on galaxy formation and evolution models.

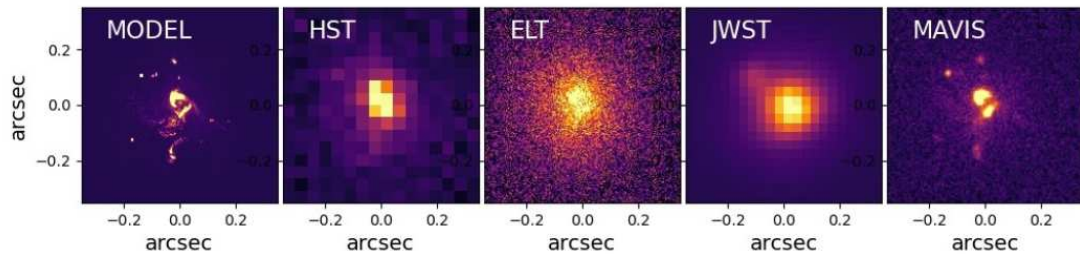


Figure 1.8: Example of the morphological study simulation of the high- z "Althæa" galaxy observed with different instruments in I band.

One of the most important parameters for understanding galaxy formation and evolution is the star formation rate (SFR). In the local universe, SFR can be measured with high spatial resolution, allowing detailed studies of star-forming regions, feedback processes, and the interstellar medium (ISM). Moreover, we can study the impact of the environment on the evolution of galaxies. For instance, in galaxy clusters, star formation is often quenched due to phenomena such as ram-pressure stripping or strangulation. While the nearby Universe is being actively investigated to address these open questions, at high redshifts, limited angular resolution has prevented direct investigations of small star-forming units. The presence of gravitational lensing phenomena significantly enhances the study of high- z galaxies, allowing to resolve structures on scales of a few tens of parsecs^[61].

Recent studies have leveraged gravitational lensing to probe the physical properties of star-forming clumps at redshifts between 2 and 6. For example, a study of 166 star-forming clumps magnified by the galaxy cluster MACS J0416 revealed that these clumps have sizes less than 100 parsecs, stellar masses below $10^7 M_\odot$, and SFRs less than $0.5 M_\odot/\text{year}$. These findings suggest that high-redshift star formation occurs in a more fragmented and hierarchical manner compared to the more massive, kpc-scale clumps observed in the local universe^[62].

MAVIS is poised to further advance our understanding of high-redshift star formation. Its high resolution imaging combined with strong lensing will allow to probe scales of 1-10 pc. Its imaging capabilities can reach spatial scales of a single clump eventually recognised as gravitationally-bound structure. Additionally, wide field of MAVIS will enable detection of "clusters of clusters", providing insights on the formation of such structures in a single shot.

Finally, combining imaging with the AO-assisted low resolution IFU spectroscopy, it will be possible to produce two-dimensional maps of high ionization emission lines of the most magnified gravitationally lensed arcs, pinpointing the location of the most massive and hot stars. These studies will make it possible to calculate star-forming efficiency in the high- z Universe and to better understand the feedback mechanisms and their potential role in cosmic reionisation.

Chapter 2

AOM optical design

At the beginning of this PhD program, MAVIS project was in the ongoing Phase B approaching the Preliminary Design Review (PDR) which happened in 2022. Given that, the optical design of MAVIS was largely completed, with all systems and subsystems in place. However, several modifications and final refinements were still necessary to meet the instrument's stringent requirements. Two such adjustments concerned the objectives in the NGS and LGS WFS channels, were carried out as part of my work and are described in this chapter. Additional changes, which resulted from trade-off studies arising from the analyses of the system, are discussed in the following chapter.

The figure 1.4 reports the optical design layout of MAVIS at the Final Design Review (FDR) stage of the project, incorporating all updates or modifications described here or in the following chapter. As previously mentioned, the instrument is composed of several modules and submodules, each of which can be individually analysed and aligned. One of the key design requirements was modularity, and this principle is clearly reflected in the optical layout of the system.

The AOM is an MCAO system, the main purpose of which is to correct the wavefront coming from a celestial object and deliver a diffraction limited image to the science instruments. Low order wavefront aberrations are sensed with the NGS, while higher order modes are measured with the LGS WFSs.

The optomechanical structure of the AOM can be divided into three main modules: the PFR optics, the NGS and the LGS channels. The RTC interfaces with these modules to process wavefront sensor data and compute the corresponding corrections in real time. Additionally, it also contains the Diagnostics and NCPA Unit (DNU). The DNU will be primarily used during the assembly, integration and testing (AIT) and commissioning phases. It will provide the ability to image the telescope pupil, and to use an on-axis SHWFS for the measurement of residual aberrations.

The common path of the AOM is considered from the field lens up to the NIR/VIS dichroic. Its first optical element is the field lens, which can move in the X and Y directions to compensate for pupil shifts. After passing through the field lens, the light is directed toward two post-focal DMs, conjugated to turbulence

layers at altitudes of 6 km and 13.5 km, respectively. The DM Low has a projected pitch of 25 cm and will have 1727 actuators over the clear aperture. The DM High has a projected pitch of 32 cm and 2109 actuators over the clear aperture. Together with the DSM, they represent the full set of the atmospheric turbulence correctors for MAVIS.

A collimator positioned after the DMs creates a collimated beam, within which several key optical components are located: the LGS dichroic, the ADC, the K-mirror, and the NGS dichroic. The K-mirror functions as a sky de-rotator. The NGS dichroic transmits NIR light (960–1740 nm) to the NGS channel, where a three-lens objective generates an F/20.6 focal plane. The remaining light, spanning 370 to 935 nm, is directed to the science channel. Meanwhile, the LGS dichroic reflects 589 nm light toward the LGS channel.

The LGS channel provides an F/8.89 focal plane to the WFSs, which is maintained by a refocusing objective containing moving elements that adjust the focus to accommodate variations in the sodium layer’s distance, changing because of the telescope elevation and ranging between 80 and 230 km. After passing through the refocusing objective, the light is directed to a focal plane splitting pyramid, which distributes it to eight WFSs, tuned for the sodium wavelength $\lambda \approx 589\text{nm}$.^[63] This channel is responsible for measuring high-order aberrations. The specific wavelength of operation demands a proper coating of the components, especially the dichroic, to avoid leakage to scientific instrumentation and pollution of the LGS WFS channel with other wavelengths. The specification and detailed verification of the coating for the dichroics are described in Section 3.4.

The NGS channel consists of three NGS WFSs and an acquisition camera. In order to maximize the sky coverage, the NGS WFS is designed in a way that each WFS can move over the whole technical FoV = 120° to pick up an NGS suitable for guiding.^[52] The NGS WFSs measure TT and low-order aberrations. The quality and area of correction, to a first approximation, depend on the number and positions of guide stars. The impact of the NGS asterism choice, for instance, on the plate scale variation, is described in Section 3.1.2. The system allows for switching between a 2×2 and a 1×1 lenslet array configuration. The latter mode is optimised for fainter stars but provides only TT measurements.

The light reflected by the NGS dichroic is directed to the SCI channel, composed of a folding mirror and a cemented doublet. It delivers an F/35.0 focal plane for the instruments and the DNU. While light to the imager is straight-through, one requires to insert a fold mirror before the focal plane to send the beam to the spectrograph or the third-port instrument.

The system is not telecentric and has the exit pupil located at a distance of 8065 mm before the focal plane. The diameter of the exit pupil is 230 mm. The exit pupil quality in terms of encircled energy is shown in Fig.2.1. The optical quality was evaluated using the full 21.2 arcsec FoV. 90% of encircled energy is reached

within 0.1% of the pupil diameter.

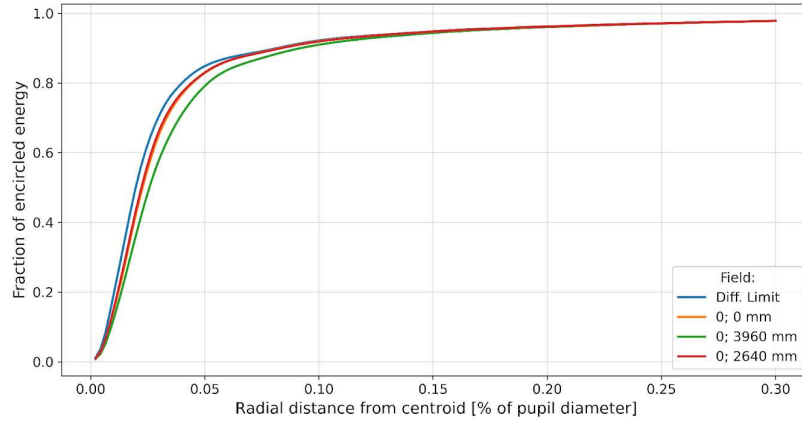


Figure 2.1: Encircled energy as a function of a fraction of the exit pupil diameter.

The image quality in terms of wavefront error (WFE) across the full FoV and the operational wavelength range (370-935 nm) is presented in Fig.2.2. The maximum RMS WFE is 20 nm.

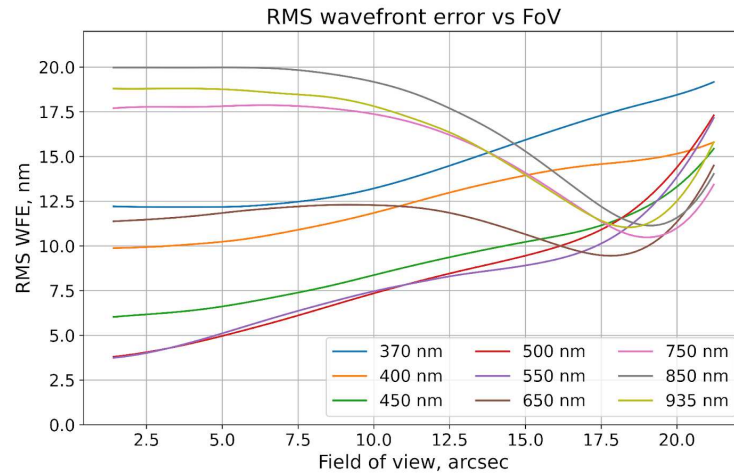


Figure 2.2: SCI channel RMS WFE as a function of field of view for different wavelengths.

2.1 Re-design of the NGS Objective

As stated above, the NGS WFS module is part of the AOM and provides TT estimation and low-order (focus and astigmatism) aberration measurements for MAVIS. The working waveband for the NGS WFS is from 960 nm to 1740 nm.

After passing through the telescope and the PFR optical elements, the NIR light from the guide stars is received by the NGS Objective, which re-images the full

FoV onto an F/20.6 focal plane. At the PDR stage, the Objective consisted of three lenses made of CaF₂, LLF1, and N-SK2HT glasses, and each with a diameter greater than 100 mm.

CaF₂ has a crystalline structure that presents significant manufacturing challenges for large optics due to its fragility. Therefore, it was decided to replace this glass with a more robust alternative. Thanks to the modularity of MAVIS' design, the re-optimisation of the NGS Objective was significantly simplified and accelerated. The redesign process followed these main steps:

1. Removal of optical elements that do not affect the NGS WFS performance. These included flat optics in the common PFR path:
 - The K-mirror, that provides compensation for the sky rotation for both the SCI and the NGS WFS channels;
 - The ADC which has a self-consistent optical scheme including two counter-rotating prisms;
 - Two deformable mirrors (DM-High and DM-Low) that are conjugated at 13.5 km and 6 km altitude from the VLT entrance pupil, respectively.
 - The LGS and the NGS dichroics.
2. Identification of a suitable replacement for CaF₂ with comparable optical properties, such as refractive index and Abbe number. Since the NGS channel operates in the NIR, refractive indices at NIR wavelengths were prioritised in the selection process. Initially, the goal was to replace only the CaF₂ component.
3. Full re-optimisation of the NGS Objective, including potential substitution of all glasses in the NGS Objective.

The re-design was constrained by several system-level requirements: the effective focal length of 164800 mm and the focal ratio of F/20.6 had to be preserved, and the distances between the collimator and the NGS Fold mirror, as well as between the Fold mirror and the focal plane, were fixed to maintain compatibility with the existing mechanical interfaces of the NGS WFS module. Additionally, the output beam was required to remain telecentric, with low distortion and diffraction limited optical quality.

The final lens configuration includes S-FPL51, S-LAL61, and S-FPL51 for the three elements. The corresponding lens diameters are 188 mm and 133 mm. The prescription data are reported in Table 2.3, and the optical layout of the re-optimised objective is shown in Fig. 2.4. The curvature radius of the focal plane in this design is 410 mm, concave towards the telescope.

The nominal image quality in terms of the RMS WFE is shown in Fig.2.5.

Surf #	Surface type	Comment	RoC [mm]	Thickness (up to the following surface) [mm]	Material	Clear Semi-Diam eter [mm]	Decenter x [mm]/Tangent of x angle (for surface type TILTSURF)/a2 coefficient (for surface type EVENASPH)	Decenter y [mm]/Tangent of y angle (for surface type TILTSURF)/a4 coefficient (for surface type EVENASPH)	Tilt x [deg]/a6 coefficient (for surface type EVENASPH)	Tilt y [deg]	Tilt z [deg]	Order for coordinate breaks
96	COORDBRK		Infinity	0.00E+00		0.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
135	STANDARD	NGS Dichroic S1	Infinity	2.00E+01	INFRASIL_301_302	9.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
136	STANDARD	NGS Dichroic S2	Infinity	0.00E+00		9.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
137	COORDBRK		Infinity	0.00E+00		0.00E+00	-4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
138	COORDBRK		Infinity	0.00E+00		0.00E+00	4.83E+00	0.00E+00	0.00E+00	2.00E+01	0.00E+00	0.00E+00
139	COORDBRK		Infinity	1.32E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
140	STANDARD	NGS Objective L1S1	4.74E+02	3.09E+01	S-FPL51	8.80E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
141	STANDARD	NGS Objective L1S2	-3.23E+02	4.00E+00		8.80E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
142	STANDARD	NGS Objective L2S1	-3.39E+02	3.60E+01	S-LAL61	8.80E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
143	STANDARD	NGS Objective L2S2	-1.61E+03	0.00E+00		8.80E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
144	COORDBRK		Infinity	4.59E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
145	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	4.50E+01	0.00E+00	0.00E+00	0.00E+00
146	STANDARD	NGS Fold Mirr 1	Infinity	0.00E+00	MIRROR	9.30E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
147	COORDBRK		Infinity	-9.50E+01		0.00E+00	0.00E+00	0.00E+00	4.50E+01	0.00E+00	0.00E+00	0.00E+00
148	STANDARD	NGS Objective L3S1	-1.31E+02	-1.67E+01	S-FPL51	6.65E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
149	STANDARD	NGS Objective L3S2	-1.21E+02	0.00E+00		6.35E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
150	COORDBRK		Infinity	-5.18E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
278	STANDARD		4.10E+02	0.00E+00		4.80E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure 2.3: Optical design prescription for the NGS channel.

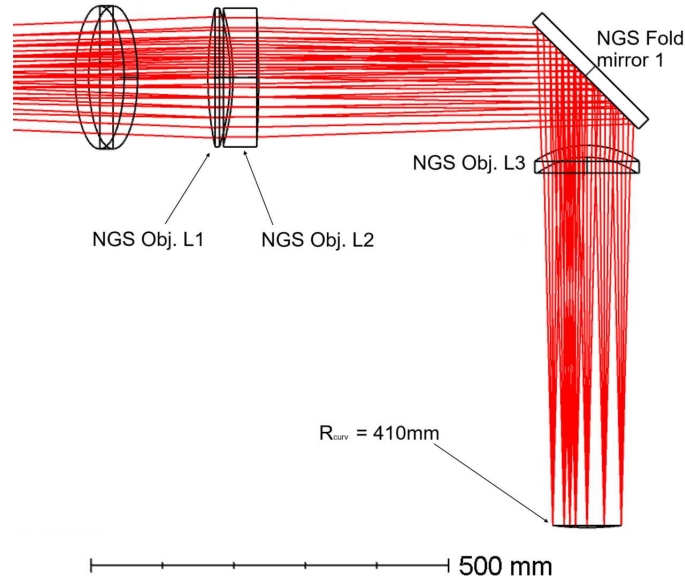


Figure 2.4: Optical layout of the NGS Objective after the glass replacement.

2.2 Re-design of the LGS Objective

The re-design of the LGS WFS Objective was required due to the increase of the FoV where guide stars can be located. The PDR design of the instrument employed eight LGSs fixed at a radius of 17.5 arcsec from the optical axis. However, based on the budget for "LGS jitter compensation", the radial FoV delivered to the LGS-WFS needed to be 25 arcsec. The group of lenses comprising the LGS Objective, that compensates for the focus and provides an F/8.89 flat focal plane to the WFSs, required to be re-optimised to meet the performance requirements for the increased FoV.

The PDR design of the LGS Objective had one of the lenses in a fixed position, while the other two were placed on a linear stage to allow motion along the optical axis to adjust the focus to the correct LGS distance while keeping the output focal plane at a fixed position. The focusing range is 80-230 km, measured from

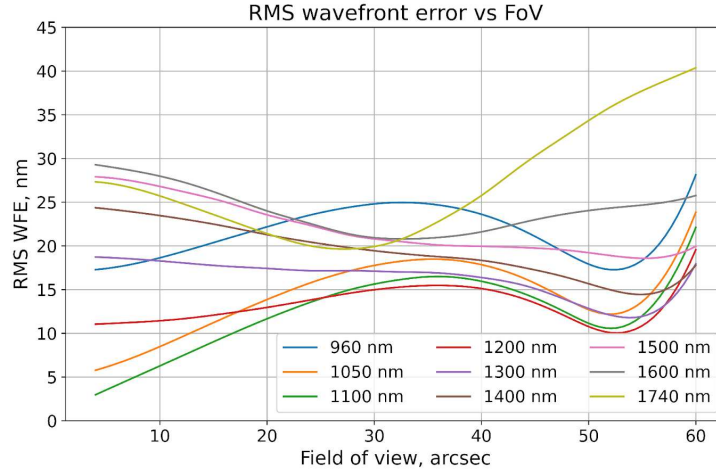


Figure 2.5: NGS channel RMS WFE as a function of field of view for different wavelengths.

the telescope entrance pupil. Across the focusing range, the objective maintains telecentricity of the output beam and a fixed physical size of the asterism. These specifications were required to remain unchanged in the new design. The surface types – such as the even aspheric surface of the first lens of the objective – could be changed, as well as the radii of curvature or glasses.

Two possible solutions were investigated to achieve a FoV of 25 arcsec. The first working solution contains the same three lenses, however with different radii of curvature and a curved focal plane.

Another possible solution involved inserting an additional lens into the fixed part of the objective or inserting an additional aspheric surface. These options allow the focal plane to remain sufficiently flat.

The final design of the LGS Objective employs three lenses made of S-LAH60 glass and a curved focal plane with a radius of curvature equal to 232 mm, concave towards the telescope. The first optical surface of the first lens is an even asphere with a deviation from the best-fitting sphere $< 3\mu\text{m}$ Peak-to-Valley (PtV). The optical design layout for the LGS Objective after the re-optimisation for a 25 arcsec FoV is shown in Fig.2.7. The design prescription data are reported in Table 2.6. Two lenses of the objective have a clear aperture of 84 mm, while the middle one is smaller with a diameter of 78 mm.

The image quality in terms of RMS WFE is shown in Fig.2.8 for the conjugation distances of 80, 155 and 230 km. The maximum WFE in all the cases is less than 50 nm RMS.

Surface #	Surface type	Comment	RoC [mm]	Thickness (up to the following surface) [mm]	Material	Clear Semi-Diameter [mm]	Decenter x [mm]/Tangent of x angle (for surface type TILTSURF)/a2 coefficient (for surface type EVENASPH)	Decenter y [mm]/Tangent of y angle (for surface type TILTSURF)/a4 coefficient (for surface type EVENASPH)	Tilt x [deg]/a6 coefficient (for surface type EVENASPH)	Tilt y [deg]	Tilt z [deg]	Order for coordinate breaks
152	STANDARD	LGS Dichroic S1	Infinity	0.00E+00	MIRROR	4.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
153	COORDBRK		Infinity	0.00E+00		0.00E+00	-2.35E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
154	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50E+01	0.00E+00	0
155	COORDBRK		Infinity	2.00E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
156	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.00E+01	0.00E+00	0
157	STANDARD	LGS Fold Mirr 1	Infinity	0.00E+00	MIRROR	4.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
158	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.00E+01	0.00E+00	0
159	COORDBRK		Infinity	-1.00E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
160	EVENASPH	LGS Objective L1S1	-5.25E+02	-1.00E+01	S-LAH60	4.20E+01	0.00E+00	2.15E-09	8.61E-14	0.00E+00	0.00E+00	0
161	STANDARD	LGS Objective L1S2	9.18E+02	0.00E+00		4.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
162	COORDBRK		Infinity	-8.18E+01		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
163	COORDBRK		Infinity	-8.18E+01		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
164	STANDARD	LGS Objective L2S1	4.06E+02	-1.00E+01	S-LAH60	3.90E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
165	STANDARD	LGS Objective L2S2	-1.13E+03	0.00E+00		3.90E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
166	COORDBRK		Infinity	-8.52E+01		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
167	STANDARD	LGS Objective L3S1	Infinity	-1.00E+01	S-LAH60	4.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
168	STANDARD	LGS Objective L3S2	3.78E+02	0.00E+00		4.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
169	COORDBRK		Infinity	-9.64E+01		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
170	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	-4.50E+01	0.00E+00	0.00E+00	0
171	STANDARD	LGS Fold Mirr 2	Infinity	0.00E+00	MIRROR	4.25E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0
172	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00	-4.50E+01	0.00E+00	0.00E+00	0
173	COORDBRK		Infinity	3.50E+02		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0

Figure 2.6: Optical design prescription for the LGS channel.

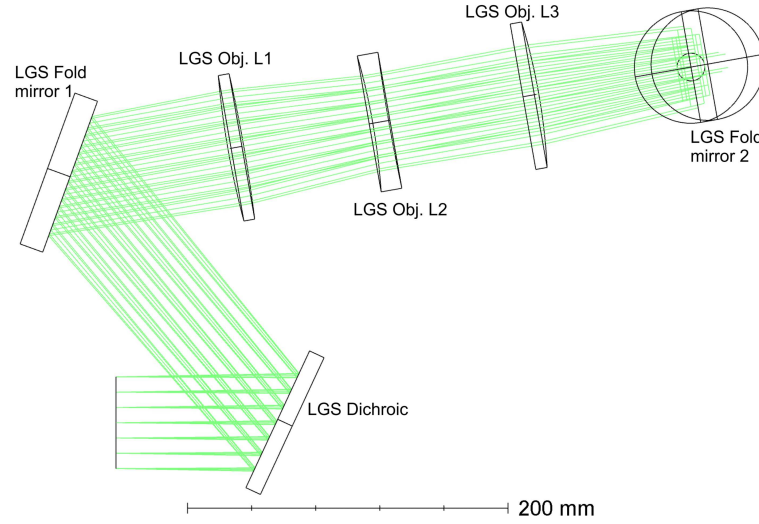


Figure 2.7: Optical design layout of the LGS Objective.

Summary: AOM optical design

The work carried out during my PhD on the AOM design focused on the re-design and modification of the NGS and LGS Objectives. The update of the NGS Objective was driven by the need to replace the crystal-like CaF_2 glass. This substitution was successfully implemented while still meeting requirements for the space and optical performance, maintaining $F\# = 20.6$ and delivering a diffraction-limited image at the focal plane.

In contrast, the re-optimisation of the LGS Objective was motivated by the increase of the full FoV from 17.5 to 25 arcsec. Following a short trade-off study, the final design consisting of three lenses made of S-LAH60 glass was selected. To recover the required nominal image quality, a curved focal plane with a radius of curvature of 232 mm, concave to the telescope, was introduced.

Both updated objectives have been implemented to the final AOM design shown

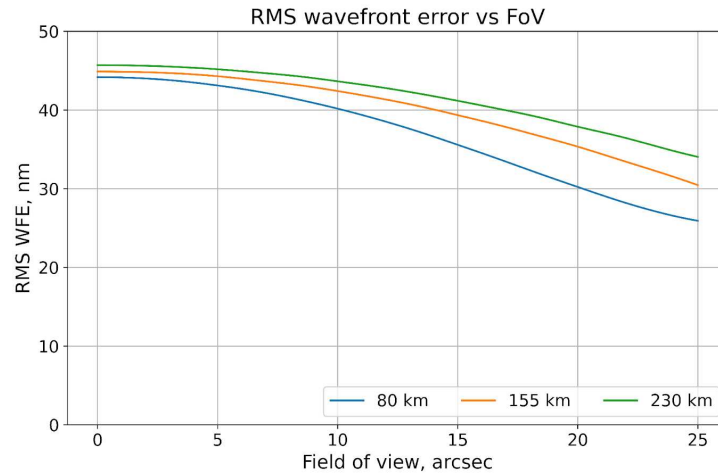


Figure 2.8: NGS channel RMS WFE as a function of field of view for different conjugations.

in Fig.1.4. These updates ensure that both WFS channels meet the optical requirements at FDR level and remain consistent with the modular design of MAVIS, while also keeping the solutions practical for manufacturing and integration.

Chapter 3

AOM optical analyses

Any newly designed system requires a series of analyses and simulations to ensure that its functionality meets the specified requirements. MAVIS, with its primary goal of delivering high-resolution observations in the visible wavelength range, has particularly strict optical performance criteria.

In addition to the wavefront aberrations introduced by the atmospheric turbulence, which are corrected by the AO system, there are other instrument-related parameters that can impact performance. For instance, distortions introduced by optical surfaces positioned along the light path can limit the astrometric precision of the instrument. Their impact and the techniques used to mitigate them are detailed in Section 3.1. Imaging capabilities, especially for faint objects, can also be significantly affected by stray light and optical ghosts. The related analyses are described in Section 3.3.

Other aspects discussed in this chapter are the uniformity of image quality, scattering and dichroic coating analyses.

3.1 Distortion analysis

Among critical parameters impacting the performance of the astronomical instrument are optical distortions, which, along with plate scale variations, can significantly decrease its astrometric capabilities.

Optical distortion is a type of geometric aberration that causes deviations from the ideal rectilinear projection of light rays onto the detector. These distortions affect the relative positions of objects in the image, causing structural deformation that is particularly critical for astrometry and high-precision imaging. The most common types of distortion are barrel and pincushion, both illustrated in Fig. 3.1. The origin of such distortions lies in the propagation of light through both the turbulent atmosphere and the optical elements of the telescope and instrument. Because distortion is fundamentally a geometric effect, it can typically be modelled using a series of polynomials of increasing order^[64]. The modeling and calibration

of optical distortion for MAVIS are described in detail in Sections 3.1.1 and 3.1.3.

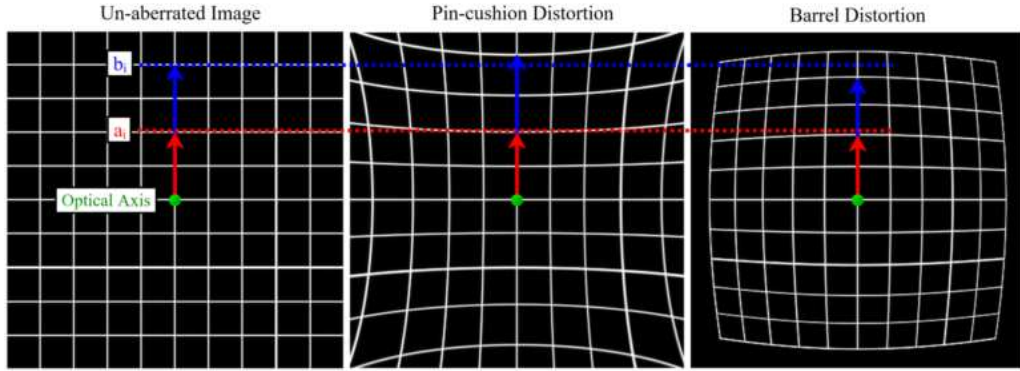


Figure 3.1: Illustration of optical distortion. Credits: Eckhardt optics.

3.1.1 MSFE originated distortions

A pivotal objective for MAVIS, together with other upcoming instruments, is achieving high-precision astrometry. While the launch of the GAIA space telescope has yielded impressive results^[65], astrometric studies still face some limitations. One of these limitations is crowded stellar fields within and beyond our galaxy. However, the promising astrometric precision and the high angular resolution offered by new instrumentation designed for large telescopes hold the potential to overcome this limitation. Consequently, the primary scientific focus of MAVIS is linked to addressing challenges posed by crowded stellar environments, particularly within GCs. More specifically, the main goal is to search for intermediate mass black holes in GC cores as mentioned in section 1.3.2. To achieve this objective, accurate astrometry is required. MAVIS has a relative astrometric requirement of $150 \mu\text{as}$ defined for two isolated point-sources separated by 1 arcsec. This final astrometric error includes contributions from various system-related factors, such as the telescope and NGS probe movements, as well as from the data extraction process^[66]. Among these contributors are distortions caused by mid-spatial frequency figure errors (MSFE) of optical elements^[67].

MSFE are unavoidable artifacts on an optical surface that occur during sub-aperture grinding or polishing stages^[68]. These errors can significantly degrade image quality and introduce distortions that directly impact the precision of astrometric measurements. Consequently, controlling MSFE becomes imperative.

Generally, surface errors introduced by any manufacturing process can be classified into three categories^[69]:

1. low-spatial frequency (traditional figure error);
2. mid-spatial frequency (ripple);

3. high-spatial frequency (microroughness).

Decomposing the surface errors into these three regimes simplifies the analysis of their impact on the overall instrument performance. For instance, low frequency errors can be represented using standard Zernike polynomials, whereas microroughness is evaluated through the application of scattering theory^[70], as presented in the following sections.

Given that MSFE are not comprehensively addressed through low-frequency analysis or scattering studies, bridging the gap between these two regimes involves modelling MSFE as perturbations to the optical surface. These perturbations can be generated by applying the inverse Fourier transform of a 2D Power Spectral Density (PSD) function with random phase^[71]. Typically, the PSD of polished optical surfaces can be well approximated by a power law of the form:

$$PSD \propto \sqrt{\frac{1}{(u^2 + v^2)^\beta}} \quad (3.1)$$

where u and v are the spatial frequencies in the horizontal and vertical directions, and β is the slope coefficient of the PSD. The actual value of the slope generally depends on the manufacturing process. However, typical values for precision polished optics are in the range $1.5 \leq \beta \leq 2.5$ ^[72]. In the case of our simulation the β value was set to 2.4.

Based on this approach, we generate figure error maps for the optical elements in the AOM of MAVIS, which we subsequently insert into the optical model to calculate the distortion via ray-tracing simulations^[73]. To model the figure error of each optical surface, we combine a low-spatial frequency map generated as a random combination of Zernike polynomials and a medium-frequency map generated using the PSD method. Examples of such maps are presented in Fig. 3.2. Optical components, for which the maps are shown, are part of the common path of the AOM and are located as depicted in the layout in Fig. 1.4^[51]. The figure also displays some components of the NGS and LGS channels, along with the Calibration Unit. Nevertheless, these elements are not considered in the present study.

The sizes of the optical elements and the corresponding footprints are shown in Table 3.1.

There are two types of apertures for the AOM optical elements, and they are treated slightly differently. We utilise the first 36 Zernike polynomials, as per Noll numbering^[74], for circular apertures, while for elliptical apertures, we apply only 15 polynomials defined by V. N. Mahajan and G. Dai^[75]. In total, there are 3 elements with elliptical apertures in the AOM, collectively forming the K-mirror used for the field de-rotation.

Zernike polynomials for elliptical apertures

Generally speaking, Zernike polynomials, commonly used to describe optical aberrations, are formally defined only for circular apertures. These polynomials are

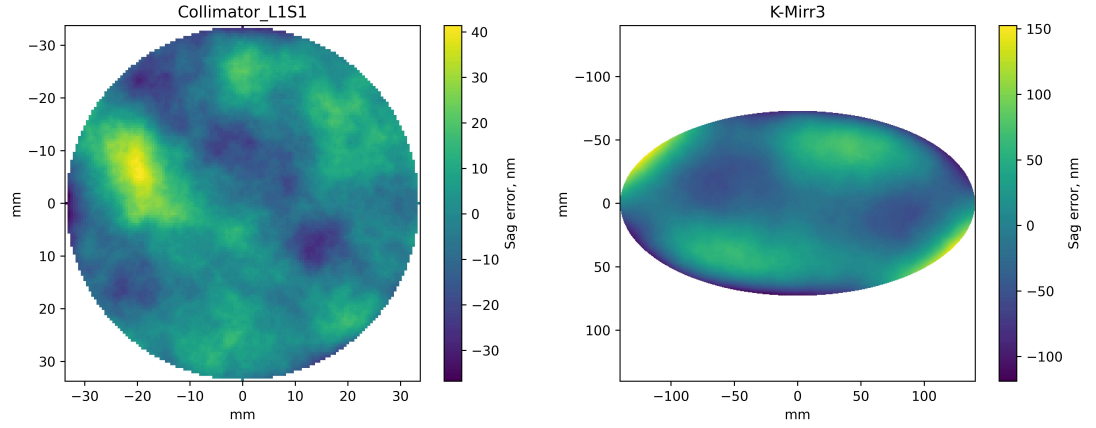


Figure 3.2: Surface figure error maps of the first lens of the collimator (left) and the third K-mirror (right). The amplitude of the MSFE component is equal to 9 nm RMS, while the amplitude of the low-order Zernike component changes for every optical surface and depends on the tolerance allocated for the overall surface figure error.

Optical element	Clear aperture diameter, mm	Footprint size, mm
Field lens 1	98	20
Field lens 2	98	20
Collimator lens 1	68	55
Collimator lens 2	68	56
Collimator lens 3	68	57
LGS dichroic	84	57
ADC prism 1	83	57
ADC prism 2	83	57
K-mirror 1	192x96 (elliptical)	57
K-mirror 2	134x116 (elliptical)	57
K-mirror 3	258x132 (elliptical)	57
NGS dichroic	180	57
SCI objective lens 1	106	57
SCI objective lens 2	106	57
SCI fold mirror	106	52
Imager filter 1	100	5
Imager filter 2	100	4
SCI Cryo window	100	1

Table 3.1: Characteristics of the optical elements used in the simulations. Footprint sizes reported here are maximum diameters of the unprojected on-axis beam.

widely used in wavefront analysis due to their key properties: they are linearly independent and orthonormal over the unit disk. However, in practical optical systems,

apertures are not always perfectly circular. By applying appropriate mathematical transformations, it is possible to extend the basis of the polynomials from circular to elliptical, or other non-circular pupils.

V. N. Mahajan and G. Dai were the first to propose using the recursive Gram-Schmidt orthogonalisation process to generate an orthonormal basis for non-circular apertures from the standard circular Zernike polynomials. According to it, any non-circular polynomial $F_k(x, y)$ can be expressed as a linear combination of the standard Zernike polynomials $Z_i(x, y)$. This relationship can be written in matrix form in the following way:

$$F_k(x, y) = \sum_{i=0}^k M_{ki} Z_i(x, y), \quad (3.2)$$

where M_{ki} is the conversion matrix, which diagonal elements $M_{kk} = \frac{1}{\|G_k\|}$ represent the normalisation constants of the recursively constructed polynomials G defined as:

$$G_1 = Z_1 = 1 \quad (3.3)$$

$$G_{j+1} = \sum_{k=1}^j F_k + Z_{j+1} \quad (3.4)$$

The general expression for computing the conversion matrix is:

$$M = (Q^T)^{-1}, \quad \text{where} \quad Q^T Q = C \quad (3.5)$$

C is the symmetric matrix of inner products of Zernike polynomials, given by:

$$C_{ij} = \int_{pupil} Z_i Z_j dx dy. \quad (3.6)$$

I implemented this analytical method in Python to numerically generate orthonormal elliptical Zernike polynomials. The implementation allows for the construction of wavefront maps with arbitrary combinations of aberrations over non-circular pupils. For more details on the theoretical background, one can refer to the aforementioned paper. The numerical implementation is available at <https://github.com/A0tools/aotools/main/aotools/functions>.

The amplitude of the MSFE in the analysis equals 9 nm RMS for both types of apertures. This amplitude is in good agreement with the high-end finishing specifications provided by manufacturers^[76]. It is important to mention that, in the process of maps generation, we intentionally omit the first four Zernike terms, which represent piston, tip, tilt, and defocus. Piston, tip, and tilt are excluded as they are not part of the surface figure error specifications, while defocus is omitted because it primarily affects the average instrument plate scale without introducing higher-order spatial distortions.

After successfully generating the figure error maps, we integrate them into the optical model of the instrument using the software Ansys Zemax OpticStudio^[77].

This software is employed to perform ray tracing throughout the entire system to calculate the distortion maps. We run the ray tracing over the entire AO corrected scientific FoV which has a radius of 15 arcsec, utilising a pupil sampling of 150x150 rays and using 40x40 field points to accurately capture the mid-spatial frequency perturbations. The distortion generated by MSF figure errors depends on wavelength and field rotation. The wavelength dependence arises from the presence of refractive components. On the other hand, the dependence on field rotation is linked to sky rotation in an alt-azimuth mounted telescope. This rotation causes the beam footprint on all optical elements upstream of the de-rotator to rotate with the parallactic angle, thereby illuminating different portions of the optical surfaces. These effects need to be properly calibrated as soon as the variation of the distortion map induced by them exceeds the tolerances. To simulate this aspect, in our analysis we account for the field rotation, considering the range of angles from 0 to 30 degrees, and we account for chromaticity by producing distortion maps covering the full wavelength range from 370 to 1000 nm.

As the last step, we use the obtained distortion maps as input for MAVISIM, available at <https://github.com/smonty93/MAVISIM>^[16]. MAVISIM is the image simulation tool for MAVIS and it allows to simulate the distortion calibration procedure necessary for our analysis. This procedure is based on a differential method aimed at mitigating the impact of manufacturing errors on the distortion retrieval^[54]. In the real calibration case, we will have the ACM placed in front of the Field lens, coincident with the input Nasmyth focal plane. The ACM contains a pinhole mask with 1607 sources that can be shifted in x and y. The schematic representation of the astrometric mask is shown in Fig. 3.3. The offsets in x and y allow us to obtain the Jacobian of the distortion field, which is then fitted using bivariate polynomials as a set of basis functions^[78]. Despite being quite beneficial, this calibration method has a drawback. Since it is based on first derivatives, it introduces internal errors due to linearization, along with other potential error sources, resulting in a noise floor in all the distortion maps obtained.

The calibration for all our distortion maps is performed in the End-to-End mode using the distortion map at a field rotation angle of $\alpha_{rot} = 0$ deg and $\lambda = 550$ nm as the calibration reference. The residuals of the calibration procedure as a function of the order of the fitting polynomials is shown in Fig. 3.4. As it can be seen from the figure, the use of polynomial orders greater than 9 does not bring in much of an improvement and the residuals are dominated by other noise sources such as the centroiding noise on the image of the pinhole mask. Despite this, we accepted the 11th order polynomial fit in the subsequent simulations. Using higher-order polynomials is not advisable, as they may amplify noise in the calibration procedure. The residuals after the calibration for the considered cases are presented in the following subsections.

To achieve the stated aim of this work – the evaluation of the relative astrometric

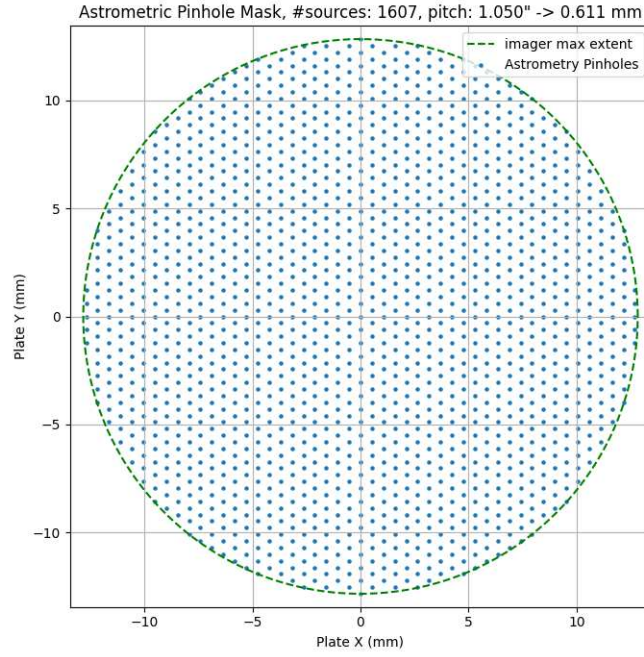


Figure 3.3: 2D scheme of the astrometric mask design, illustrating the spatial configuration of pinholes.

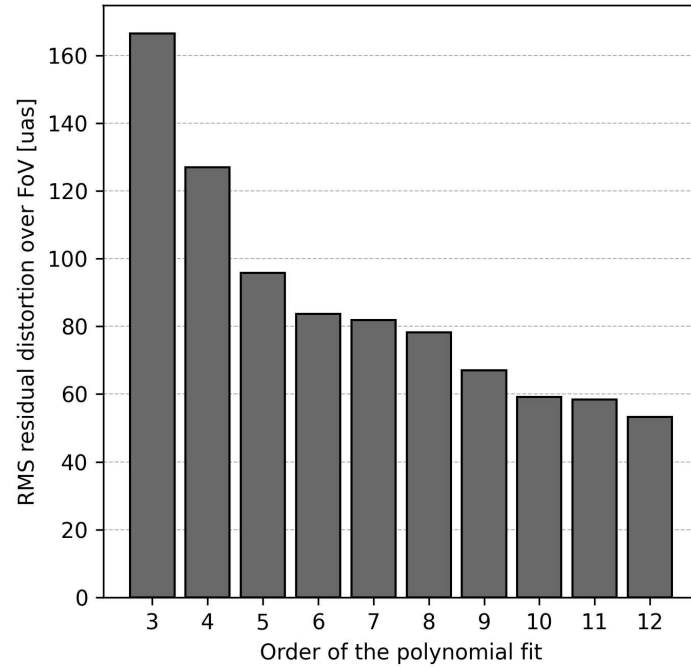


Figure 3.4: The RMS residual distortion after calibration for the reference case: 0 deg field rotation at $\lambda = 550nm$.

error, – we randomly generated 400 point sources over the full FoV. The astrometric error is then calculated as a function of the distance between sources, comparing their true separation values with the ones reconstructed after the calibration procedure.

3.1.1.1 Post-focal relay optics

The first part of the analysis considers all the optics in the PFR of MAVIS. Namely, surface figure error maps were added to the following elements: field lens, collimator, LGS dichroic, ADC, K-mirror, NGS dichroic, science objective and science fold mirror (see Fig. 1.4). Following the procedure described above, we extracted the residual distortion after the calibration. An example of the obtained residual distortions for the static scenario is presented in Fig. 3.5a. The values of the RMS residuals in this case are slightly higher than $50 \mu\text{as}$.

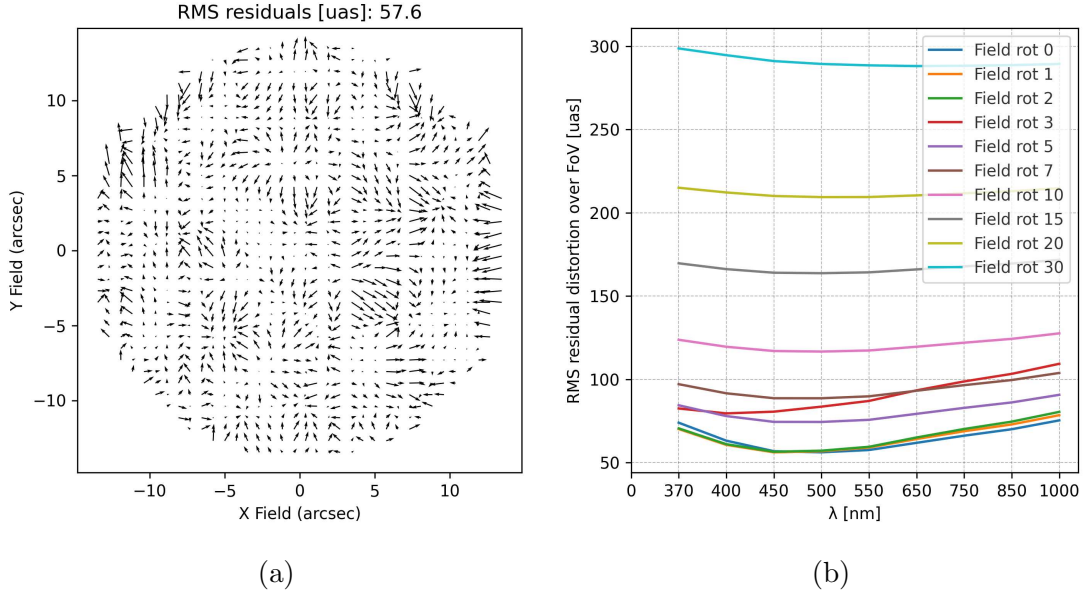


Figure 3.5: (a) Residual distortion maps after calibration with 11th order polynomial. Here: the field rotation angle α_{rot} is 0 deg, $\lambda = 550 \text{ nm}$. (b) RMS residual distortion over the full scientific FoV after calibration with 11th order polynomial.

The RMS residual distortion over the full scientific FoV is presented in Fig. 3.5b. Although no significant wavelength dependence is observed, the distortions appear to be more sensitive to it at smaller field rotation angles. Taking into account the fact that we carry out the calibration at $\lambda = 550 \text{ nm}$, it is expected to get the lowest RMS residual at that wavelength. Despite some variations in values, the lowest residuals are indeed found around the calibration wavelength. Therefore, the expected residual distortion due to figure errors of the optical elements of the AOM common path is in the range of 50 to $300 \mu\text{as}$ RMS depending on field rotation angle and wavelength. As mentioned above, the astrometric budget includes contributions from various parameters, with PSF variability and tip-tilt residuals being among the most significant sources of error^[79]. Therefore, the obtained results highlight the necessity of frequent calibrations to minimize the contribution of MSF distortions. Recalibrating distortions every 7-10 degrees should help keep the relative astrometric error within the required limit.

The main aim of this study is to estimate the relative astrometric error due to distortions induced by optics. Figure 3.6 shows the foreseen astrometric error as a function of the separation between pairs of stars. We considered a range of the stars' separations to examine the behaviour of the final astrometric error after the calibration. It is clearly seen from the plots that larger rotation angles lead to greater astrometric error. Moreover, there is a trend in all of the cases, showing bigger uncertainties in the astrometric measurements for larger separation between sources. Such behaviour is due to the fact that, for larger separations, the points are likely farther from the center, leading to greater relative displacements caused by field rotation. Additionally, the decrease in values after a certain separation is due to the smaller number of points at the largest distances.

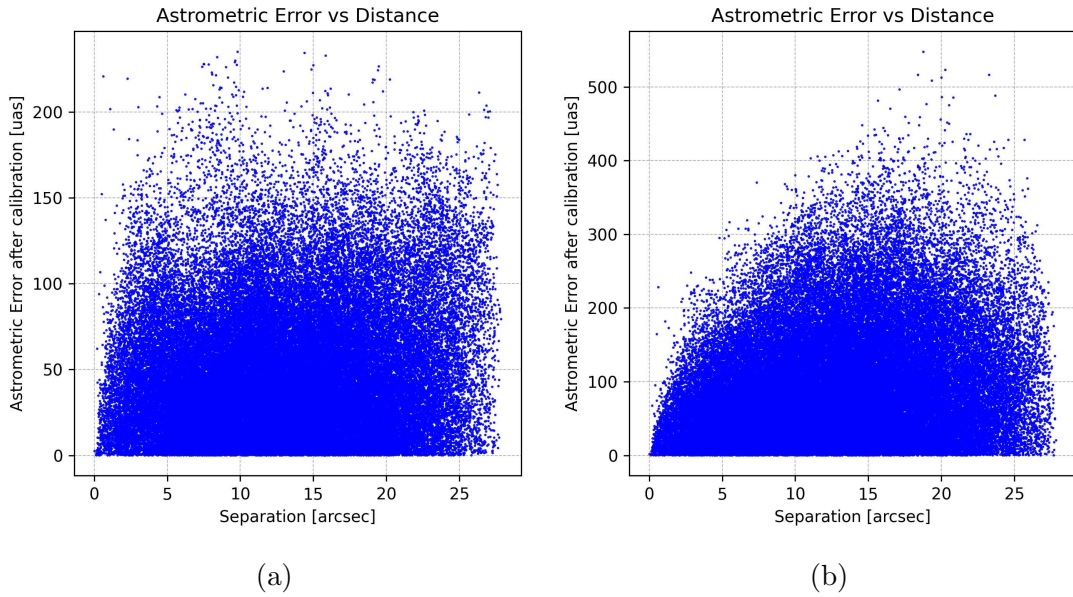


Figure 3.6: The astrometric error as a function of star separation after calibration with the 11th order polynomial fit to the static distortion map at 550 nm. (a) : $\alpha_{rot} = 0$ deg, $\lambda = 550nm$; (b) : $\alpha_{rot} = 10$ deg, $\lambda = 550nm$.

Better understanding of the derived results can be provided by Fig. 3.7 and 3.8 that show the 98th percentile of the astrometric error for different wavelengths and field rotation angles. The calculations are done for all pairs of stars with separations smaller than a certain threshold distance d . Fig. 3.7 demonstrates that the 11th and 12th order polynomial fits yield the best results for the relative astrometric error. However, since we chose to use an 11th order polynomial for our fit, Fig. 3.8 presents the astrometric error for 1 arcsec and 15 arcsec separations between sources demonstrating the dependence of the field rotation angle and the wavelength for these cases. It is explicit that the dependence on the field rotation is stronger, leading to higher astrometric error for bigger angles. However, sources separated by 1 arcsec exhibit fluctuations in values due to the lower sensitivity of the distortion to the field rotation angles at such small distances. Regarding wavelength dependence,

it is almost untraceable with an exception for the blue end of the wavelength range. The errors in the UB bands are larger compared with other wavelengths for the same field rotation angle. Nevertheless, looking at the results, we see that the astrometric error is in the range $65\text{--}105\ \mu\text{as}$ for 1 arcsec separation and $80\text{--}720\ \mu\text{as}$ for 15 arcsec.

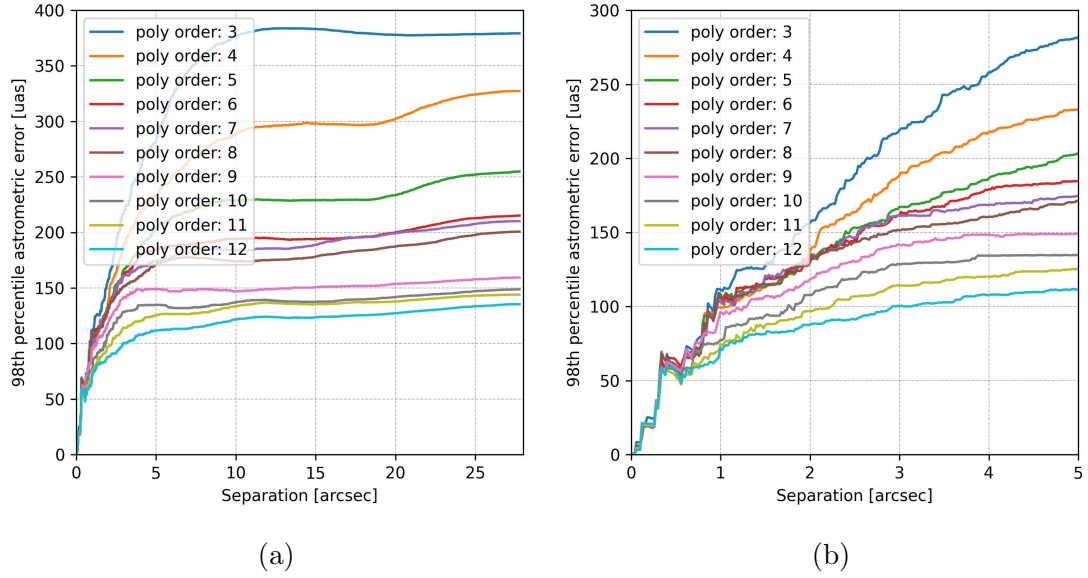


Figure 3.7: (a) 98th percentile astrometric error as a function of separation between sources for $\alpha_{rot} = 0\text{deg}$ and $\lambda = 550\text{nm}$. (b) Zoomed in plot for the separation between 0 and 5 arcsec.

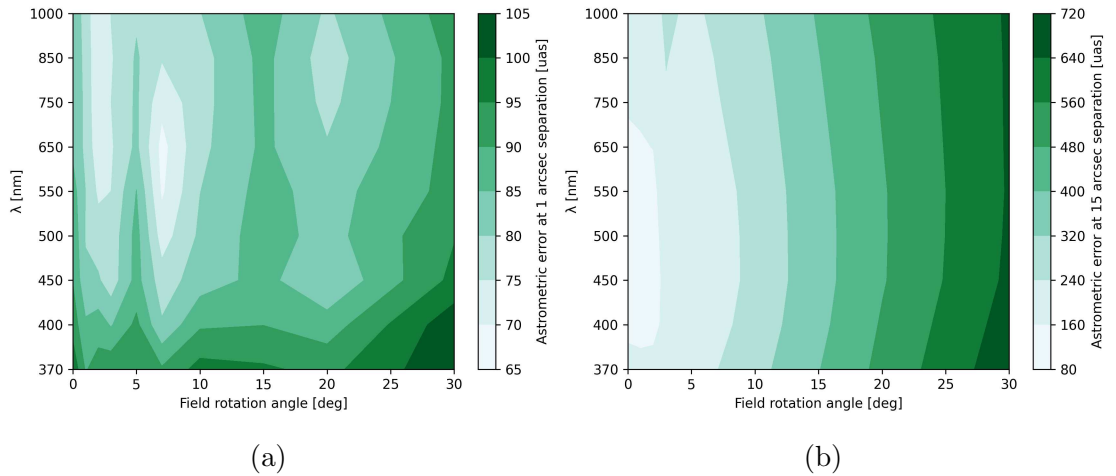


Figure 3.8: 98th percentile relative astrometric error at (a) 1 arcsec and (b) 15 arcsec separation as a function of wavelength and field rotation angle.

3.1.1.2 Atmospheric Dispersion Corrector

Since the refractive index of the atmosphere, n_{atm} , depends on the wavelength, it can lead to significant challenges in achieving precise astrometry. Atmospheric dispersion changes the apparent angular distance between observed sources based on their colour differences. Additionally, it elongates the shape of the PSF along the elevation direction^[80], reducing the Strehl ratio and causing issues in the PSF fitting. To overcome these issues, MAVIS uses an ADC composed by two counter-rotating Amici prisms^[81]. However, the use of the ADC may also impact the astrometric error since, due to the rotation of the prisms, this optical element can introduce varying distortion across the FoV. Therefore, we performed a dedicated analysis using the method described in subsection 3.1.1.

The simulation, based on ray-tracing, accounts for the atmospheric dispersion and its correction by the ADC. We used the Ciddor model for the refractive index of air^[82]. We calculated distortion maps for several zenith distances of observation and wavelengths, considering only monochromatic sources. To only capture the distortion variation produced by the ADC, the field rotation was not considered in this analysis.

Thus, the procedure for the ADC can be summarised as follows:

- Surface figure error perturbations were introduced only to the ADC optical surfaces;
- No field rotation was introduced;
- Calibration was performed at different zenith angles (ZA).

We consider a range of ZA from 0 to 65 degrees covering the full working range of MAVIS. Figure 3.9 and Table 3.2 present the results for the RMS distortion residuals. Calibration was performed for each zenith angle, with a comparison to neighbouring angles. The order of the polynomial used for fitting is the same as that used for the PFR optics.

The obtained results show that, when observing at a specific ZA and calibrating to it, the residual distortion is minimal, approximately 35-36 μas . However, as one deviates from the calibration angle, the expected residuals increase. The distortion residuals are particularly sensitive to small deviations from the calibration angle, especially as the observation approaches the horizon. Therefore, in such cases, the difference between the observation and calibration angles should be significantly smaller than the step size considered in this analysis.

The last part regarding distortion of the ADC is to check if there is some wavelength dependence present. It was evaluated by using 550 nm as the calibration wavelength to be consistent with the rest of the study. The resulting plot for the cases of ZA = 15, 30 and 45 deg calibrated to the zenith angle of 30 deg is shown

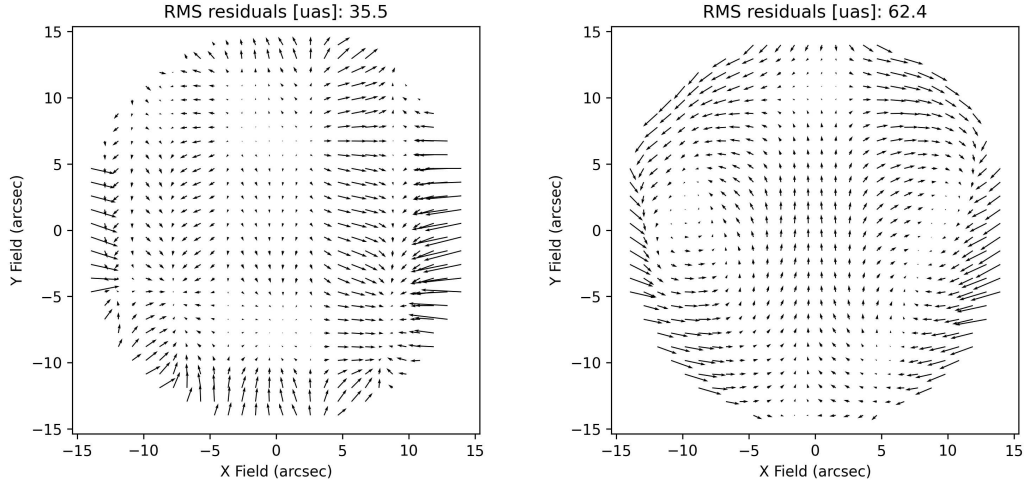


Figure 3.9: Examples of the residual distortion maps at 550 nm for the ZA of 30 deg (left) and 45 deg (right) with the calibration to the distortion map at ZA = 30 deg.

		Zenith angle, deg					
		0	15	30	45	51	65
Calibration ZA, deg	0	35.8	53.5				
	15	60.2	35.2	56.7			
	30		62.9	35.5	62.4		
	45			65.6	35.7	44.5	
	51				44.3	35.6	192.7
	65					183.0	35.8

Table 3.2: RMS residual distortion after calibration for different zenith angles. Units are μas . Diagonal values are the ones calibrated to the proper zenith angle.

in Fig. 3.10. This plot contains the information about both chromatic and achromatic components. The general behaviour is similar to the case of PFR optics (e.g. Fig. 3.8) with the blue end being the most sensitive to calibration, especially when observing far from the zenith. However, the calibration method itself isolates the achromatic component by considering separate distortion maps for each wavelength. Therefore, the residual at 550 nm represents only the achromatic distortion component. Interestingly, the residuals are smaller in the wavelength range from 370 to 430 nm for ZA = 15 deg compared to ZA = 30 deg, which was used for calibration. This is likely due to the chromatic error partially counterbalancing the variation of distortion produced at the different zenith angles.

In this subsection, we presented the impact of the MSFE of the ADC optical surfaces on the astrometric error due to the rotation of the ADC prisms during observations. This rotation introduces variability in the distortion map on the Imager. Additionally, the ADC contributes to image wobble and low-order distortions,

such as anamorphic plate scale variations. In MAVIS, these image motions can be detected by the NGS wavefront sensor and are partially corrected by the AO loop. However, the chromatic dependence of these motions, which is propagated through the DMs by the low-order AO loop, cannot be fully compensated. This limitation may result in small variations in plate scale and pointing on the Imager focal plane. Plate scale variations can be corrected if at least three astrometric reference stars are available in the frame. Nevertheless, variations occurring during the exposure time can lead to PSF smearing, which partially reduces the astrometric accuracy of the instrument. A more detailed investigation of plate scale variations and differential distortions is presented in the subsequent sections.

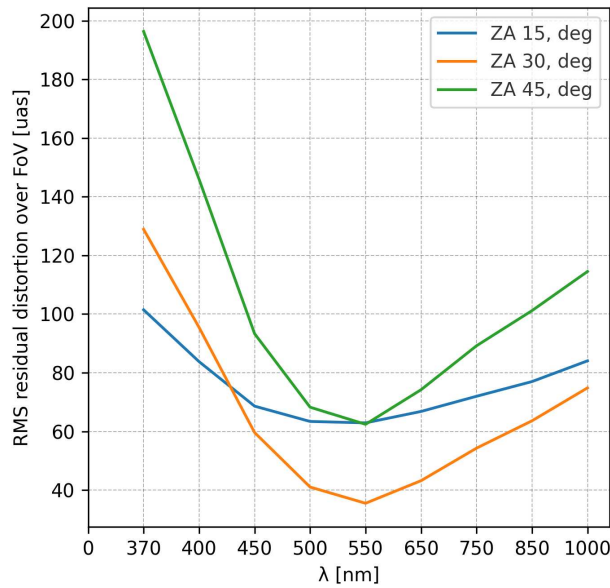


Figure 3.10: RMS residual distortion after calibration for ADC only as a function of wavelength. Data for the cases of 15, 30 and 45 deg ZA calibrated to the ZA = 30 deg and $\lambda = 550nm$.

3.1.1.3 Imager

In the framework of MAVIS, the imager essentially employs a detector at the F/35 image plane provided by the AOM, without the use of re-imaging optics. However, two filters and the cryostat window are planned to be incorporated. Therefore, it is important to assess the impact of distortions arising from the MSFE of their optical surfaces on the overall astrometric error. All elements of the Imager are positioned after the K-Mirror; thus, the field rotation dependence should be minimal or nearly absent. Indeed, the results confirm this expectation.

We conducted the analysis by calibrating the distortion maps to a wavelength of 550 nm, consistent with previous cases. However, due to the Imager elements being

located very close to the focal plane, the relationship between distortion residuals and wavelength becomes more complex. For the same reason, the amplitude of distortions stemming from the MSFE of the filters and the cryostat window is also greater. To address this, we found it beneficial to use a higher-order polynomial for calibration. We opted for a 12th-order polynomial fit, which captures the complex distortions slightly better than the 11th-order fit. The results for the RMS residual distortions are presented in Fig. 3.11, which shows the wavelength dependence. The minimum of the RMS residuals is slightly shifted relative to the calibration wavelength. Although the difference in values is small, this shift could be attributed to numerical uncertainties in the method.

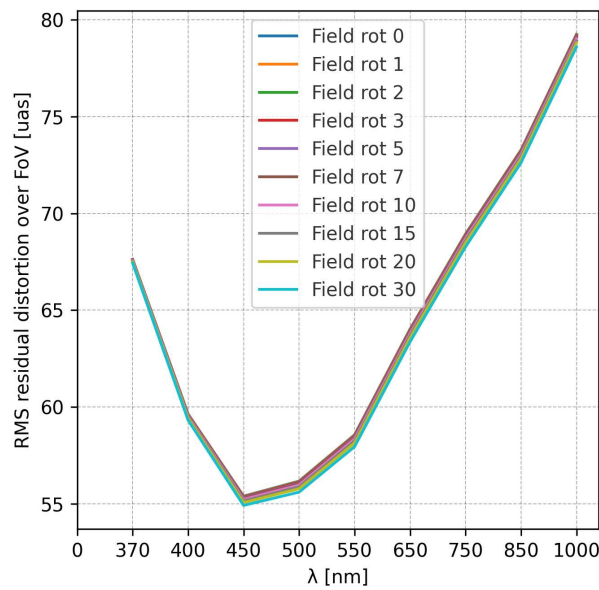


Figure 3.11: RMS distortion residual as a function of wavelength. Calibration was done to the static distortion map at 550nm, using the 12th order polynomial fit.

The results for the relative astrometric error as a function of field rotation and wavelength are presented in Fig. 3.12. It can be observed that the values remain almost constant across all considered rotation angles, thus confirming the stabilisation of the field by the K-Mirror. The range of the expected astrometric error is from 76 to 89 μ as for sources 1 arcsec away from each other and from 120 to 200 μ as for sources separated by 15 arcsec.

3.1.1.4 Application to the NGC 3201 cluster

A practical application of the distortion effects induced by MSFE is presented through a simulation of MAVIS observations of the globular cluster NGC 3201. The aim of this simulation is to assess the expected precision in measuring the kinematic and dynamic properties of the cluster, as well as the accuracy in detecting a

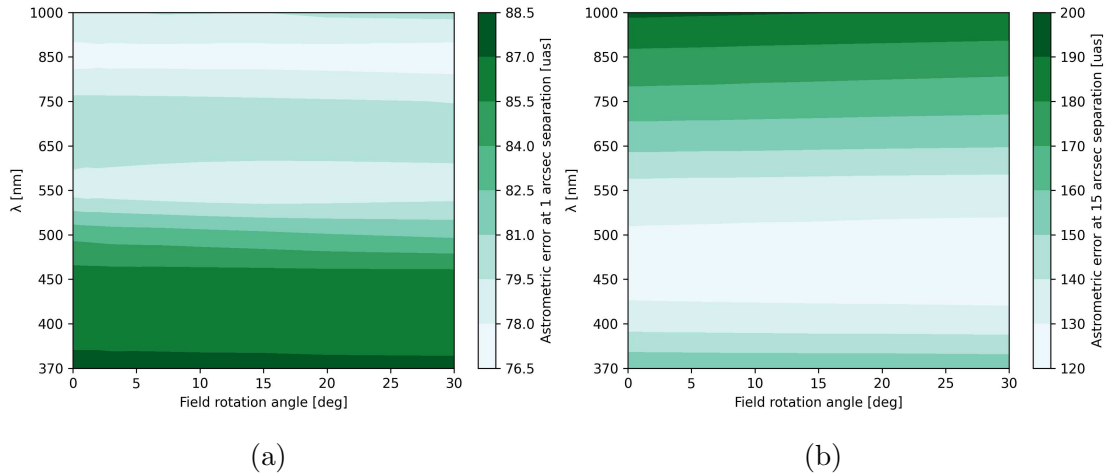


Figure 3.12: 98th percentile astrometric error at 1 arcsec (a) and 15 arcsec (b) separation as a function of wavelength and field rotation. Calibration was done to the static distortion map at 550nm.

numerically ”planted” IMBH. The approach follows the same principles as the main science case described in subsection 1.3.2. However, here we consider the temporal variation of optical distortions during an one-hour observation.

NGC 3201 is a relatively nearby globular cluster, situated approximately 4.55 kpc from Earth in the southern constellation of Vela. It is a metal-poor system with an inhomogeneous stellar population. It has attracted significant attention from astronomers as it is believed to be a harbour of many IMBHs due to its relatively low density and the fact that it is not undergoing core collapse. Interest in this object was further heightened by a study conducted by E. Vitral and collaborators^[83], who reported the discovery of a hundred stellar-mass black holes in the cluster, using combined data from GAIA EDR3 and HST.

The cluster reaches its culmination around March-April. The chosen date for the mock observation is April 6th. The simulated one-hour observation consists of 120 exposures, each lasting 30 seconds. The simulation of optical distortions takes into account their dependence on both the parallactic angle, which affects field rotation, and the elevation of the target. Here, we consider the combined contributions of the AOM and the imager to simulate the total distortion across the system. Distortion maps are produced for every third exposure, as ray-tracing through such a complex instrument model is extremely time-consuming, even though the simulation is limited to monochromatic light at 550 nm. Examples of the resulting distortion maps are shown in Fig 3.13. The input distortion map, which is the direct output of the ray-tracing simulation, represents the optical distortions present in the system, with the dominant component being the plate scale variation. It is referred to as ”input” because it serves as the initial map provided to the calibration pipeline. The corresponding residual distortion map is obtained after applying the calibration method

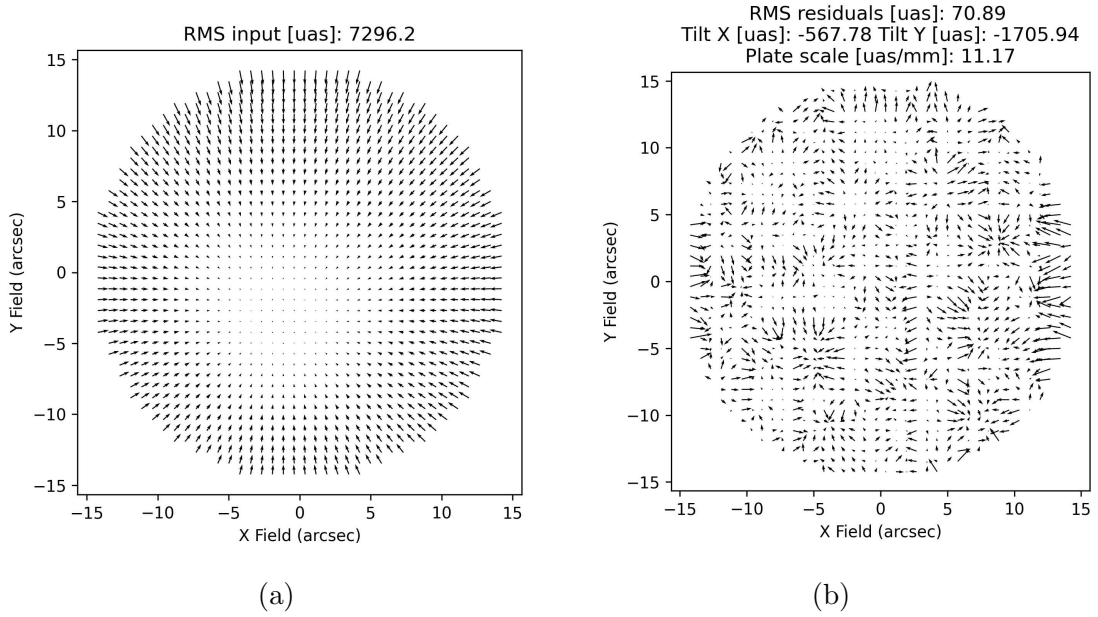


Figure 3.13: (a) Example of the combined distortions of the AOM and the imager for the parallactic angle of 57.95 deg; (b) Residual distortion map after calibration with 11th order polynomial

described above.

A mock image of a simulated 30-second exposure of the NGC 3201 stellar field is shown in Fig. 3.14. The simulation incorporates both system distortions and the PSF model of MAVIS to recreate, as closely as possible, a realistic observation. A set of these modelled exposures has been processed by the MAVIS astrometry team to address the initial scientific questions, and the results are reported in the MAVIS internal report.

3.1.2 Plate scale variations induced by the NGS WFS control loop

In contrast to SCAO, MCAO provides the correction for both global TT errors and plate scale distortions. The latter is generated by the projection of focus and astigmatism in altitude onto the TT in the pupil^[13]. Hence, to ensure optimal instrument stability, it is crucial to analyse how distortions can impact the variation of the plate scale.

In this and subsequent analyses, I focus on the non-common path distortions between NGS WFS and the science path that may have the biggest impact on plate scale variations in the image focal plane. This study provides a comprehensive analysis of the measurements and correction process, facilitating the understanding of plate scale behaviour during tracking operations.

The simulation of the variation of the plate scale is based on the work of Negro that provides equations to retrieve full aperture aberration using multiple sub-

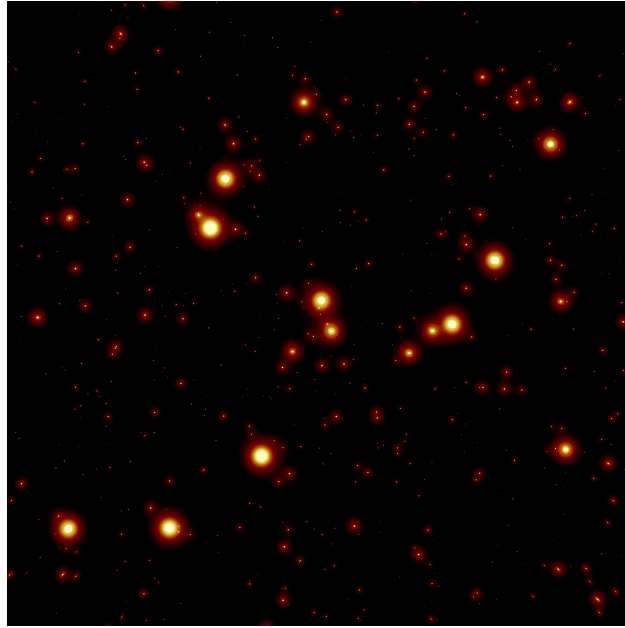


Figure 3.14: Log intensity image of the globular cluster NGC 3201 integrated over 30 s, as it would be observed with MAVIS.

aperture wavefront measurements^[84]. My study primarily focuses on TT measurements, which are typically sensed by the NGS WFS, since laser beacons are not sensitive to this type of aberrations as mentioned above^[85]. Therefore, the starting point of the study is the generation of a set of NGS asterisms. We considered only full asterisms consisting of three stars within the technical field of view of MAVIS, which is 2 arcmin in diameter. This choice was motivated by the fact that plate scale variation cannot be retrieved from fewer than three stars. The minimum possible separation between stars in the asterism was set to 1 arcsec. Figure 3.15a depicts a schematic view of 9 NGS asterisms from the first set, which contains 500 asterisms in total. The positions of NGSs in this set were generated randomly. Although in reality fully one-sided or poorly spread asterisms would be discarded in favour of better ones, provided such options are available, we keep them here for the sake of overall statistics. Figure 3.15b instead displays a set of equilateral asterisms with increasing distance from their barycenter. The minimum radial distance considered in the simulation is 9 arcsec, so that all three stars lie fully within the science FoV. The maximum radius of asterisms is instead 54 arcsec, which is slightly less than the full technical FoV. Both sets are used to evaluate the required correction for the plate scale variations.

The primary objective of this study is to investigate the optical distortions present in the NGS channel of MAVIS and to assess their impact on the image in the science focal plane. We also consider the optical components of the common path of the AOM^[86], which are located upstream of the NGS dichroic, as illustrated in Fig. 3.16. It is essential to properly account for these common-path optics, as the light directed toward both the NGS wavefront sensors and the scientific instruments

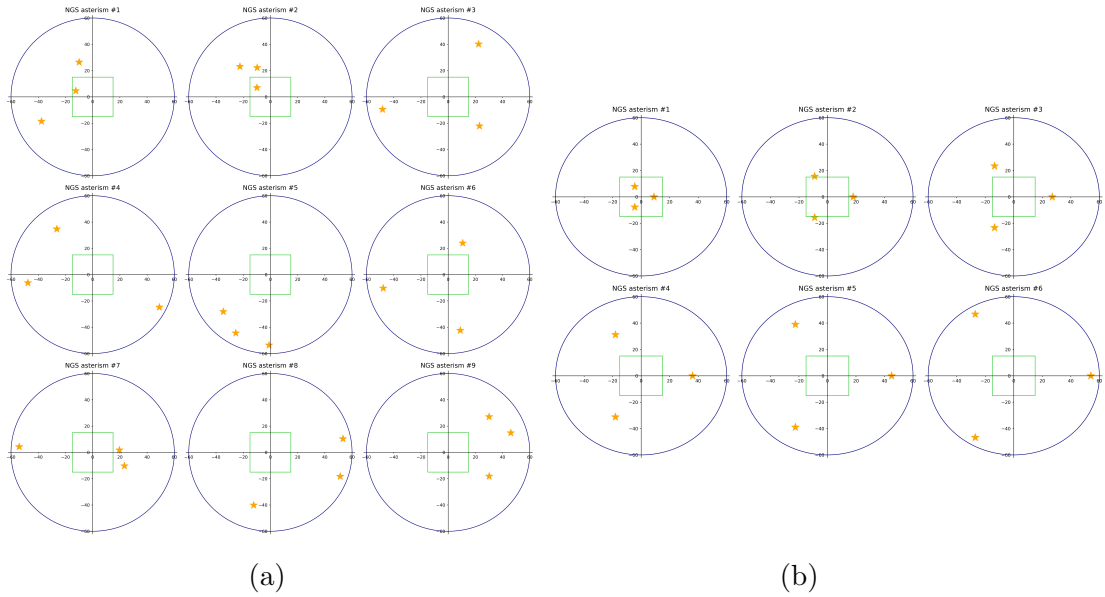


Figure 3.15: Schematic view of the sets of NGS asterisms used in the simulation. Blue circle corresponds to the technical FoV = 60" radial, green square corresponds to the science FoV = 30"x30". (a) Examples of the randomly generated NGS asterisms (500 in total); (b) Radially increasing equilateral NGS asterisms.

passes through the same elements and therefore experiences similar distortions. The NGS dichroic separates the NIR light, 960 - 1740 nm, which is transmitted to the NGS channel, and the visible light reflected towards the science channel. The NGS channel consists of a three-lens objective and a flat folding mirror. Optical imperfections, which in our case include low-frequency and mid-frequency errors, are introduced as perturbations to all optical elements from the field lens to the NGS objective.

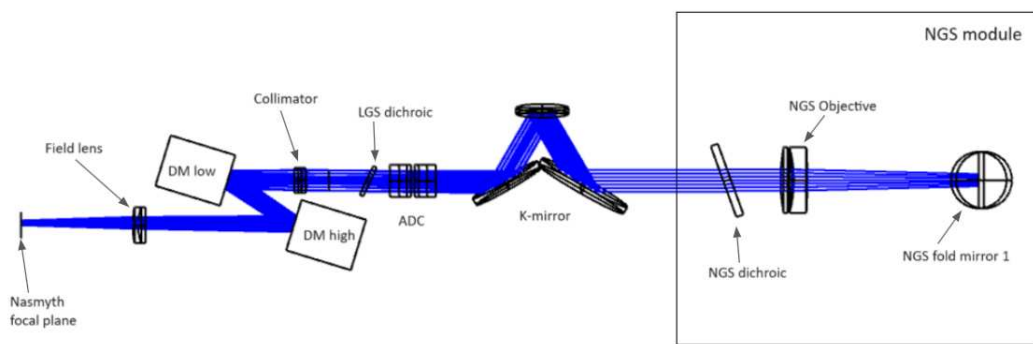


Figure 3.16: Optical design scheme of the NGS channel of MAVIS.

We consider the resulting distortions across a range of field rotation angles, specifically up to 30 degrees. The TT signals, which are measured by the NGS WFS and required for deriving of the DMs commands, were calculated numerically for each simulated scenario. It is worth reminding that in the case of MAVIS, the field

rotation is compensated by the K-mirror. As a result, any differential TT signal, relative to the signal measured at 0 degrees of rotation, arises solely from variable distortions within the optical system. In the simulations, we assume that the K-mirror compensation is ideal, meaning that field rotation is perfectly corrected.

The RMS tip-tilt WFE, in nanometers, associated with a displacement of a reference NGS star of Δx and Δy can be calculated as:

$$c_2 = \frac{D \cdot 10^9}{4} \cdot \arctan\left(\frac{\Delta x}{f}\right) \quad (3.7)$$

$$c_3 = \frac{D \cdot 10^9}{4} \cdot \arctan\left(\frac{\Delta y}{f}\right), \quad (3.8)$$

where $D = 8m$ is the diameter of the VLT entrance pupil and $f = 164800mm$ is the effective focal length at the NGS channel focal plane.

The obtained TT signals are related to the commands that are sent to the DM via the interaction matrix that can be represented analytically in the following way^[84]:

$$\begin{pmatrix} c_{21} \\ c_{31} \\ c_{22} \\ c_{32} \\ c_{23} \\ c_{33} \end{pmatrix} = \begin{pmatrix} \frac{r}{R_G} & 0 & 2\sqrt{3}\frac{h_1}{R_H}\frac{r}{R_H}\cos\alpha_1 & \sqrt{6}\frac{h_1}{R_H}\frac{r}{R_H}\sin\alpha_1 & \sqrt{6}\frac{h_1}{R_H}\frac{r}{R_H}\cos\alpha_1 \\ 0 & \frac{r}{R_G} & 2\sqrt{3}\frac{h_1}{R_H}\frac{r}{R_H}\sin\alpha_1 & \sqrt{6}\frac{h_1}{R_H}\frac{r}{R_H}\cos\alpha_1 & -\sqrt{6}\frac{h_1}{R_H}\frac{r}{R_H}\sin\alpha_1 \\ \frac{r}{R_G} & 0 & 2\sqrt{3}\frac{h_2}{R_H}\frac{r}{R_H}\cos\alpha_2 & \sqrt{6}\frac{h_2}{R_H}\frac{r}{R_H}\sin\alpha_2 & \sqrt{6}\frac{h_2}{R_H}\frac{r}{R_H}\cos\alpha_2 \\ 0 & \frac{r}{R_G} & 2\sqrt{3}\frac{h_2}{R_H}\frac{r}{R_H}\sin\alpha_2 & \sqrt{6}\frac{h_2}{R_H}\frac{r}{R_H}\cos\alpha_2 & -\sqrt{6}\frac{h_2}{R_H}\frac{r}{R_H}\sin\alpha_2 \\ \frac{r}{R_G} & 0 & 2\sqrt{3}\frac{h_3}{R_H}\frac{r}{R_H}\cos\alpha_3 & \sqrt{6}\frac{h_3}{R_H}\frac{r}{R_H}\sin\alpha_3 & \sqrt{6}\frac{h_3}{R_H}\frac{r}{R_H}\cos\alpha_3 \\ 0 & \frac{r}{R_G} & 2\sqrt{3}\frac{h_3}{R_H}\frac{r}{R_H}\sin\alpha_3 & \sqrt{6}\frac{h_3}{R_H}\frac{r}{R_H}\cos\alpha_3 & -\sqrt{6}\frac{h_3}{R_H}\frac{r}{R_H}\sin\alpha_3 \end{pmatrix} \cdot \begin{pmatrix} c'_{2G} \\ c'_{3G} \\ c'_{4H} \\ c'_{5H} \\ c'_{6H} \end{pmatrix} \quad (3.9)$$

Here, R_G and R_H are the radii of the ground DM and the metapupil of the high-altitude DM, respectively; $r = \frac{D}{2}$ is the radius of the entrance pupil; h and α are polar coordinates of the stars on the metapupil. For MAVIS, $R_G = 4$ m and $R_H = 7.95$ m. The geometrical configuration of the DMs' metapupil positions and the star's coordinates is depicted in Fig. 3.17. The polar coordinates of a star are then defined as follows:

$$h = \sqrt{h_x^2 + h_y^2} \quad (3.10)$$

$$\alpha = \arctan\left(\frac{h_y}{h_x}\right), \quad (3.11)$$

where

$$h_x = z \tan \gamma_x \quad (3.12)$$

$$h_y = z \tan \gamma_y \quad (3.13)$$

Here, z is the conjugation altitude of the DMs, and (γ_x, γ_y) are the on-sky coordinates of a source.

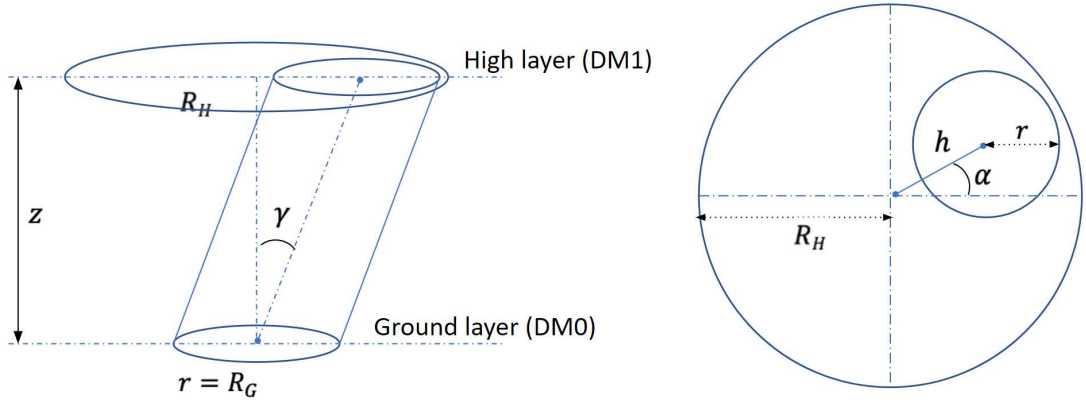


Figure 3.17: Geometrical configuration of the DMs' pupil positions and the coordinates of the NGS star.

By using the relation 3.9 and applying some algebra, we derive the command vector that has components to control TT, defocus, and vertical and oblique astigmatism aberrations. Specifically, the TT correction is intended for the ground DM, whereas defocus and astigmatism corrections are meant for the post-focal DM.

The values of the command vector are then used to estimate the resulting displacement of the stars in the science FoV. To achieve this, we employ the formula 3.9, where now h and α are the polar coordinates of the star we want to observe. These displacements provide us with information on the plate scale correction applied to the observed source:

$$\Delta x = f \tan \left(\frac{4c_2}{D \cdot 10^9} \right) \cdot \text{platescale} \quad (3.14)$$

$$\Delta y = f \tan \left(\frac{4c_3}{D \cdot 10^9} \right) \cdot \text{platescale}, \quad (3.15)$$

where $f = 280000\text{mm}$ is the effective focal length of the science channel; c_2 and c_3 are displacements of the target star, analogous to the TT signals of NGS; D is the entrance pupil diameter. The plate scale, equal to 0.736 arcsec/mm , is used to convert the obtained corrections into arcsec.

The resulting plate scale correction simply represents the shifts applied to the star's coordinates due to the DMs compensating for the average image motion and plate scale variations measured by the NGS WFSs.

All the results presented here consist of two stages. In the first part, we calculated shifts due to plate scale variations for a target star that is 1 mm off-axis on the science focal plane. This was performed across the entire range of field rotation angles and using a set of randomly generated NGS asterisms (see fig. 3.15a). In total, there are 500 such NGS asterisms. The resulting histograms are depicted in Fig. 3.18.

These plots show the shifts in both the x and y directions. In most cases, the shifts are approximately within 1-2 mas, but the scatter increases with the field rotation angle. This information can provide insights into choosing the most suitable

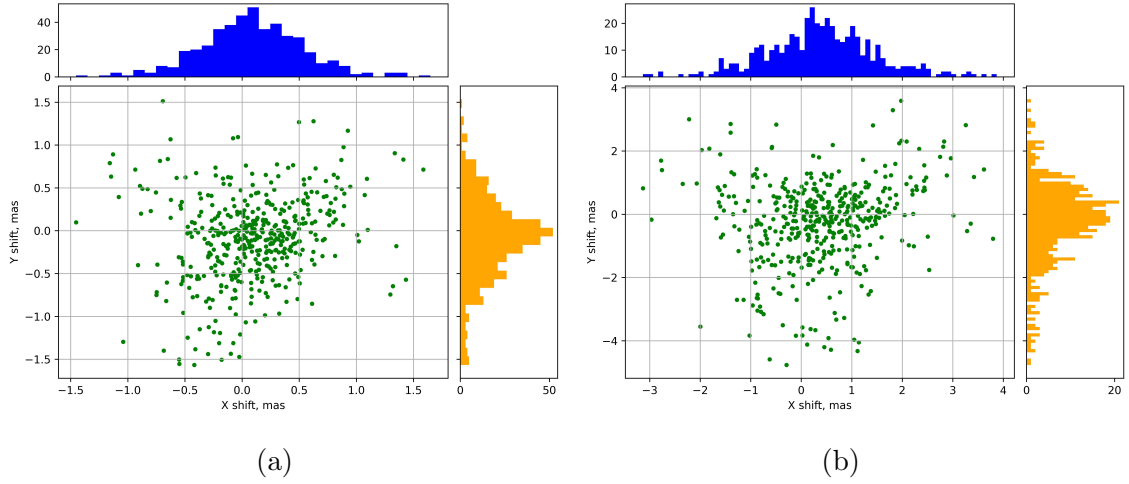


Figure 3.18: Coordinate shifts applied to the coordinates of 1 mm off-axis star due to the correction of plate scale variations. (a) 10 deg and (b) 30 deg of field rotation.

asterisms, particularly when there is an opportunity to obtain a few reference stars in a starry field. In the ideal scenario, these shifts would be minimized. However, it's important to note that here we do not account for differences in the magnitude of NGSs or for variations in the atmospheric condition. The increase of shifts with the field rotation angle is illustrated in figure 3.19 for ten asterisms of the set 3.15a. A more uniform distribution of stars in the technical FoV leads to smaller shifts in the science focal plane.

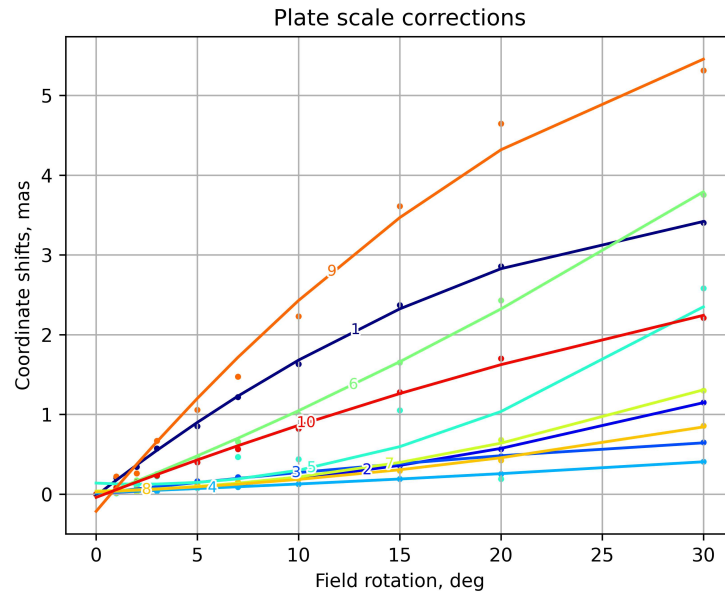


Figure 3.19: Magnitude of the plate scale corrections for the first ten asterisms from the set 3.15a.

However, the target object can be located anywhere within the science FoV.

Therefore, it is important to verify whether a radial dependence exists for the plate scale corrections. This analysis is carried out using a set of equilateral NGS asterisms, whose schematic layout is shown in Fig. 3.15b. We computed the required correction magnitudes for 1000 stars randomly distributed at increasing radial distances across the science FoV (see 3.20). The derived results, averaged over the azimuthal distance, are presented in Fig. 3.21.

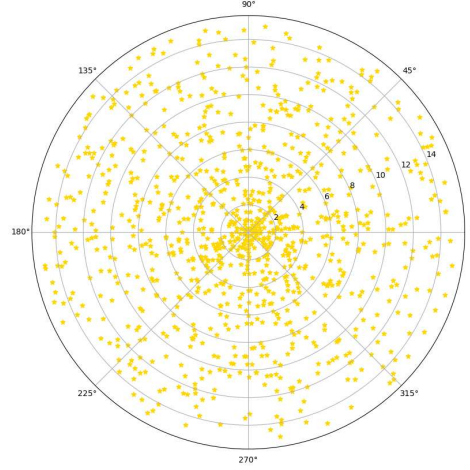


Figure 3.20: 1000 randomly distributed stars in the science FoV.

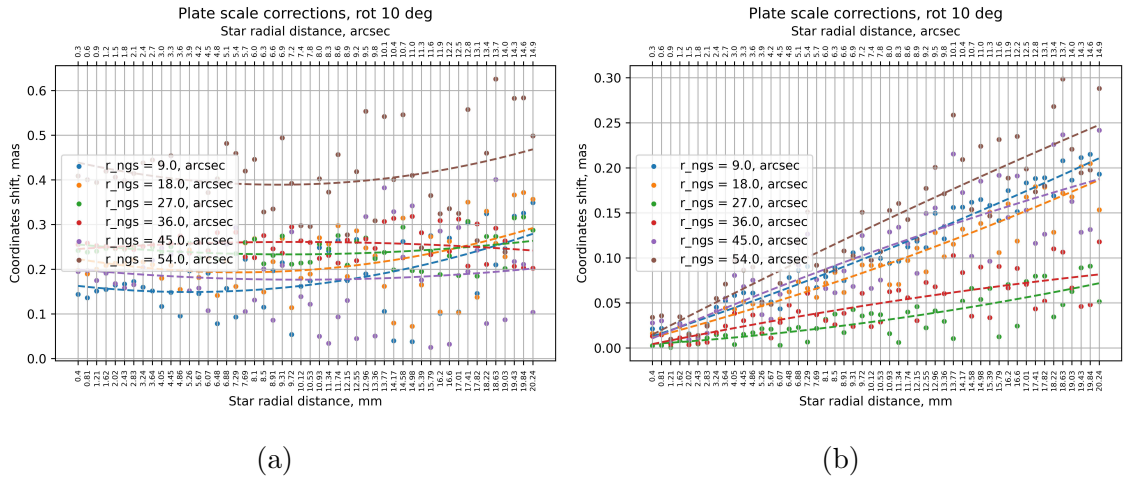


Figure 3.21: Magnitude of the plate scale corrections for 50 stars with increasing radial distance in the science focal plane. Field rotation angle is 10 deg. Right: common tilt is subtracted.

Equilateral NGS asterisms provide a more uniform correction of the TT wavefront errors, resulting in smaller required coordinate shifts compared to scenarios with randomly distributed NGSs within the technical FoV (see Fig. 3.19). The calculated coordinate shifts include a common tilt component affecting all stars equally.

This component is expected, as tip and tilt errors introduce a coherent shift rather than a localized distortion. Once this common tilt is subtracted, the residuals reveal that the best correction — corresponding to smaller plate scale variations — occurs when the NGS asterisms are located slightly outside the science FoV. Furthermore, we observe an increase in the residual coordinate shifts with the radial distance of the stars, indicating a radial dependence of the plate scale variation. However, one should keep in mind that the actual MSF errors of the optics may differ from those used in the simulations, and therefore the optimal asterism radius may vary slightly in practice.

Calculating the shift of several stars in the science FoV allows us to retrieve the average plate scale variation. We used the same 1000 stars in the science FoV and 500 randomly generated asterisms to get a statistical estimate. The plate scale variation is calculated as the magnitude of the required coordinate adjustments divided by the radial distance of the stars from the axis.

$$PS = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{r}, \quad (3.16)$$

where r is the radial distance of a star in mm.

The derived plate scale variations are averaged over the science FoV for each NGS asterism and field rotation angle. The results are depicted in fig. 3.22. Also in the case of plate scale variation, there is an increase in values with increasing field rotation angle. Nevertheless, the 98th percentile of the average plate scale variations remains well within 0.5 mas/mm.

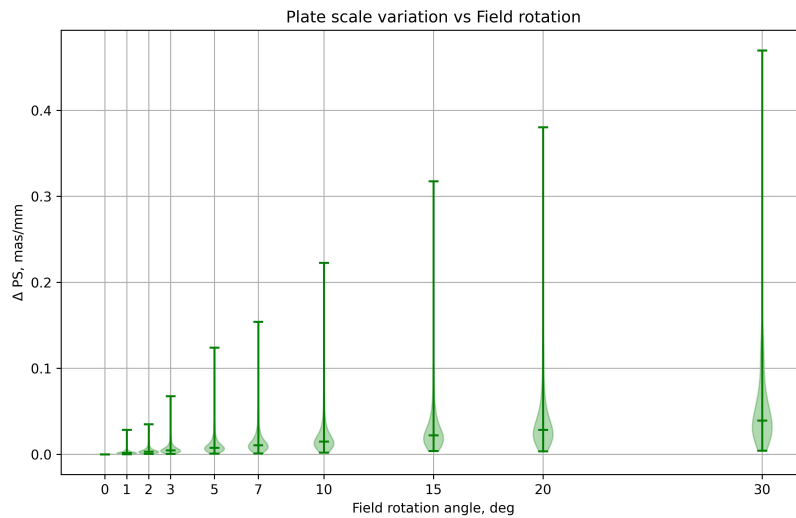


Figure 3.22: 98 percentile of the average plate scale variation over the science FoV for 500 NGS asterisms as a function of field rotation angle. Horizontal bars show the median value of the distribution.

3.1.3 Differential distortions

In the previous subsection, we treated mainly distortions occurring in the NGS channel. However, any variable distortion of the NGS reference sources measured and compensated by the AO control loop, can potentially induce distortions on the science focal plane. Therefore to properly understand the propagation of these distortions, it is important to also account for the optical components located after the NGS dichroic. In the case of MAVIS, those components are a doublet creating the SCI Objective, followed by the SCI Fold mirror and two filters that together with the Cryo Window compose the Imager. The last three are especially crucial for consideration, as also shown in Section 3.1.1, since they are located very close to the focal plane and the beam footprint has a size comparable to the spatial scale of mid-spatial frequency errors.

In a closed-loop AO system, any distortions present in the wavefront sensing channel – such as those in the NGS WFS channel – are compensated by the DM. The main analytical calculations of this process are detailed in Subsection 3.1.2; however, a brief overview is provided here:

1. The NGS WFSs receive light from the guide stars and provide measurements of the TT signals for them.
2. These TT signals serve as inputs for computing the DM commands via the interaction matrix, which is practically obtained numerically for each DM.
3. The computed commands are then sent to the DM to correct the wavefront shape.

While this procedure is conceptually straightforward, the presence of different optical elements along the light paths to the WFSs and to the scientific camera can lead to discrepancies in the resulting images. The primary cause of these differences is differential distortions between the two channels. In the case of MAVIS, the most critical contributors to variable differential distortions are the K-mirror, the ADC, and the Field Lens. Each of these components will be analysed separately in the following subsections^[87].

3.1.3.1 ADC-induced distortion. Linear distortions

The optical design of the ADC of MAVIS is based on two counter-rotating Amici prisms. The glasses composing them are S-FPL55, N-PK51, and PBL1Y.

To properly simulate the differential distortions, we expand the described procedure to account for all optical elements along the light path. We consider only equilateral asterisms like those shown in Fig. 3.15b. After defining the stars' coordinates, we apply rotation to the ADC to compensate for the atmospheric dispersion. The DM commands obtained from the TT measurements are used to drive stars

to their nominal positions on the NGS WFS focal plane. However, since the light passes through different optical elements on the way to the science camera, the final positions of the stars on the science focal plane may differ from the initial ones. We include only the five lowest-order Zernike modes – tip, tilt, defocus, and astigmatism – in the DM correction. Unlike the study on plate scale variations, here we also introduce a control loop for the K-mirror rotation angle. This is fundamental to accurately compensate for the positions of the three NGS star centroids in the presence of variable field distortion.

The distortion maps are derived via ray-tracing of the MAVIS model with the applied DM corrections. The variation of these differential distortions is obtained by subtracting the reference distortion map at a zenith angle of 0 deg from those computed at different zenith angles.

The distortion introduced by the ADC turned out to be significantly high. This might cause issues for the astrometric performance of MAVIS. Therefore several strategies were investigated to minimize these distortions. The distortion shows a pattern that appears, as we move from the zenith, both in the SCI channel and in the NGS channel. It follows the law:

$$\Delta x = y \cos \theta \sin \theta \quad (3.17)$$

$$\Delta y = x \cos \theta \sin \theta, \quad (3.18)$$

where θ is the counter-rotation angle of the ADC prisms.

The maximum distortion is reached when $\theta = 45^\circ$, which corresponds to approximately $ZA = 57^\circ$. The minimum, instead, occurs when two prisms are perfectly counter-rotated, which happens at zenith observations ($\theta = 0^\circ$), or when they are aligned at $ZA = 65^\circ$ ($\theta = 90^\circ$). Distortions scale linearly from the field centre, and therefore they are referred to as "linear distortions"^[88]. An example of the map with the linear distortion pattern is shown in Fig. 3.23. The fastest evolution of the distortions occurs between $ZA = 57^\circ$ and $ZA = 65^\circ$. The maximum value of the "linear" distortion reaches 540 mas at the edge of the technical FoV ($r = 60''$) and for the worst case of $ZA = 57^\circ$.

There are three mitigation techniques to decrease the distortion induced by the ADC.

- The distortion pattern is essentially equivalent to a change in plate scale. As such, it will be sensed by the NGS WFS and will be compensated by adding astigmatism on the high-altitude DM. However, in the worst case conditions, the required amplitude is a significant fraction of the maximum DM stroke and the astigmatism on the DSM may affect other VLT subsystems (e.g. guider/acquisition).
- Limiting the maximum observation time based on the pointing, and reducing the observation time where the ADC rotates very fast. However, this solution

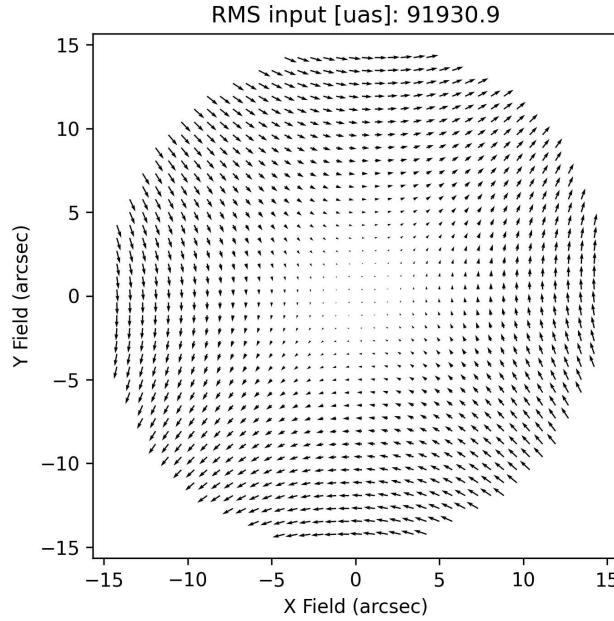


Figure 3.23: Example of the distortion map observed in the SCI FoV at $ZA = 51^\circ$ and $\lambda = 550nm$.

also implies that the plate scale is reset between every single exposure (to limit the astigmatism/plate scale correction applied to the DMs). By necessity, this means a different plate scale for different images, and thus the need to apply an a posteriori correction to stack the images.

- Modifying the ADC optical design.

Compensation with the DMs Considering the distortion pattern (see 3.23) and the results from the subaperture analysis using three NGSs, the dominant term characterizing this pattern, and therefore applied to the DM for compensation, is oblique astigmatism. The compensation is more effective when applied to the DM-High.

Compensation for the worst-case distortions requires the application of:

- $4.3\mu m$ RMS ($21.1\mu m$ PTV) of astigmatism (mirror shape) on the DM-High.
- $1.1\mu m$ RMS ($5.4\mu m$ PTV) of astigmatism (mirror shape) on the DSM. This is required to correct the wavefront of the sources in the science FP, which are impacted by the added astigmatism on the altitude DM. To a first approximation, astigmatism is field-constant and can therefore be corrected by the DSM.

If instead we use the DM-Low, the stroke will reach $5.1\mu m$ RMS of astigmatism (mirror shape). This yields to $2.5\mu m$ RMS on the DSM. The DM-Low is less effective

in correcting the distortion and requires more compensation of the WFE with the DSM.

Other modes applied to the DMs to compensate for variable distortions are tip-tilt on the DSM, and defocus along with both astigmatism terms on one of the post-focal DMs. We study the behaviour of these distortions in two photometric bands: $V = 0.49 - 0.64 \mu m$ and $I = 0.68 - 0.9 \mu m$. The results shown in Fig. 3.24 confirm the elimination of the linear distortion terms in the NGS channel after the DM compensation. However, although this term is still present in the science channel due to its chromatic dependence, it is greatly reduced and can be further corrected through astrometric calibration. The plots demonstrate the case for the NGS asterism located at 45 arcsec radial distance.

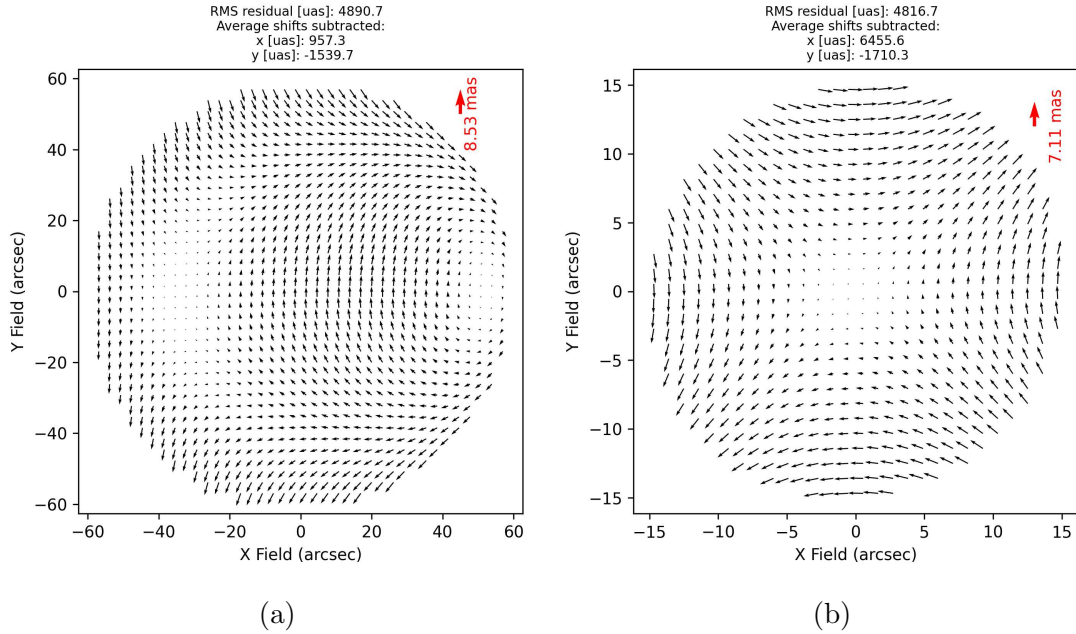


Figure 3.24: Distortion map in the technical FoV (left) and in the SCI FoV for V band (right) after the DM compensation for variable distortions.

The variation of the distortions with the zenith angle is presented in Fig. 3.25. While the requirement of the astrometric precision is $150 \mu as$, variable distortions, even after compensation with DMs, significantly exceed this value. The maximum distortion variation in V band, after subtracting the reference map, reaches 7 mas at $ZA = 57^\circ$.

In addition to the insufficient reduction of the distortions, another limitation of the compensation with DMs is the significant consumption of the available stroke. According to the DM requirements, the maximum mirror surface deformation achievable by actuating 5 by 5 actuators should be $\pm 10 \mu m$ PtV. From this, we estimated an average surface slope between two neighbouring groups of 5×5 actuators of $1.3 \cdot 10^{-3}$ radians. Applying astigmatism compensation of $4.3 \mu m$ RMS on the DM-High leads to the surface slope maps shown in Fig. 3.26, with slopes reaching up to $5.5 \cdot 10^{-4}$ radians at the edge of the aperture.

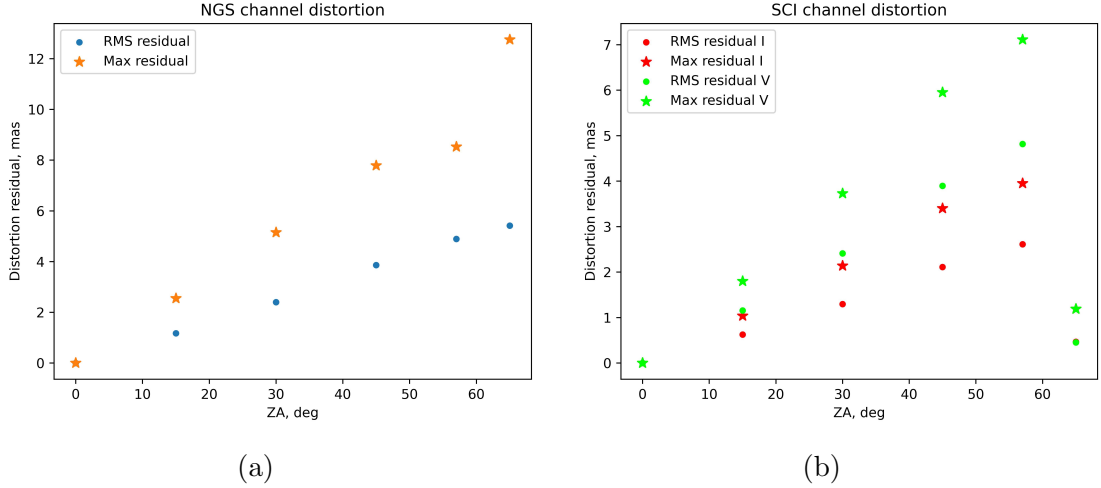


Figure 3.25: Variation of the differential distortions induced by the ADC as a function of the zenith angle on (a) the NGS WFS focal plane; (b) the science focal plane.

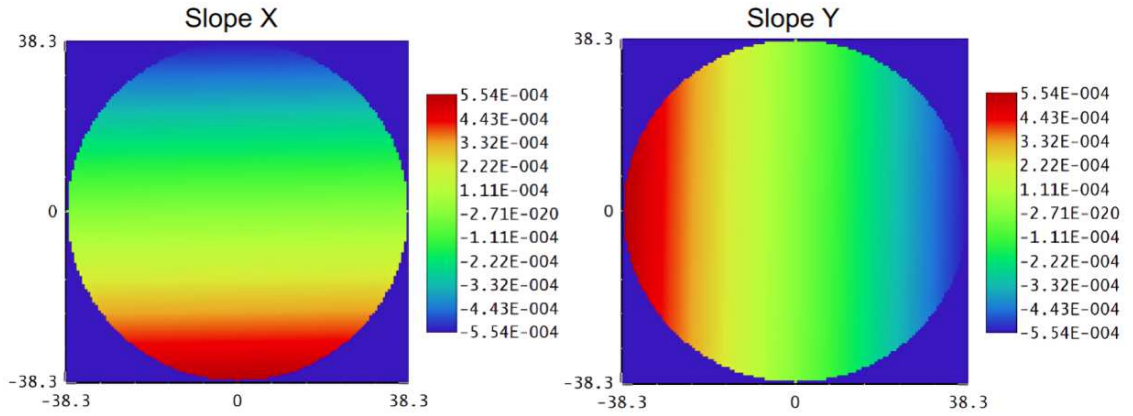


Figure 3.26: Slope maps of the DM-High after applying 4.3 μm RMS of astigmatism.

Reduction of the observing time The distortion is a vector field. Therefore, the variation of the distortion vector over time can be decomposed into two orthogonal components (see Fig. 3.27):

- **Amplitude variation:** This component alters the position of an object along the direction of the distortion vector. For a fixed field point, the amplitude variation depends on the counter-rotation angle of the ADC.
- **Direction (rotation) variation:** For small rotations, this component shifts the position of an object orthogonally to the distortion vector. This effect arises because the direction of atmospheric dispersion changes relative to the star field according to the parallactic angle. The positional variation can be approximated as the product of the distortion amplitude and the change in the parallactic angle.

Since these two components are orthogonal, the total distortion variation can be approximated as the root-sum-square of the two.



Figure 3.27: Schematic representation of the vectorial decomposition of the distortion variation.

The variation of the distortion with time can be calculated using the equatorial coordinates of the object of interest through the following formulae:

$$\tan p = \frac{\sin h}{\tan \Phi \cos \delta - \sin \delta \cos h} \quad (3.19)$$

$$\sin a = \sin \delta \sin \Phi + \cos \delta \cos h \cos \Phi \quad (3.20)$$

$$ZA = 90^\circ - a \quad (3.21)$$

$$\theta = \arccos \left(\frac{\tan ZA}{\tan 65^\circ} \right) \quad (3.22)$$

$$|D| \propto \cos \theta \sin \theta \quad (3.23)$$

$$\frac{d\vec{D}}{dh} = \frac{d|D|}{dh} + |D| \frac{dp}{dh} \quad (3.24)$$

Here, $\Phi = -24.617^\circ$ is the latitude of the VLT, δ and h are the declination and the hour angle of the object, p – the parallactic angle, a – the altitude, and $\vec{D}$ is the distortion vector.

To estimate the gradient of the distortion variation, we consider objects with ZA ranging from 0.5° to 65° . The resulting distortion variation as a function of hour angle and object declination is shown in Fig. 3.28. The colour scale in the plot represents the rate of distortion variation, measured in arbitrary units per hour (a.u./hour).

For better visualization of the central part of the plot, the maximum value on the colour scale has been set to 0.2 a.u./hour . However, it is important to note that the yellow regions are saturated, indicating that the distortion variation rate in these areas can reach values as high as 1.6 a.u./hour . These zones, which exhibit a very high variation of the distortion vector, correspond to observations where the zenith distance lies between 55° and 65° .

Given a relatively short observing time, such as 5 minutes, it is reasonable to consider the distortion variation rate as approximately constant. Under this assumption, the expected PSF shift during the observation can be derived using a linear approximation. It is practical to consider two distinct cases:

- A 5 min observation in an extreme scenario, where the target is located near

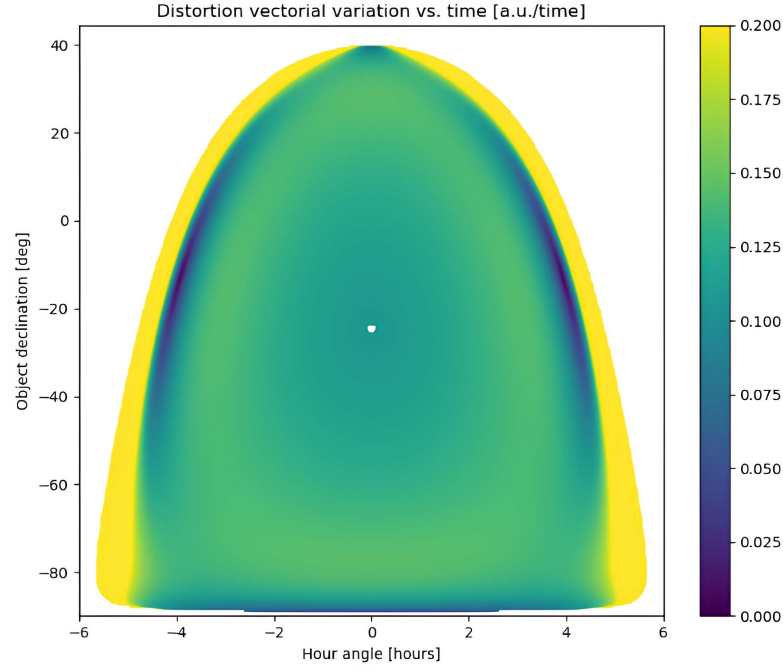


Figure 3.28: Variation rate of the distortion vector as a function of hour angle and object declination.

the $ZA = 65^\circ$. In this situation, the distortion variation rate is approximately $1.6a.u./hour$. This value corresponds to the 99th percentile, indicating that only 1% of the possible observing conditions exhibit higher values. This represents a worst-case scenario, where distortion effects are most pronounced.

- A 5-minute observation under more typical conditions, characterised by a distortion variation rate of $0.145a.u./hour$, which corresponds to the 99th percentile of the AO-observable sky ($ZA < 60^\circ$).

To convert the distortion variation rate from arbitrary units to a PSF shift expressed in arcseconds on the sky, an appropriate scaling must be applied. The following formula is used for this conversion:

$$\Delta PSF = \left| \frac{d\vec{D}}{dh} \right| * \frac{D_{edge}}{\Delta x(\Delta y)_{max}} * h, \quad (3.25)$$

where $\Delta x(\Delta y)_{max} \propto 0.5$ is the maximum of the mathematical function describing the linear distortion term; $D_{edge} = 540mas$ represents the maximum distortion at the edge of the technical field; $h = 0.08(3)h$ is the duration of an observation.

To obtain the PSF shift for the SCI FoV, a further rescaling is required, taking into account the ratio between the SCI and technical FoVs. After applying this scaling, we obtain the following results:

- For observations near $ZA = 65^\circ$:

PSF shift at the edge of the SCI FoV: 36 mas

PSF shift at the edge of the NGS FoV: 144 mas

- For observation with $ZA < 60^\circ$:

PSF shift at the edge of the SCI FoV: 3.26 mas

PSF shift at the edge of the NGS FoV: 13.1 mas

Considering that the FWHM of the PSF is 15-30 mas, the PSF shift induced by ADC-related distortions can significantly affect the quality and accuracy of scientific observations. These shifts may compromise astrometric precision and reduce the reliability of high-resolution imaging, particularly during observations conducted at large zenith angles.

New design of the ADC The linear distortion term is sensitive to tilts and the combination of optical glasses. Therefore, one potential approach to reducing distortions is to modify the design of the ADC. However, this is not a trivial task, as it is essential to preserve the primary function of the ADC, which is to correct atmospheric dispersion.

One strategy we explored was to vary the apex angles of the prisms. Although this adjustment helped to reduce distortions while maintaining acceptable dispersion residuals, it ultimately led to a highly unfeasible design involving two overlapping prisms.

Another viable approach is to replace the glass types used in the nominal ADC design. The original configuration, comprising S-FPL55, N-PK51, and PBL1Y glasses, can be substituted with a combination of K10, N-BAK1, and CaF_2 glasses. Such a replacement yields similar dispersion correction over the range from 370 to 1740 nm. The comparison between two dispersion residual curves at $ZA = 65^\circ$ is shown in Fig. 3.29.

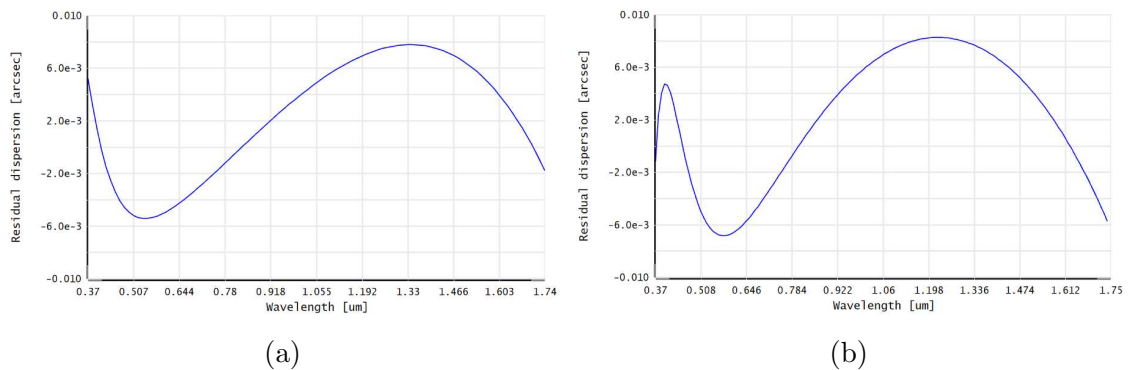


Figure 3.29: Dispersion residual of (a) the old design and (b) the new design.

This combination of glasses results in a significantly smaller worst-case distortion of 80 mas, measured at $ZA = 57^\circ$ at the edge of the technical field. This value is

more than six times lower compared to the nominal design. Consequently, the compensation range required for the DMs will also be reduced by a factor of six.

The variation of differential distortions obtained with this new configuration is shown in Fig. 3.30. Despite successfully removing the linear distortion term from the NGS path, the residual distortion, peaking at $ZA = 57^\circ$ after subtracting the average tilt component related to atmospheric dispersion, indicates the presence of some remaining linear distortion in the SCI focal plane. However, even in less favourable conditions, such as when the NGS asterism is located 45 arcseconds off-axis, the residual distortion is still significantly smaller than that observed in the nominal design.

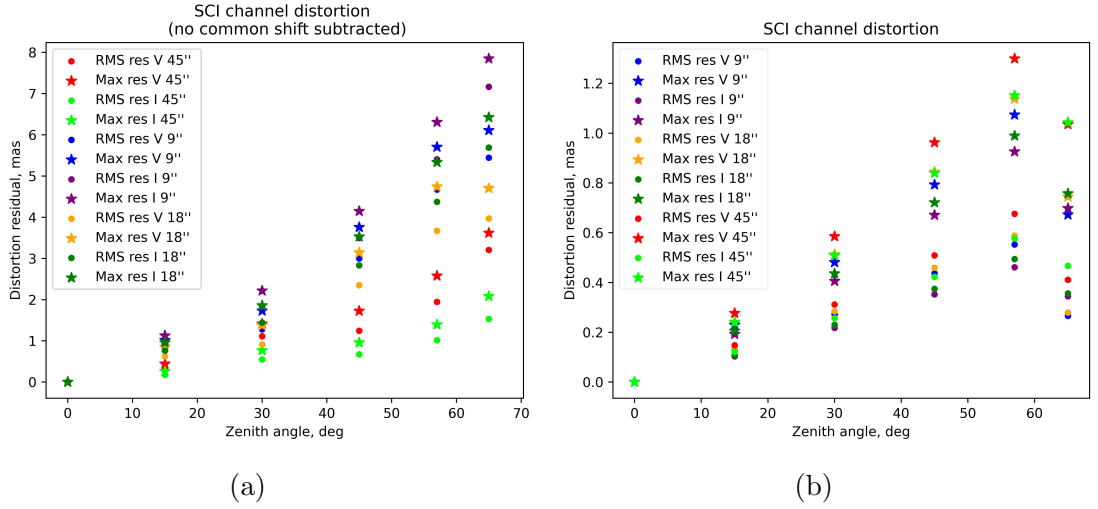


Figure 3.30: Variation of the differential distortions induced by the new design of the ADC as a function of the zenith angle on the SCI focal plane: (a) without average shift subtraction; (b) with average shift subtraction.

The table below reports the optical prescription data of the new ADC design. The optical elements are slightly thinner in the new design due to the reduced apex angles.

Pupil stability is controlled by the design. Both ADC prism assemblies are configured to have zero beam shift at $\lambda = 633$ nm. However, there is a slight wobble due to the chromaticity and the fact that the ADC is not positioned at the pupil plane. As shown in Fig. 3.32, the maximum deviation is 0.4% of the pupil diameter at $\lambda = 370$ nm for ZA values from 0° to 65° . This effect impacts the instruments and NGS WFS, but not the LGS WFS, as the latter is split prior to the ADC.

Given that CaF_2 has a high scratch sensitivity and wears down more quickly in severely humid conditions, we explored the possibility of positioning it between two other glasses. Although this arrangement shows no change in the dispersion residuals, it reintroduces significant distortion of more than 500 mas. Taking that into account, we returned to the original setup with CaF_2 at the end.

The throughput of the new combination of glasses is shown in Fig. 3.33. It is

	Surface type	Comment	RoC [mm]	Thickness [mm]	Material	Semi-diameter [mm]	X Tangent	Y tangent
10	TILTSURF	ADC1 P1S1	Infinity	1.50E+01	K10	4.25E+01	-3.12E-02	0.00E+00
11	TILTSURF	ADC1 P2S1	Infinity	1.85E+01	N-BAK1	4.25E+01	2.21E-01	0.00E+00
12	TILTSURF	ADC1 P3S1	Infinity	1.30E+01	CAF2(ARF)	4.25E+01	-1.05E-01	0.00E+00
13	TILTSURF	ADC1 P3S2	Infinity	0.00E+00		4.25E+01	3.37E-02	0.00E+00
14	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00
15	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00
16	STANDARD		Infinity	0.00E+00		3.33E+01	0.00E+00	0.00E+00
17	COORDBRK		Infinity	9.90E+00		0.00E+00	0.00E+00	0.00E+00
18	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00
19	COORDBRK		Infinity	0.00E+00		0.00E+00	0.00E+00	0.00E+00
20	TILTSURF	ADC2 P1S1	Infinity	1.30E+01	CAF2(ARF)	4.25E+01	3.37E-02	0.00E+00
21	TILTSURF	ADC2 P2S1	Infinity	1.85E+01	N-BAK1	4.25E+01	-1.05E-01	0.00E+00
22	TILTSURF	ADC2 P3S1	Infinity	1.50E+01	K10	4.25E+01	2.21E-01	0.00E+00
23	TILTSURF	ADC2 P3S2	Infinity	0.00E+00		4.25E+01	-3.12E-02	0.00E+00

Figure 3.31: Optical design prescription of the ADC.

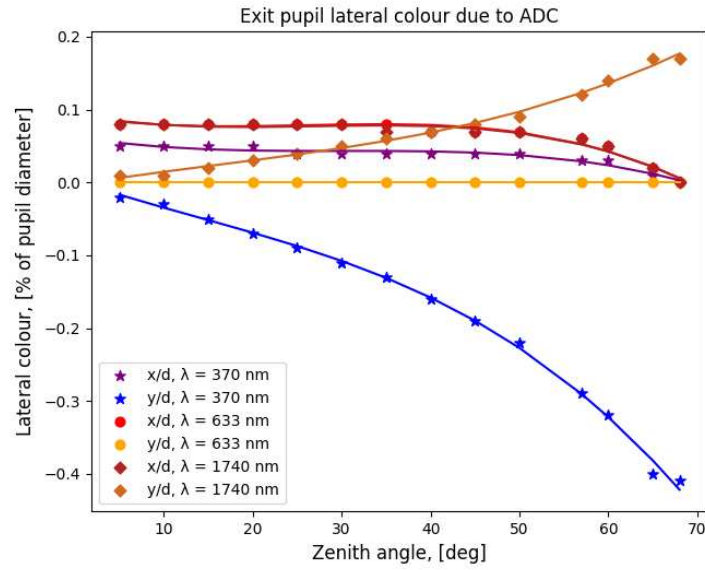


Figure 3.32: ADC chromatic pupil shift.

relatively similar to the nominal design. However, even though it exhibits a slight improvement in the red part of the spectrum, the values are lower in the UV region and drop more quickly beyond $1.55\mu m$.

3.1.3.2 K-mirror and field rotation dependence

The K-mirror functions as a field de-rotator, compensating for the apparent rotation of the sky due to the Earth's rotation. It consists of three mirrors arranged in a configuration that reflects the incoming light sequentially. When the K-mirror assembly is rotated by an angle θ , it induces a rotation of the image by 2θ . This means that to counteract a sky rotation of angle α , the K-mirror must be rotated by $\theta = \alpha/2$ in the opposite direction. This design ensures that the orientation of the image remains fixed relative to the instrument, maintaining alignment between the NGS WFS and the science camera.

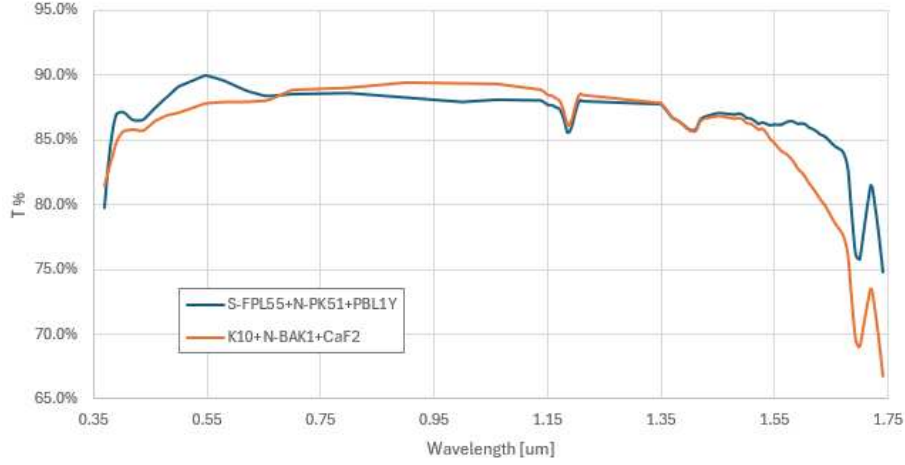


Figure 3.33: Throughput comparison of the nominal and the new designs of the ADC.

Upstream of the K-mirror, the optical footprints rotate, thus passing through different parts of the optical elements surfaces. Therefore, to keep the simulation as close to the reality as possible, we keep the perturbations representing the MSF errors on all optical elements in the Zemax model. The process of generating the surface figure error maps is described in detail in Section 3.1.1.

The distortion maps in the case of the K-mirror are derived only for monochromatic wavelengths, specifically $1.3 \mu\text{m}$ for the NGS channel, and $0.55 \mu\text{m}$ for the science channel. Examples of the distortion maps for the NGS asterism at 9 arc-sec radial distance are shown in Fig. 3.34. Distortions for small angles show some stretching or compression at different field points. This is likely the pure effect of the K-mirror rotation. This pattern disappears after 5° of rotation. Distortion maps at larger angles are dominated by a term very similar to the “linear” distortion mentioned in the ADC section. Although in this case, it is more likely related to the tilted optics (i.e. dichroics) than the ADC itself, given that the ADC is at 0° .

The variation of differential distortions as a function of the field rotation angle is shown in Fig. 3.35. The dependence is approximately linear for rotation angles up to around 25° of rotation. However, extending the analysis up to 180° reveals a square-root-like behaviour of the RMS residuals. In contrast, the maximum distortion values exhibit two distinct peaks, which are attributed to the geometry of the mirrors during rotation, which determines how the distortion field rotates relative to the focal plane. Due to the double reflection in K-mirror assembly, the distortion vector can be transformed as

$$\vec{D}(x, y, \theta) = R(2\theta)D_0(R(-2\theta) \begin{bmatrix} x \\ y \end{bmatrix}), \quad (3.26)$$

where $D_0(R(-2\theta) \begin{bmatrix} x \\ y \end{bmatrix})$ is the distortion vector corresponding to the positions of the

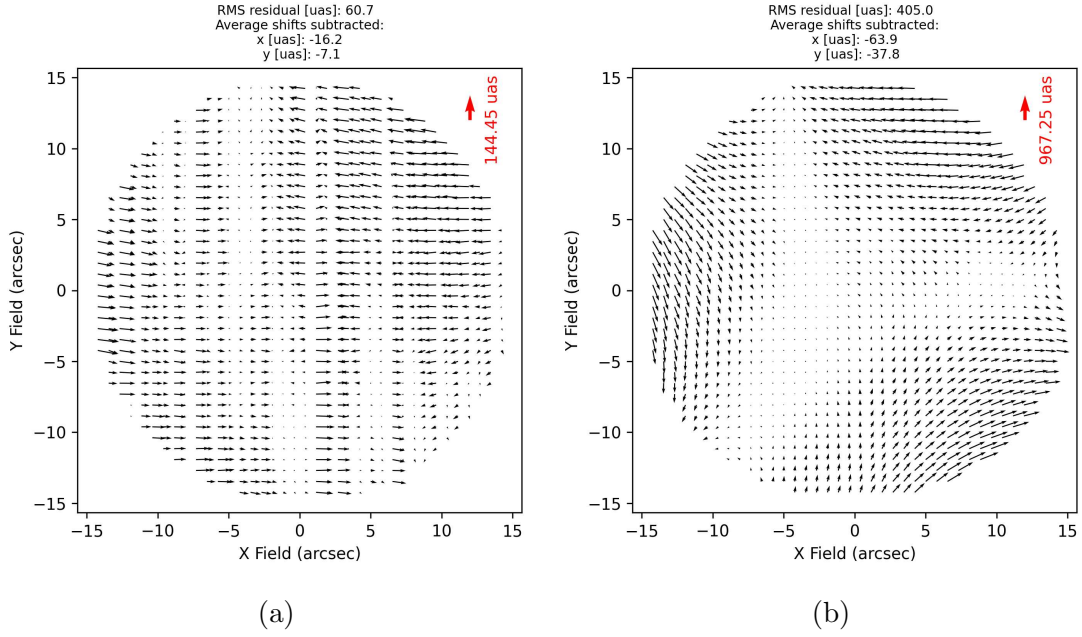


Figure 3.34: Examples of the distortion variation maps for the 9 arcsec radial NGS asterism at (a) 1 deg and (b) 30 deg of field rotation.

rays on the K-mirror surfaces as the mirror rotates to de-rotate the sky; and

$$R(2\theta) = \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \quad (3.27)$$

is the K-mirror rotation matrix. The combination of harmonics and small surface figure errors produce a non-linear dependence of the norm $\|\vec{D}\|$ of the distortion vector.

Despite these variations, the maximum distortion change remains relatively small, reaching approximately 2.5 mas over the full rotation range. This value corresponds to the typical configuration where the NGS asterism is located 20 arcseconds off-axis.

Using polynomial fitting of the distortion maps demonstrated that most of the distortions are low-order, corresponding to tilts and plate scale, and thus can be successfully calibrated with the small number of reference stars in the FoV (i.e. GAIA stars). Comparison of the RMS residual distortions after the fitting is shown in Table 3.3.

3.1.3.3 Field lens and pupil shift dependence

The field lens is the first element in the optical train of MAVIS. It is positioned at a distance greater than 500 mm from the Nasmyth adaptor/rotator flange. This positioning is intentional and aims to ensure that no parts of the AOM need to be moved during maintenance activities involving the UT4 adaptor/rotator. The primary function of the field lens is to produce an image of the 13.5 and 6 km

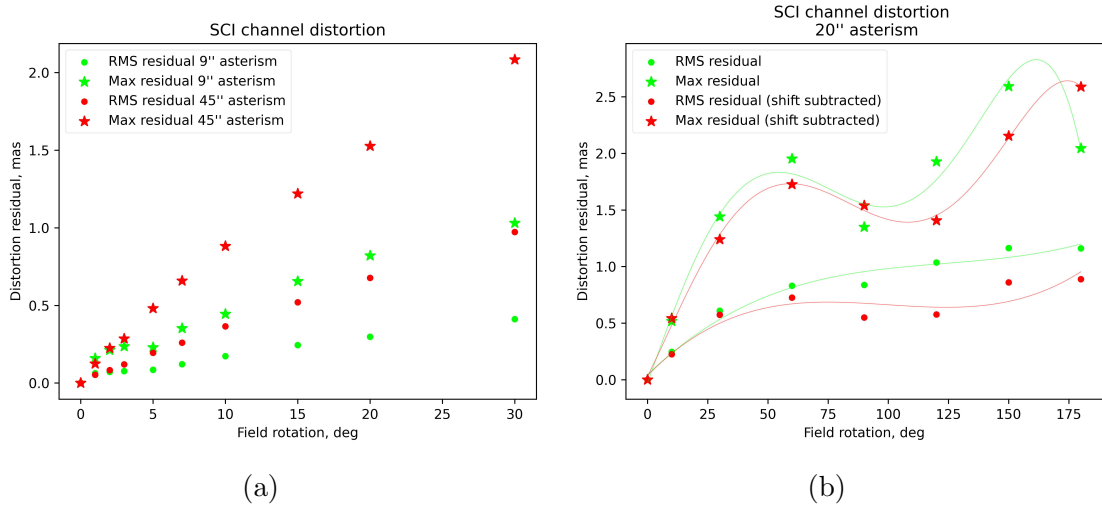


Figure 3.35: Variation of differential distortions as a function of field rotation. (a) Maximum and RMS distortion variations for NGS asterisms with radial distances of 9'' and 45''; (b) Maximum and RMS distortion variations across a full 180° field rotation for NGS asterisms located at a 20'' radial distance.

		Field rotation, deg								
		0	1	2	5	7	10	15	20	30
Polynomial order	Input	0	53.2	82.8	194.5	259.7	365.1	520.1	677.5	972.6
	1	-	42.96	43.96	74.41	94.84	127.8	186.17	239.46	328.74
	2	-	53.77	50.91	53.79	51.19	50.93	63.68	68.75	76.64
	3	-	54.56	51.52	55.01	54.02	49.58	63.09	66.41	62.81
	4	-	50.3	47.15	51.72	52.7	48.32	60.37	63.46	56.43
	5	-	48.68	46.64	49.21	48.02	48.65	60.68	64.16	55.34
	6	-	49.14	45.45	49.04	48.0	48.77	58.56	62.55	51.49
	7	-	49.34	44.55	50.19	49.54	47.5	56.33	60.47	50.03
	8	-	49.15	44.8	49.98	49.55	46.49	55.76	58.64	47.76

Table 3.3: RMS residuals of the differential distortions after the polynomial fitting.

altitude meta-pupils on the DMs with proper sampling. Additionally, it is used to compensate for the entrance pupil shifts. Its X–Y movement will be controlled by linear stages, allowing a maximum displacement of $\pm 2\%$ of the pupil diameter, which corresponds to approximately ± 1 mm of lateral motion of the lens itself.

As a moving component, however, the field lens may also introduce some differential distortions. To assess this effect, we analysed the impact of its decentring on the resulting distortion observed in the system. The corresponding results are presented in Fig. 3.36. Most of the distortions introduced by the field lens dis-

placement are low order and are expected to be effectively calibrated with reference stars. Simulations indicate that a first-order polynomial already reduces the RMS residuals by a factor of 10. While using six reference stars in the field yields to less than $50\mu\text{s}$ of residual distortions for the maximum decenter of the field lens.

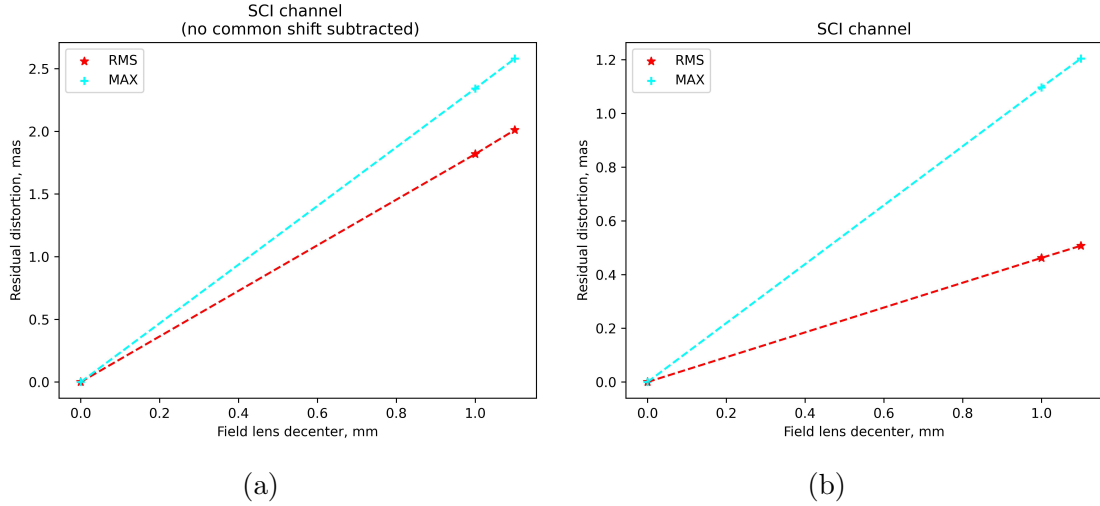


Figure 3.36: Variation of differential distortions as a function of field lens decenter. (a) Maximum and RMS distortion variations without average shift subtraction; (b) with average shift subtraction.

3.2 Image uniformity analysis

One of the key scientific instruments of MAVIS is the imager. Therefore, verifying the image quality is crucial. The requirement states that the uniformity of image quality (IQ) delivered by the combined AO+imager module, including the AO optical train up to the imager (but excluding the DMs), all filters, and the camera serving the imager port, shall be $\leq \pm 5\%$ PtV of the nominal design average value across the full imager FoV on the detector. In this context, IQ is understood in terms of spatial FWHM, anywhere in the field, of the PSF produced by a monochromatic, diffraction-limited source at the entrance of the instrument for wavelengths representative of the minimum, peak, and maximum operational wavelength range.

The uniformity of the image quality was evaluated using seven Monte Carlo simulations derived from the manufacturing tolerances. The average WFE in these simulations ranged from 0.033 to 0.082 waves. Monochromatic PSFs were generated for several field points within the squared 30×30 arcsec scientific FoV for each MC realization.

Given the presence of aberrations in the Monte Carlo realizations, standard Gaussian or Moffat fitting was insufficient. All PSF images were therefore fitted with elliptical contours, and the FWHM was measured along the minor (x) and major (y) axes. Finally, we calculated the relative variation of each PSF compared to the

average across the field. The distribution of the FWHM for each MC realization at several wavelengths is shown in Fig. 3.37.

With the exception of a few cases at the 370 nm and one outlier at 500 nm, all the PSFs satisfy the $\pm 5\%$ FWHM uniformity requirement. Higher values are attributed to the fact that in some MC simulations with highest WFE, the PSFs at 370 nm exhibit some aberrations since the system has been optimized for 550 nm.

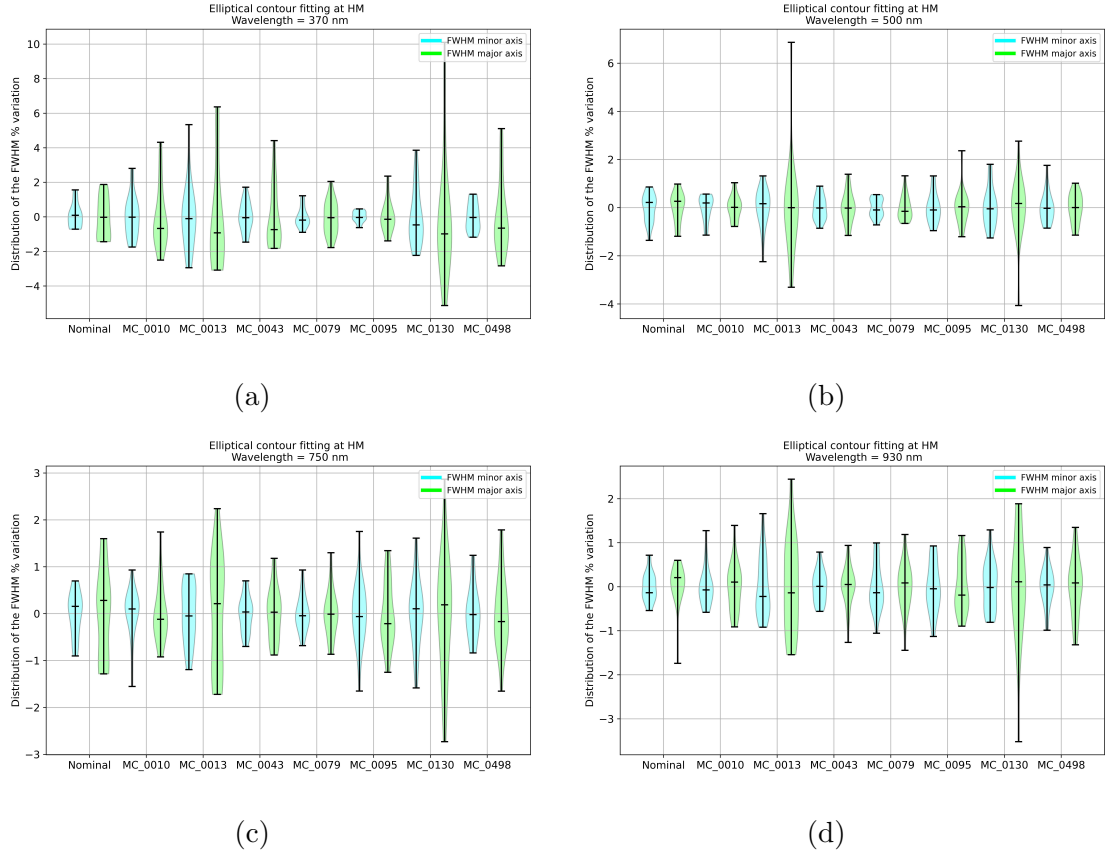


Figure 3.37: Distribution of the FWHM values of the PSFs for (a) 370 nm; (b) 500 nm; (c) 750 nm; (d) 930 nm.

3.3 Stray light analysis

Astronomical imaging is very demanding regarding stray light in the system. Any unwanted light can significantly compromise the imaging of celestial objects, especially the faint ones. The presence of a bright source, for example, can create optical ghosts that blend with the light from other sources in the field, making it hard to distinguish and derive the properties of those objects. The origin of stray light varies and requires different mitigation strategies during the design and manufacturing stages.

The most common sources of stray light include:

- Scattering due to optical surface imperfections, such as scratches, poor polishing, dust and so on.
- Multiple internal reflections between optical surfaces.
- Reflection from a window or the detector itself.
- Reflection and scattering from mounting elements.

In this section, we analyse only the scattering and the optical ghosts originating from sources within the FoV of MAVIS. Any scattering from mechanics or thermal radiation are not discussed here.

3.3.1 In-field scattering

The scattered light from optical and mechanical components results in lost or diffused light on the science detector. We estimate the in-field scattered light arising from micro-roughness of the optical components and/or dust on their surfaces. Although some of the effects of scattered light can be removed through flat fielding techniques or data analysis in the post-processing, modelling the actual scattered light can be too complex and may not fully eliminate its impact. Therefore, it is preferable to reduce the amount of unwanted light as much as possible during the design and manufacturing the instrument.

We evaluate the stray light generated by micro-roughness and dust contamination for a point source within the science FoV using an analytical model by Peterson^[89]. This model gives the radial stray light irradiance profile on the detector plane from j -element:

$$E_j = \pi(NA)^2 T \frac{a_{ent}^2}{a_j^2} BSDF \left((NA) \frac{r}{a_j} \right) E_{ent} \quad (3.28)$$

Here, NA is the numerical aperture of the telescope, T is the transmission of the system, a_{ent} and a_j are the beam semi-diameter on the first and the j element, correspondingly, r is the distance from the source, and E_{ent} is the irradiance at the entrance aperture.

The total magnitude and distribution of the in-field stray light on the focal plane are calculated using the bi-directional scatter distribution function (BSDF) of each optical component. The BSDF is modelled with the 3-parameter Harvey profile^[90]:

$$BSDF(|\sin \theta_s - \sin \theta_i|) = b_0 \left[1 + \left(\frac{|\sin \theta_s - \sin \theta_i|}{l} \right)^2 \right]^{s/2}, \quad (3.29)$$

where θ_s and θ_i are, respectively, the angle of scattering and the angle of incidence to the surface normal; b_0 is the value of the BSDF in the specular direction; l and s are the roll-off angle and slope, respectively.

Substituting the BSDF to the Equation 3.28, one can calculate the irradiance on the j-element in the following way:

$$E_j = \pi(NA)^2 T \frac{a_{ent}^2}{a_j^2} b_0 \left(1 + \frac{(NA)r/a_j + (1/6)((NA)r/a_j)^3}{l} \right) E_{ent} \quad (3.30)$$

The f-number of the system $F\# = 35.0$, which leads to the numerical aperture $NA = \frac{1}{2F\#} = 0.81^\circ$. The calculations are done only for an on-axis source. Any bulk scattering from the glass and scattering from surface imperfections are not taken into account.

Scattering from micro-roughness of optical surfaces is modelled with a Harvey profile with a slope s of -1.8 and a roll-off angle $l = 0.001rad$. The b_0 parameter and the resulting Total Integrated Scatter (TIS) depend on the RMS roughness of the surface and the index of refraction, and thus are different for each optical element. To first order:

$$TIS \approx \left(4 \cdot \pi \frac{R_q}{\lambda} \right)^2, \quad (3.31)$$

where R_q is the RMS surface roughness.

Scattering from particle contamination is modelled with a Harvey profile, whose parameters were obtained by fitting the BSDF profile calculated using Mie scattering theory. The BSDF strongly depends on the particle distribution, and therefore is different for clean and non-cleaned surfaces. The cleaning process removes larger particles, leaving only the smaller ones. As a result, the non-cleaned surface profile peaks more at small angles, since large particles scatter more light at small angles. The BSDF profile of the non-cleaned surface is more complex than the one of the cleaned surface, and is described by the sum of two Harvey profiles. The parameters for these Harvey profiles are reported in Table 3.4. The amount of particle contamination is expressed in terms of Percentage of Area Coverage (PAC).

Cleaned surface		Non-cleaned surface			
Profile 1		Profile 1		Profile 2	
b_0	0.562	b_0	32.4	b_0	$5 \cdot 10^{-5}$
s	-1.75	s	-2.7	s	-0.5
l	0.0035	l	0.001	l	0.1
TIS	0.054%	TIS	0.029%	TIS	0.006%

Table 3.4: Parameters for the Harvey profiles for dust contamination (PAC = 250pm).

However, the profile 2 for the non-cleaned surface is negligible for scattering angles less than $\approx 10^\circ$. Therefore, it is not considered in the simulation.

We consider two cases for the optical elements of the PFR:

1. Non-cleaned surfaces assembled in a clean-room environment;

2. Cleaned surfaces assembled in a clean-room environment.

The amount of dust contamination that defines the cleanliness level of a surface can be expressed as:

$$CL = 10^{\sqrt{\frac{1}{0.926}} \lg \left(F_{orient} \rho t \left[10^{N_{ISO}} \left(\frac{0.1}{5} \right)^{2.08} \right]^{0.773} \right) - A}, \quad (3.32)$$

where F_{orient} is the orientation factor, which equals 1 for up-ward facing surfaces, 0.1 for vertical surfaces and 0.01 for downward-facing surfaces; ρ is a constant determined by the number of air changes per hour of the clean-room ($\rho = 81$ for a clean-room with fewer than 15-20 changes/hour and approaching still air, $\rho = 8.1$ for a conventional clean-room with 15-20 changes/hour, and $\rho = 2.7$ for a laminar flow clean-room); N_{ISO} is the ISO 14644-1 class of the clean-room and the coefficient $A = -1.8889$.

Assuming vertical surfaces, 1200 days of exposure to a clean-room environment, $\rho = 8.1$, and $N_{ISO} = 6$, one obtains $CL = 477$. The equivalent PAC for this cleanliness level is then about 0.25% or 2500 ppm.

The typical value of CL for cleaned optics is 300, which corresponds to $PAC = 250$ ppm.

The calculations were performed for two wavelengths, 550 nm and 370 nm, with the latter being the worst case limit, since scattering from micro-roughness is generally bigger at shorter wavelengths. We consider close to ideal conditions with $SR = 100\%$ for the diffraction-limited source and the throughput of the system is assumed to be 1. Optical elements included in the simulation span from the Field Lens to the Imager optics. It is important to note that the surface of the Cryo Window facing the detector is always kept clean, with $PAC = 250$ ppm.

Table 3.5 reports the parameters for each optical surface used in the simulation. The surface micro-roughness of the Imager filters and Cryo Window is required to be $< 10 \text{ \AA}$ RMS, given their proximity to the focal plane.

Surface	Beam footprint semi-diameter, mm	Δn	RMS roughness, $\text{\AA}$	Cleaned optics PAC, ppm	Non-cleaned optics PAC, ppm
Field lens L1S1	9.94	0.589	20	250	2500
Field lens L1S2	10.04	0.175	20	250	2500
Field lens L2S1	10.04	0.025	20	250	2500
Field lens L1S1	10.04	0.439	20	250	2500
DM-High	19.03	2.0	20	250	2500
DM-Low	23.72	2.0	20	250	2500
Collimator L1S1	27.62	0.620	20	250	2500
Collimator L1S2	27.86	0.206	20	250	2500
Collimator L2S1	27.86	0.025	20	250	2500
Collimator L2S2	28.07	0.025	20	250	2500
Collimator L3S1	28.07	0.194	20	250	2500

Collimator L3S2	28.54	0.607	20	250	2500
LGS Dichroic S1	28.53	0.459	20	250	2500
LGS Dichroic S2	28.53	0.459	20	250	2500
ADC1 P1S1	28.53	0.501	20	250	2500
ADC1 P1S2	28.53	0.088	20	250	2500
ADC1 P2S1	28.53	0.159	20	250	2500
ADC1 P2S2	28.53	0.159	20	250	2500
ADC1 P3S1	28.53	0.02	20	250	2500
ADC1 P3S2	28.53	0.434	20	250	2500
ADC2 P1S1	28.53	0.434	20	250	2500
ADC2 P1S2	28.53	0.02	20	250	2500
ADC2 P2S1	28.53	0.159	20	250	2500
ADC2 P2S2	28.53	0.159	20	250	2500
ADC2 P3S1	28.53	0.088	20	250	2500
ADC2 P3S2	28.53	0.501	20	250	2500
K-mirror 1	28.53	2.0	20	250	2500
K-mirror 2	28.53	2.0	20	250	2500
K-mirror 3	28.53	2.0	20	250	2500
NGS Dichroic S1	28.53	2.0	20	250	2500
SCI Objective L1S1	28.53	0.589	20	250	2500
SCI Objective L1S2	28.28	0.175	20	250	2500
SCI Objective L2S1	28.28	0.083	20	250	2500
SCI Objective L2S2	28.11	0.497	20	250	2500
SCI Fold mirror 1	24.28	2.0	20	250	2500
SCI Filter 1 S1	2.97	0.459	10	250	2500
SCI Filter 1 S2	2.85	0.459	10	250	2500
SCI Filter 2 S1	2.15	0.459	10	250	2500
SCI Filter 2 S2	2.03	0.459	10	250	2500
SCI Cryo Window S1	0.50	0.459	10	250	2500
SCI Cryo Window S2	0.35	0.459	10	250	2500

Table 3.5: In-field scattering parameters for each optical surface.

The scattered light distribution on the focal plane is derived as the irradiance profile of scattered light, normalised to the peak irradiance of the image as a function of the distance from the image of the source. The results are shown in Fig.3.38. It can be seen that scattering produced by particle contamination dominates in all cases. Cleaning up to $CL = 300$ reduces the light scattered by dust by a factor of 100.

The main contributors to the irradiance of scattered light due to dust are the Imager's elements, filters, and the Cryo Window, given their proximity to the focal plane. The contribution of each optical element to the total irradiance is shown in Table 3.6. The total amount of light loss due to scattering is estimated to be in the range of 10 – 15% for non-cleaned optics and 3 – 5% for cleaned optics.

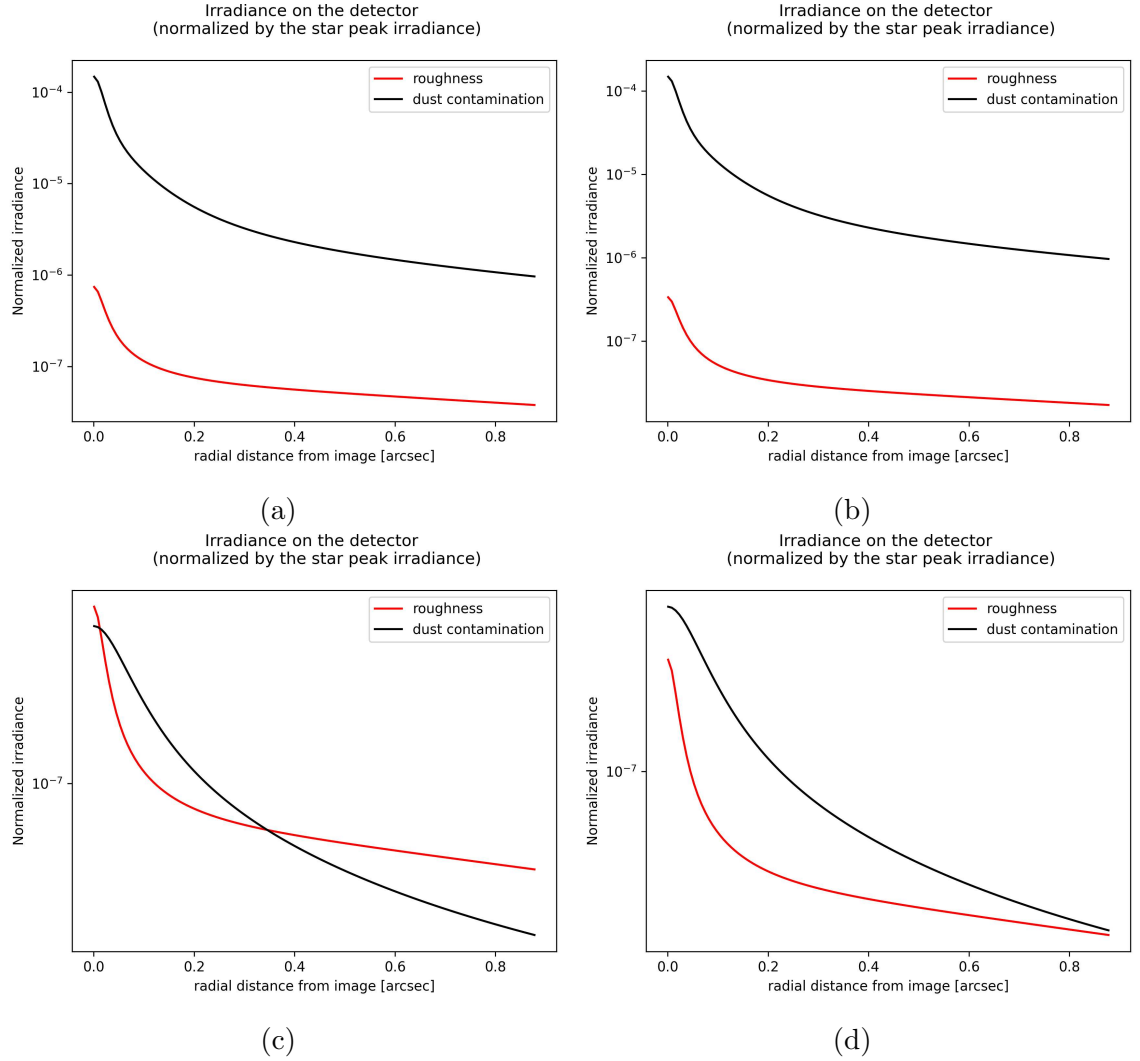


Figure 3.38: Scattered light irradiance profile, normalised by the peak irradiance of the image, as a function of the distance from the image of the source. *Top:* Calculation is performed for non-cleaned surfaces exposed to 1200 days of cleanroom ISO-6 environment (CL=477, non-cleaned surface BRDF). *Bottom:* Calculation is performed for cleaned surfaces (CL=300, cleaned surface BRDF). (a) and (c) $\lambda = 370nm$; (b) and (d) $\lambda = 550nm$

Element	$\lambda = 370nm$				$\lambda = 550nm$			
	Cleaned		Non-cleaned		Cleaned		Non-cleaned	
	$E_{mean,rough}, [ph/s/mm^2]$	$E_{mean,dust}, [ph/s/mm^2]$	$E_{mean,rough}, [ph/s/mm^2]$	$E_{mean,dust}, [ph/s/mm^2]$	$E_{mean,rough}, [ph/s/mm^2]$	$E_{mean,dust}, [ph/s/mm^2]$	$E_{mean,rough}, [ph/s/mm^2]$	$E_{mean,dust}, [ph/s/mm^2]$
Field lens	$2.66 \cdot 10^4$	$1.24 \cdot 10^4$	$2.66 \cdot 10^4$	$4.08 \cdot 10^6$	$8.1 \cdot 10^3$	$8.33 \cdot 10^3$	$8.1 \cdot 10^3$	$2.75 \cdot 10^6$
DM-High	$6.79 \cdot 10^4$	$9.08 \cdot 10^2$	$6.79 \cdot 10^5$	$4.08 \cdot 10^5$	$2.07 \cdot 10^4$	$6.12 \cdot 10^2$	$2.07 \cdot 10^4$	$2.75 \cdot 10^5$
DM-Low	$4.62 \cdot 10^4$	$5.88 \cdot 10^2$	$4.62 \cdot 10^4$	$2.84 \cdot 10^5$	$1.41 \cdot 10^4$	$3.96 \cdot 10^2$	$1.41 \cdot 10^4$	$1.91 \cdot 10^5$
Collimator	$7.12 \cdot 10^3$	$2.54 \cdot 10^3$	$7.12 \cdot 10^3$	$1.28 \cdot 10^6$	$2.17 \cdot 10^3$	$1.71 \cdot 10^3$	$2.17 \cdot 10^3$	$8.63 \cdot 10^5$
LGS dichroic	$3.49 \cdot 10^3$	$8.16 \cdot 10^2$	$3.49 \cdot 10^3$	$4.13 \cdot 10^5$	$1.06 \cdot 10^3$	$5.5 \cdot 10^2$	$1.06 \cdot 10^3$	$2.78 \cdot 10^5$
ADC	$8.24 \cdot 10^3$	$4.9 \cdot 10^3$	$8.24 \cdot 10^3$	$2.48 \cdot 10^6$	$2.51 \cdot 10^3$	$3.3 \cdot 10^3$	$2.51 \cdot 10^3$	$1.67 \cdot 10^6$
K-mirror	$9.92 \cdot 10^4$	$1.23 \cdot 10^3$	$9.92 \cdot 10^4$	$6.2 \cdot 10^5$	$3.02 \cdot 10^4$	$8.25 \cdot 10^2$	$3.02 \cdot 10^4$	$4.18 \cdot 10^5$
NGS dichroic	$3.31 \cdot 10^4$	$4.08 \cdot 10^2$	$3.31 \cdot 10^4$	$2.07 \cdot 10^5$	$1.01 \cdot 10^4$	$2.75 \cdot 10^2$	$1.01 \cdot 10^4$	$1.39 \cdot 10^5$
SCI Objective	$5.28 \cdot 10^3$	$1.66 \cdot 10^3$	$5.28 \cdot 10^3$	$8.39 \cdot 10^5$	$1.61 \cdot 10^3$	$1.12 \cdot 10^3$	$1.61 \cdot 10^3$	$5.65 \cdot 10^5$
SCI Fold mirror	$4.43 \cdot 10^4$	$5.62 \cdot 10^2$	$4.43 \cdot 10^4$	$2.73 \cdot 10^5$	$1.35 \cdot 10^4$	$3.78 \cdot 10^2$	$1.35 \cdot 10^4$	$1.84 \cdot 10^5$
SCI Filter 1	$2.43 \cdot 10^4$	$5.15 \cdot 10^4$	$2.43 \cdot 10^4$	$8.5 \cdot 10^6$	$7.42 \cdot 10^3$	$3.47 \cdot 10^4$	$7.42 \cdot 10^3$	$5.73 \cdot 10^6$
SCI Filter 2	$3.56 \cdot 10^4$	$8.25 \cdot 10^4$	$3.56 \cdot 10^4$	$1.21 \cdot 10^7$	$1.08 \cdot 10^4$	$5.55 \cdot 10^4$	$1.08 \cdot 10^4$	$8.12 \cdot 10^6$
SCI Cryo Window	$2.12 \cdot 10^5$	$5.85 \cdot 10^5$	$2.12 \cdot 10^5$	$3.16 \cdot 10^7$	$6.46 \cdot 10^4$	$3.94 \cdot 10^5$	$6.46 \cdot 10^4$	$2.13 \cdot 10^7$

Table 3.6: Contribution of the optical elements to the total irradiance of the scattered light.

3.3.2 Ghost analysis

Given the complex design of MAVIS, optical ghosts can occur from many different elements. The requirement on ghost intensity is that, for any source, the intensity of focused ghosts anywhere on the output focal planes shall be less than $5 \cdot 10^{-4}$ for sources outside the nominal FoV and $5 \cdot 10^{-3}$ for sources inside the nominal FoV.

The analysis was performed for the PFR optics, evaluating ghosts on the SCI, the NGS, and the LGS channel focal planes. The optical model of MAVIS was converted to a non-sequential model to run ray-tracing simulations with Zemax OpticStudio. Only ghosts up to the second order are considered, since higher-order ghosts have negligible power and irradiance and are therefore discarded. This means we consider a maximum of two ghost reflections at air/glass interfaces.

The detectors placed at the interface focal plane of each channel have the on-sky-projected pixel size generally bigger than the real pixel size. This is done to increase the computational efficiency. However, this leads to an underestimation of the irradiance of focused ghosts, whose footprint is smaller than the pixel pitch. To overcome this issue, the irradiance ratio between a focused ghost and an image is calculated as the ratio of their respective integrated powers, assuming both are perfectly focused.

A maximum number of rays traced for each source is limited to 10^5 . Consequently, ghosts that are extremely out-of-focus do not appear as smooth due to the insufficient pupil sampling. This results in an overestimation of the ghost irradiance, providing a conservative estimate. Nevertheless, these ghosts are not critical because they are largely out of focus and their irradiance is generally very small.

The coatings of the optical elements considered in this simulation are assumed to be ideal, with a uniform transmission over the wavelength range. The simulated throughput is close to the expected one. Tables with the assumed coatings for each channel are reported in the following subsections. However, as a first approximation, ghost power and irradiance are proportional to the reflectivity of the ghosting surfaces, which allows the results to be rescaled later to account for the real coating reflectivity.

3.3.2.1 Ghosts caused by the LGS dichroic

In the simulation run for the previous design, we discovered that the relative intensity of one of the focused ghosts exceeds the requirement, reaching $7.34 \cdot 10^4$ in the irradiance ratio. The ghost originated from a double reflection in the LGS dichroic, as shown schematically in Fig. 3.39.

There are two options to deal with the optical ghost in this case. The first one requires adding a wedge to the dichroic, thus sending the ghost outside of the focal plane. This approach was analysed using a simplified model with the LGS dichroic in the collimated beam. The difference between the image and the ghost positions

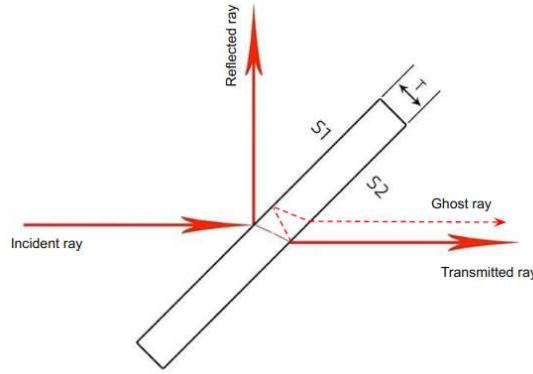


Figure 3.39: Schematic view of the primary and ghost ray paths at the LGS dichroic.

was calculated as the quadratic sum of the centroid coordinates:

$$r = \sqrt{(x_{im} - x_g)^2 + (y_{im} - y_g)^2} \quad (3.33)$$

Evaluating the feasibility of making the ghost coincident with the image, for the maximum of $10\mu\text{m}$ distance, the required wedge should be $0.33''$, which might be unfeasible for the system.

Another solution is to defocus the ghost. This can be achieved by either de-collimating the beam where the dichroic is placed or adding power to the dichroic itself. De-collimating the beam can be done in several ways; however some constraints should be considered:

- the optical interfaces between modules should be kept fixed;
- the ADC should be kept in a perfectly collimated beam, otherwise it will generate a variable amount of astigmatism during tracking;
- introducing additional lenses should be avoided, as it would reduce the system's throughput, which is tightly constrained by strict performance requirements;

The best compromise identified implies moving the collimator after the LGS dichroic. A quick re-optimisation of the design was performed to address this change. The resulting design is reported in Fig. 3.40, superimposed with the PDR design.

The amount of defocus added to the ghost is only $\Delta z = 5.5\text{ mm}$, but it should be enough to guarantee compliance with the requirement. However, this option leads to an increased diameter of many optical components, and the back focal distance also becomes longer due to maintaining the same optical interface. This, therefore, will require verification of volume availability.

The second way of de-focusing the ghost is by adding curvature, optical power, to the LGS dichroic without changing its position. A ray-tracing simulation showed that a spherical radius of curvature of $2 \cdot 10^5\text{ mm}$ on the second surface is sufficient

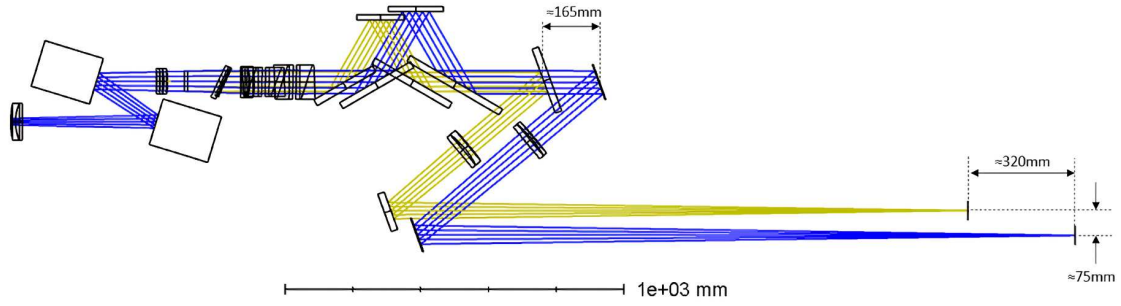


Figure 3.40: Optical layout of the science path. Blue color: re-optimized design, yellow color: the PDR baseline design.

to de-focus the ghost, creating a spot of 1.5-2 mm in diameter. The curvature adds 45 nm RMS of the astigmatism to the transmitted beam, which can be considered as a part of the NCPA budget.

The manufacturability of the dichroic with such a shallow curvature was confirmed by the providers, thus becoming our adopted solution for the LGS dichroic generated ghost.

3.3.2.2 Ghost analysis of the FDR design

The results of the ghost analysis presented below include the final version of the AOM design, which incorporates major changes in the LGS dichroic and the ADC discussed above.

SCI channel ghosts The simulation was performed for two source positions: an on-axis point source and a point source located at 21.2 arcsec from the optical axis, corresponding to the corner of the detector. Both sources are monochromatic with $\lambda = 632.8$ nm, and are conjugated at infinity.

The detector used in the simulation is slightly oversized with respect to the science detector and has a size of 30.22×30.22 arcsec, with a pixel pitch of $83\mu\text{m}$ (60 mas).

The assumptions on the elements coatings are reported in Table 3.7.

Element	Surface	Coating
Field lens	Field lens L1S1	I.98
	Field lens L1S2	uncoated
	Field lens L2S1	uncoated
	Field lens L2S2	I.98
Collimator	Collimator L1S1	I.98
	Collimator L1S2	uncoated
	Collimator L2S1	uncoated
	Collimator L2S2	uncoated
	Collimator L3S1	uncoated

	Collimator L3S2	I.98
LGS dichroic	LGS dichroic S1	I.98
	LGS dichroic S2	I.98
ADC1	ADC1 P1S1	I.98
	ADC1 P1S2	uncoated
	ADC1 P2S1	uncoated
	ADC1 P2S2	uncoated
	ADC1 P3S1	uncoated
	ADC1 P3S2	I.98
ADC2	ADC2 P1S1	I.98
	ADC2 P1S2	uncoated
	ADC2 P2S1	uncoated
	ADC2 P2S2	uncoated
	ADC2 P3S1	uncoated
	ADC2 P3S2	I.98
NGS dichroic	NGS dichroic S1	I.02
	NGS dichroic S2	I.98
SCI Objective	SCI Objective L1S1	I.98
	SCI Objective L1S2	uncoated
	SCI Objective L2S1	uncoated
	SCI Objective L2S2	I.98
Imager filter 1	Imager filter 1 S1	I.98
	Imager filter 1 S2	I.98
Imager filter 2	Imager filter 2 S1	I.98
	Imager filter 2 S2	I.98
Imager Window	Imager Window S1	I.98
	Imager Window S2	I.98
Imager chip	Imager chip	I.95

Table 3.7: Coating assumptions for each optical surface in the SCI channel. I.xx means an ideal coating: xx is the transmissivity, and the reflectivity is 100-xx.

The appearance of the ghosts on the science detector for an on-axis and off-axis sources is shown in Fig.3.41. Table 3.8 reports the worst paths producing the highest irradiance on the detector. The integrated power and the peak irradiance are calculated as ratios to those of the diffraction-limited image. The worst paths coincide for the on-axis and off-axis sources. The highest irradiance is produced by some focused ghosts generated by flat optics placed in the collimated beam, namely the ADC prisms. In this case, the ghosts originate from reflections between two prisms and not inside each prism. Thus, the positions of the ghosts depend both on the prism rotations and their relative alignment. The focused ghost previously occurring due to the double reflection in the LGS dichroic was successfully defocused by adding a shallow curvature to its second surface, as mentioned above.

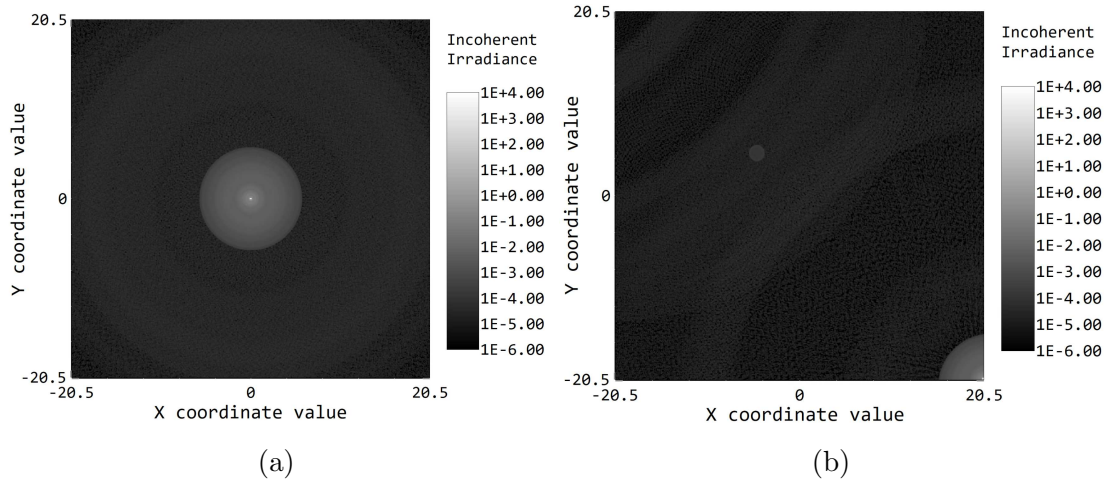


Figure 3.41: Ghost images on the science detector: (a) a source on-axis; (b) a source off-axis.

On-axis source			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
ADC1 P3	ADC2 P1	$4 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
ADC1 P1	ADC2 P3	$3.36 \cdot 10^{-4}$	$3.36 \cdot 10^{-4}$
Imager filter 1	Imager filter 1	$4.26 \cdot 10^{-4}$	$1.18 \cdot 10^{-6}$
Imager filter 2	Imager filter 2	$4.26 \cdot 10^{-4}$	$1.18 \cdot 10^{-6}$
Imager Window	Imager Window	$4.26 \cdot 10^{-4}$	$8.41 \cdot 10^{-7}$
Imager Window	Imager Chip	$1.96 \cdot 10^{-3}$	$4.88 \cdot 10^{-7}$
Imager Filter 1	Imager Filter 2	$1.54 \cdot 10^{-3}$	$8.92 \cdot 10^{-8}$
LGS Dichroic	LGS Dichroic	$4.01 \cdot 10^{-4}$	$6.78 \cdot 10^{-8}$
Imager Filter 2	Imager Window	$1.52 \cdot 10^{-3}$	$2.10 \cdot 10^{-8}$
Imager Filter 2	Imager Chip	$1.81 \cdot 10^{-3}$	$1.60 \cdot 10^{-8}$
Off-axis source at 21.2 arcsec			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
ADC1 P3	ADC2 P1	$4.02 \cdot 10^{-4}$	$4.02 \cdot 10^{-4}$
ADC1 P1	ADC2 P3	$3.35 \cdot 10^{-4}$	$3.35 \cdot 10^{-4}$
Imager filter 1	Imager filter 1	$2.36 \cdot 10^{-4}$	$1.06 \cdot 10^{-6}$
Imager filter 2	Imager filter 2	$2.36 \cdot 10^{-4}$	$1.06 \cdot 10^{-6}$
Imager Window	Imager Window	$2.04 \cdot 10^{-4}$	$7.35 \cdot 10^{-7}$
Imager Window	Imager Chip	$5.04 \cdot 10^{-4}$	$4.44 \cdot 10^{-7}$
Imager Filter 1	Imager Filter 2	$3.26 \cdot 10^{-4}$	$8.51 \cdot 10^{-8}$
LGS Dichroic	LGS Dichroic	$1.24 \cdot 10^{-4}$	$6.95 \cdot 10^{-8}$
Imager Filter 2	Imager Window	$2.90 \cdot 10^{-4}$	$2.06 \cdot 10^{-8}$
Imager Filter 2	Imager Chip	$3.33 \cdot 10^{-4}$	$1.64 \cdot 10^{-8}$

Table 3.8: Highest irradiance ghost paths for the SCI channel.

NGS channel ghosts Simulations for the NGS channel were also performed for the monochromatic source at $\lambda = 1400nm$. The sources were located in three positions: an on-axis source and sources at 30 and 60 arcsec off-axis.

The detector located at the NGS focal plane is slightly oversized with respect to the NGS FoV, and has a size of 125×125 arcsec, leading to a pixel pitch of $200\mu\text{m}$ (250 mas).

The assumptions regarding the coatings for the NGS channel elements are reported in Table 3.9.

Element	Surface	Coating
NGS Dichroic	NGS Dichroic S1	I.98
	NGS Dichroic S2	I.98
NGS Objective L1	NGS Objective L1S1	I.98
	NGS Objective L1S2	I.98
NGS Objective L2	NGS Objective L2S1	I.98
	NGS Objective L2S2	I.98
NGS Objective L3	NGS Objective L3S1	I.98
	NGS Objective L3S2	I.98

Table 3.9: Coating assumptions for each optical surface in the NGS channel. I.xx means an ideal coating.

The worst paths in terms of peak irradiance are reported in Table 3.10. There are three focused ghosts produced by the NGS dichroic and the ADC prisms. Despite this, their relative irradiance remains within the requirements.

On-axis source			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
ADC1 P3	ADC2 P1	$4.0 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$
NGS Dichroic S1	NGS Dichroic S2	$3.98 \cdot 10^{-4}$	$3.98 \cdot 10^{-4}$
ADC1 P1	ADC2 P3	$3.19 \cdot 10^{-4}$	$3.19 \cdot 10^{-4}$
LGS Dichroic S1	LGS Dichroic S2	$3.85 \cdot 10^{-4}$	$4.07 \cdot 10^{-6}$
NGS Objective L1	NGS Objective L2	$4.21 \cdot 10^{-4}$	$2.64 \cdot 10^{-6}$
NGS Objective L3	NGS Objective L3	$4.07 \cdot 10^{-4}$	$7.51 \cdot 10^{-9}$
Off-axis source at 30 arcsec			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
ADC1 P3	ADC2 P1	$4.0 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$
NGS Dichroic S1	NGS Dichroic S2	$3.98 \cdot 10^{-4}$	$3.98 \cdot 10^{-4}$
ADC1 P1	ADC2 P3	$3.19 \cdot 10^{-4}$	$3.19 \cdot 10^{-4}$
LGS Dichroic S1	LGS Dichroic S2	$3.87 \cdot 10^{-4}$	$4.39 \cdot 10^{-6}$
NGS Objective L1	NGS Objective L2	$4.16 \cdot 10^{-4}$	$2.87 \cdot 10^{-6}$
NGS Objective L3	NGS Objective L3	$4.07 \cdot 10^{-4}$	$7.50 \cdot 10^{-9}$
Off-axis source at 60 arcsec			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
ADC1 P3	ADC2 P1	$3.94 \cdot 10^{-4}$	$3.94 \cdot 10^{-4}$
NGS Dichroic S1	NGS Dichroic S2	$3.98 \cdot 10^{-4}$	$3.98 \cdot 10^{-4}$

ADC1 P1	ADC2 P3	$3.08 \cdot 10^{-4}$	$3.08 \cdot 10^{-4}$
LGS Dichroic S1	LGS Dichroic S2	$3.85 \cdot 10^{-4}$	$5.46 \cdot 10^{-6}$
NGS Objective L1	NGS Objective L2	$3.99 \cdot 10^{-4}$	$9.53 \cdot 10^{-7}$
NGS Objective L3	NGS Objective L3	$4.05 \cdot 10^{-4}$	$7.40 \cdot 10^{-9}$

Table 3.10: Highest irradiance ghost paths for the NGS channel.

LGS channel ghosts The simulation for the LGS channel was conducted for three cases of the LGS sources conjugations – 80, 155 and 230 km. The source is monochromatic at $\lambda = 589nm$ and located $17.5''$ off-axis in all of the cases. The detector used in the simulation is slightly oversized with respect to the LGS FoV, and has a size of 46.5×46.5 arcsec, with a pixel pitch of $64\mu m$ (186 mas). The assumptions regarding the coatings are reported in Table 3.11.

Element	Surface	Coating
LGS Dichroic	LGS Dichroic S1	I.00
	LGS Dichroic S2	I.98
LGS Objective L1	LGS Objective L1S1	I.99
	LGS Objective L1S2	I.99
LGS Objective L2	LGS Objective L2S1	I.99
	LGS Objective L2S2	I.99
LGS Objective L3	LGS Objective L3S1	I.99
	LGS Objective L3S2	I.99

Table 3.11: Coating assumptions for each optical surface in the LGS channel. I.xx means an ideal coating.

The worst paths in terms of peak irradiance are reported in Table 3.12. There are no focused ghosts in this channel.

LGS at 80 km			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
Collimator L1	LGS Objective L3	$1.21 \cdot 10^{-4}$	$3.98 \cdot 10^{-5}$
Field lens L2	Collimator L1	$3.05 \cdot 10^{-4}$	$1.48 \cdot 10^{-6}$
Field lens L1	Collimator L1	$4.11 \cdot 10^{-5}$	$8.35 \cdot 10^{-7}$
Field lens L2	LGS Objective L3	$7.34 \cdot 10^{-5}$	$6.80 \cdot 10^{-7}$
Collimator L1	LGS Objective L2	$3.32 \cdot 10^{-5}$	$2.12 \cdot 10^{-7}$
LGS Objective L2	LGS Objective L3	$1.99 \cdot 10^{-5}$	$2.07 \cdot 10^{-7}$
LGS at 155 km			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
Field lens L2	Collimator L1	$2.93 \cdot 10^{-4}$	$1.45 \cdot 10^{-6}$
Field lens L1	Collimator L1	$9.46 \cdot 10^{-6}$	$7.20 \cdot 10^{-7}$
Collimator L1	LGS Objective L3	$5.72 \cdot 10^{-5}$	$3.98 \cdot 10^{-7}$

Field lens L2	LGS Objective L3	$4.58 \cdot 10^{-5}$	$2.59 \cdot 10^{-7}$
Field lens L2	LGS Objective L2	$1.11 \cdot 10^{-5}$	$1.64 \cdot 10^{-7}$
LGS Objective L2	LGS Objective L3	$1.24 \cdot 10^{-5}$	$1.61 \cdot 10^{-7}$
LGS at 230 km			
1st object	2nd object	Ghost/Image power	Ghost/Image irradiance
Field lens L2	Collimator L1	$2.8 \cdot 10^{-4}$	$1.32 \cdot 10^{-6}$
Collimator L1	LGS Objective L3	$4.04 \cdot 10^{-5}$	$2.51 \cdot 10^{-7}$
Field lens L2	LGS Objective L3	$3.97 \cdot 10^{-5}$	$2.13 \cdot 10^{-7}$
LGS Objective L1	LGS Objective L2	$8.38 \cdot 10^{-6}$	$1.69 \cdot 10^{-7}$
LGS Objective L2	LGS Objective L3	$1.05 \cdot 10^{-5}$	$1.51 \cdot 10^{-7}$
Field lens L2	LGS Objective L3	$1.0 \cdot 10^{-5}$	$1.36 \cdot 10^{-7}$

Table 3.12: Highest irradiance ghost paths for the LGS channel.

3.4 Dichroic coating performance and requirement verification

As an MCAO-assisted instrument, MAVIS will correct the wavefront using measurements from the NGS and the LGS modules. These modules operate at different wavelengths than those of the scientific instrumentation. This requires dichroic components with a proper coating on the light path in the system.

A dichroic is usually a glass plate with one reflective surface, designed to work at a specific angle of incidence (AOI). A dichroic coating is a type of dielectric coating, typically multilayered, that selectively transmits or reflects specific wavelengths. Depending on the application, there are different types of dichroic mirrors, such as longpass, shortpass, notch or multi-band mirrors.

The working principle of a dichroic is very similar to that of a beam splitter, with the key difference being that the light is split by wavelength rather than by intensity. This effect results from the interference phenomenon: part of the light entering the first layer of the coating is reflected while another portion is transmitted, and then partially reflected from the second layer, and so on. The constructive or destructive interference pattern depends on the film thickness and the AOI. The schematic image of a multilayer dichroic coating is shown in Fig. 3.42. Whether the waves interfere destructively or constructively depends on the optical path difference (OPD):

$$L = m \cdot \lambda \quad (3.34)$$

If the OPD is an integer multiple of the wavelength, the resulting interference will be constructive, leading to stronger reflection. If m instead is a half-integer, the waves will interfere destructively.

Both substrates of the dichroic mirrors of MAVIS are made of fused silica glass. While the type of dichroic coating on the first surface differs due to their different

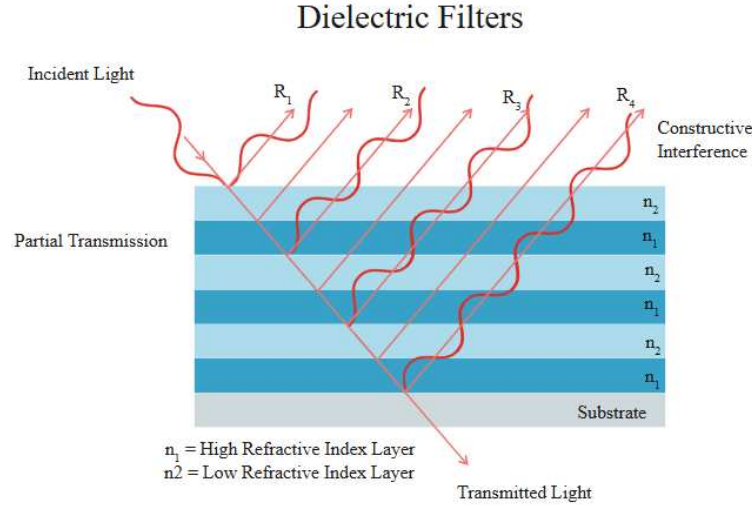


Figure 3.42: Multilayer dielectric coating working principle. Partial reflections and transmissions happen at each layer. Credit: Meetoptics

purposes, the second surface of both dichroics is coated with a high-transmission anti-reflection (AR) coating.

The first dichroic encountered by the beam is the LGS dichroic, located after the collimator, which reflects the 589 nm wavelength to the LGS WFS module and transmits all other wavelengths. The diameter of the dichroic is 94 cm, with a clear aperture of > 84 cm. The angle of incidence at which the dichroic operates is 25° with a tolerance of 1° for visible light. The purpose of this dichroic sets demanding requirements for the coating of its surfaces. Main coating specifications are reported in Table 3.13.

Surface 1. Reflective notch coating	$T_{avg} > 98\%$ for 370-580 nm, $AOI = 25^\circ \pm 1^\circ$ $T_{avg} > 98\%$ for 598-1000 nm, $AOI = 25^\circ \pm 1^\circ$ $T_{avg} > 98\%$ for 1000-1740 nm, $AOI = 25^\circ \pm 2.5^\circ$ $R_{avg} > 98\%$ at 589 nm, $FHWM < 15nm$, $AOI = 25^\circ \pm 1^\circ$
Surface 2. BBAR coating	$R_{avg} < 1.5\%$ for 370-1740 nm $A_{avg} < 0.5\%$ for 370-1740 nm

Table 3.13: Coating specifications for the LGS dichroic.

The second dichroic is located after the K-mirror and is larger, with a diameter of 200 cm. This is the NGS dichroic that operates as a longpass filter, transmitting the NIR part of the spectrum to the NGS WFS module, and reflecting wavelengths from 370 to 935 nm to the SCI channel. The dichroic is placed in the collimated beam and its operating AOI is 20° . Coating specifications for the element are reported in Table 3.14.

The out of band coating ripple shall be better than $0.5\%/\text{\AA}$ for spectral scales

Surface 1. Dichroic coating	$T_{avg} > 98\%$ for 960-1740 nm, $AOI = 20^\circ \pm 2.3^\circ$ $R_{avg} > 98\%$ for 370-935 nm, $AOI = 20^\circ \pm 0.85^\circ$ Transition region: 935-960 nm
Surface 2. BBAR coating (NIR)	$R_{avg} < 0.5\%$ for 960-1740 nm $A_{avg} < 0.5\%$ for 960-1740 nm

Table 3.14: Coating specifications for the NGS dichroic.

$< 1\text{\AA}$ for both dichroic coatings. This shall apply for more than 98% of the covered wavelength range.

The specification documents for both dichroics were sent to the manufacturing companies. However, before placing an order, we should verify their coating designs. For this purpose, dedicated software written in python was developed and can be found on GitHub at the link <https://github.com/alphaCassi/OpticalDesignAnalyses/Tools>.

The software is written in the OOP style and contains the main class named *DichroicSpectra*. Input parameters for this class are the path and the filename of the data table containing wavelength and transmission or reflection coefficients of a coating design. There are several methods that allow a full analysis of the data. The description of the methods is as follows:

1. *LoadData()*: This function provides checks for the file extension and loads it accordingly. Supported formats are '.xlsx', '.xls', '.xslm', '.txt', '.csv'. One can choose which sheet and columns to load if the file contains more than one sheet or two columns. After the data is loaded, it is converted into Numpy arrays for easier processing.
2. *PlotRawData()*: A simple plotting feature for the data, that allows one to plot the transmission or reflection curve and organise the plot area as needed. This includes setting coordinate limits, grids, labels, titles, and changing line thicknesses or colours. The corresponding variables to activate these personalised changes should be stated as input parameters. Examples of the theoretical coating curves for MAVIS' dichroics are shown in Fig. 3.43.
3. *MeanTranRef()*: This method used to calculate the mean transmission or reflection over a given wavelength range.
4. *Ripple()* and *PlotRipple()*: Two methods whose main purpose is to calculate and plot ripple, $\Delta T(\lambda)/\Delta\lambda$, respectively. They use the *Mask()* function to choose the region, where to calculate the ripple. By default, all data is considered in the calculations. Another key feature is the check for the presence of a notch, and if that is true, the notch region is left out of the calculation. The output of the method is 98th-percentile value of the ripple over a given wave-

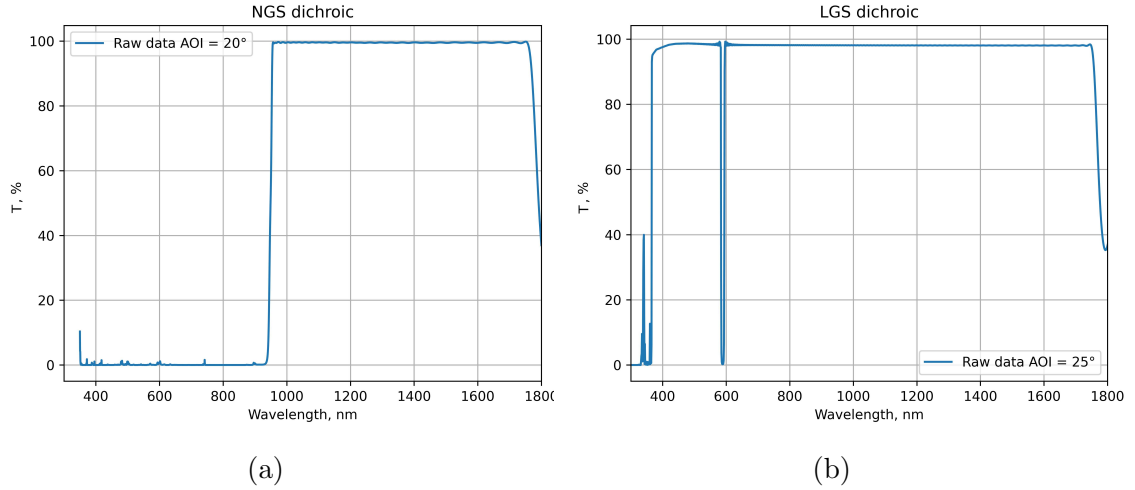


Figure 3.43: Theoretical curves of (a) the NGS and (b) the LGS dichroics of MAVIS. Coating data provided by Chroma Technology Corp. and Materion Balzers Optics.

length range and the percentage of the out-of-band ripple if some threshold is given. An example of the ripple plot is shown in Fig. 3.44.

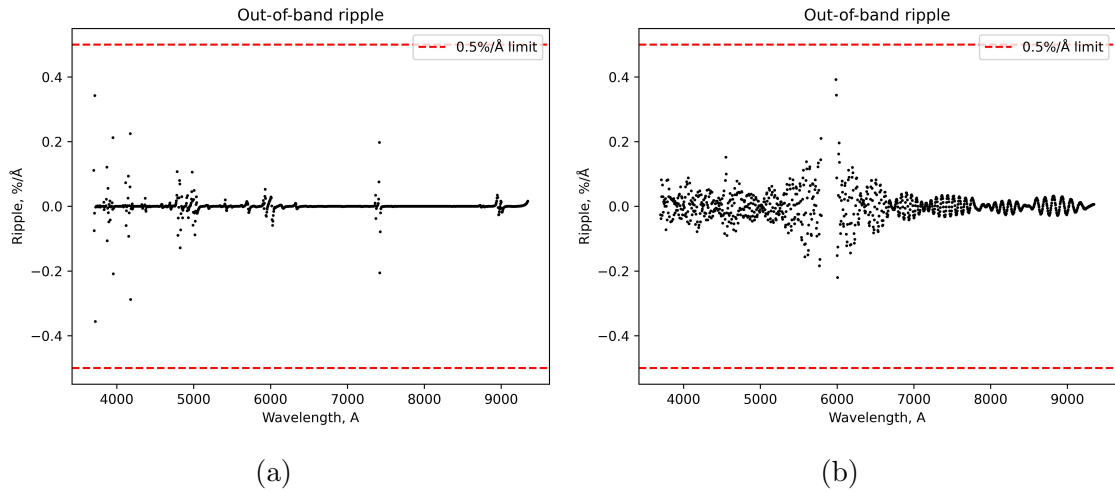


Figure 3.44: Coating ripple plot of (a) the NGS and (b) the LGS dichroics of MAVIS. Horizontal lines denote the out of band ripple threshold. Coating data provided by Chroma Technology Corp..

5. *FitNotch()*: This method is used to fit and calculate the FWHM of the notch for the notch dichroic coating. Although a simple notch can be successfully fitted with a Gaussian profile, this is not always the case in practice. The function uses a machine learning method to find the best fit of the notch, based on the Gaussian Process Regressor. The Gaussian process is a non-parametric supervised learning method that is typically used for solving regression or classification problems. To obtain the best fit of the data, the user can specify

different kernels or optimizers that can be restarted multiple times. Given that our theoretical coating data were noiseless, no noise tuning parameter was implemented. However, it can be added in future developments. After the fit is done, it identifies the maximum and calculates the FWHM, accordingly. An example of the fitted notch can be seen in Fig. 3.45.

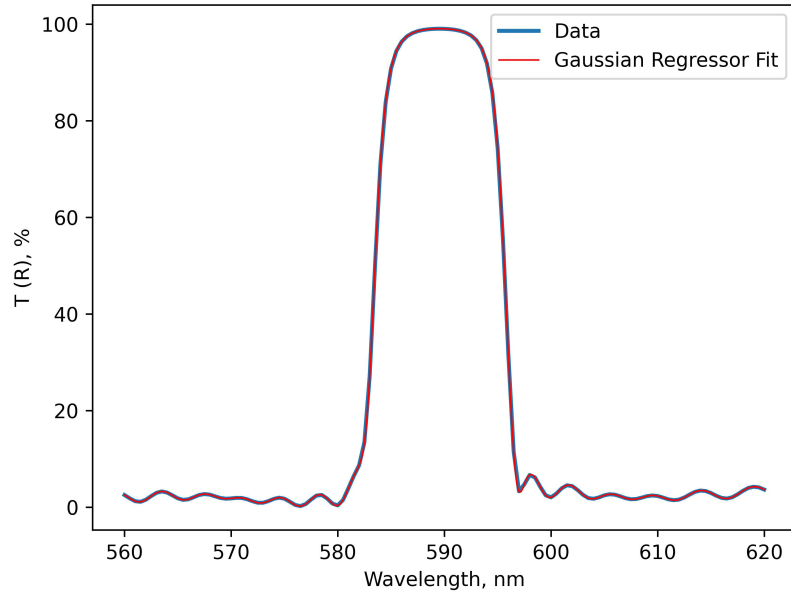


Figure 3.45: Notch fitting of the LGS dichroic coating curve.

6. *FindTransitionRegion()*: The function searches for the transition region using the derivative method and calculates its width. It is used for longpass or shortpass filters. It can be especially useful when constraints on the transition region arise from scientific applications that may be affected by changes in transmission. An example of the detected transition region in the coating of the NGS dichroic is shown in Fig. 3.46.
7. *OpticalDensity()*: As the name suggests, this method calculates the optical density, $OD = -\lg \frac{T}{100}$, of a coating in the specified region. Note that transmission T should be expressed in percent, as this function does not yet provide automatic check or conversion of data units.
8. *ResolutionSelection()*: This function allows the user to select the resolution of the data by filtering it.
9. *LocalMaximum()*: This method seeks peaks or spikes in the coating data. This function, in combination with others, can be used to analyse spike ripples that may occur in high resolution multilayer coatings due to unwanted light interference from different layers. An example of such spikes is shown in Fig. 3.47.

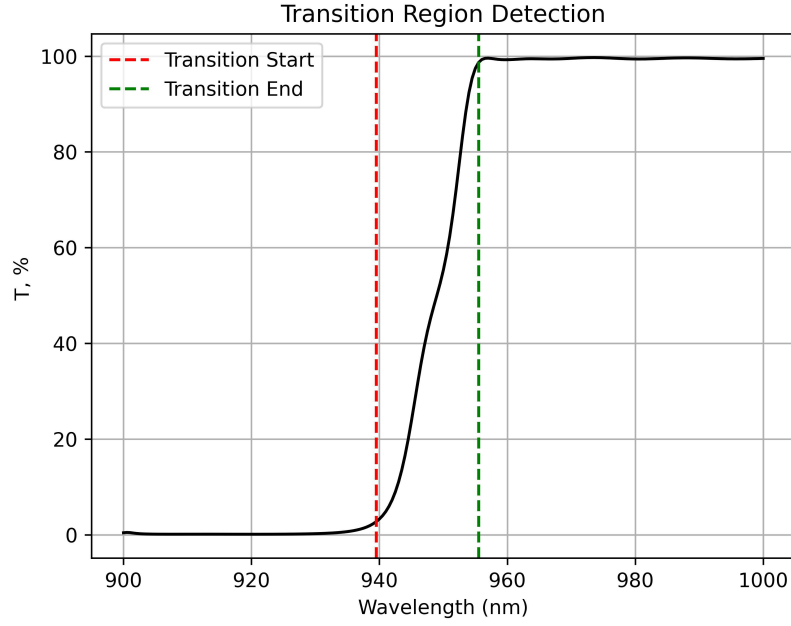


Figure 3.46: Detection of the transition region in the longpass NGS dichroic coating.

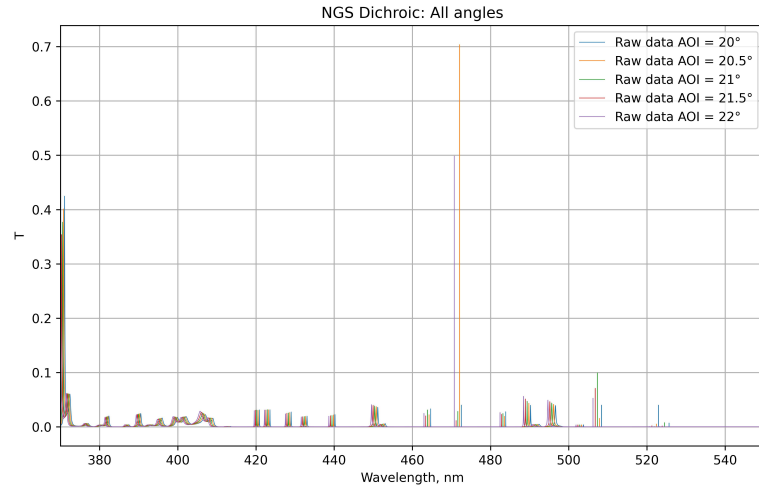


Figure 3.47: High-resolution ripple spikes present in part of the coating curve of the NGS dichroic. Spectral resolution $\Delta\lambda/\lambda = 1\text{\AA}$. Coating data provided by ANU Research School of Physics.

Several coating designs from different companies were analysed using the aforementioned software. Such analysis enabled the selection of the best design within the given tolerances for the coatings of MAVIS' dichroics.

Although the software was developed primarily for dichroic coating analysis and contains some specific functionality, its general methods can be used for any kind of coating data with equal effectiveness.

Summary: AOM optical analyses

This chapter summarises various analyses that were done prior to the FDR of MAVIS. The major part was related to the distortions evaluations, including MSF-induced and differential distortions between channels. This work together with subsequent simulation by the astrometry team allowed us to verify the compliance of MAVIS with the astrometric requirement. The final astrometric error, including all relevant sources of errors in addition to distortions, was confirmed to remain within $150\mu s$. Additionally, the results from the MSF distortion simulation supported the definition of the frequency of day-time and night-time astrometric calibration with the ACM.

The differential distortion analysis instead pointed out a large contribution originating from the ADC. As a result, this element was re-designed maintaining the same dispersion correcting performance while reducing the distortion residuals. This updated design was subsequently integrated to the final AOM design.

The analyses of image uniformity, in-field scattering, and ghosts demonstrated that the instrument meets the corresponding requirements.

Given the complexity of the dichroics in the AOM, interactions with the manufacturers were carried out throughout Phases B and C. The software I developed was used to verify coating designs and check their compliance with the required specifications. These results were used to select the most suitable manufacturer.

Chapter 4

Verification Test Bench

The operational wavelength range of MAVIS covers the visible part of the spectrum. Wavefront correction in the visible is a very challenging task. Hence, we need to rigorously test MAVIS and ensure its seamless integration into operational workflows before its on-sky deployment. For this reason, we have developed a dedicated Verification Test Bench (VTB)^[91]. The VTB serves as an internal tool during the Assembly, Integration, and Testing (AIT) phase. It plays a pivotal role in conducting essential tests related to WFE correction by providing a ground-conjugated DM. In normal operation on the VLT, the DSM of the telescope will function as this ground layer DM, hence the need for this alternative during AIT. The presence of such a tool will enable tests and verification activities in the laboratory that would not otherwise be possible until MAVIS is installed on the VLT. This capacity to undertake a more comprehensive test campaign in the laboratory will make a significant contribution to the overall robustness and effectiveness of MAVIS once it is on the telescope.

The tests that the MAVIS team intends to undertake with the VTB can be divided into three groups:

Functional Verification of AO loops

This includes comprehensive testing of all loops in which the DSM acts as the correcting element. The main focus is the functionality of the MCAO loop, covering tests related to the performance of the high-order loop or, for instance, the active vibration control. Other tests will verify the performance of the focus compensation loop, the pupil steering loop, and the NCPA loop.

End-to-End Testing Scenarios

These tests encompass various operational cases such as the verification of the Synthetic Interaction Matrix (IM), misregistration estimation, including X-Y shifts, rotation and magnification, and evaluation of the differential rotation commands between the VTB Deformable Mirror (VDM) and the LGS compared to the other DMs. The objective is to ensure accurate command, measurement, and differentiation between the High and Low DMs.

High Level software testing with the Real-Time Computer

This involves all procedures associated with adaptive optics loop management, including loop closure, pausing of the NGS tracking loops, and subsequent loop reclosure. These tests are critical for verifying the robustness and reliability of the RTC in managing complex adaptive optics operations.

4.1 Optical design of the VTB

Given the purpose of the VTB, it should emulate the characteristics of the VLT Nasmyth focal plane, where MAVIS will be installed. This leads to the following optical design requirements:

- Aperture ratio: F/15
- Focal plane curvature radius: 2089 mm concave towards the telescope
- Exit pupil position: 16.7 m before the focal plane.

Moreover, the VTB should allow the simultaneous use of the NGS and LGS sources. The LGS sources should be provided with a continuous range of conjugation between 80 km and 230 km.

It is desirable to keep the VTB as simple as possible, while keeping its capability for all the required testing. Due to this, the working FoV is reduced compared to the full technical field of MAVIS, which is 2 arcmin. The FoV for the infinity-conjugated sources is 30 arcsec radial for the NGS and 30×30 arcsec squared for the SCI sources, respectively. The FoV of the LGS is 25 arcsec.

The working wavebands are limited as follows:

- SCI: 0.48-0.65 μm
- NGS: 1.1 - 1.6 μm
- LGS: 0.589 μm

All design considerations here assume the use of replicas of the CU sources at the VTB input, specifically the NGS/NCPA and LGS calibration sources. The NGS/NCPA CU sources are two sets of high power LEDs. One set emits at a peak wavelength at 1150 nm with the FWHM of 120 nm, while the second set emits at a peak wavelength of 1550 nm with the FWHM of 240nm. The LGS calibration source is the fiber-coupled high-power LED with a peak wavelength of 590 nm and the FWHM of 120 nm. All sources used for the VTB, once it is built, should be bright enough to allow the AO loop to close at 1 kHz. Additionally, the lower brightness limit of the NGS sources should enable the simulation of stars with an R magnitude of 19.

Following the VTB requirements specified by the system engineer, I developed two options for the optical design of the VTB, with the principal difference being the

deformable mirror used. Initially, there were two DMs under consideration: ALPAO DM277 and ALPAO DM820. I present both designs, comparing their characteristics and performance, which determined the final choice of the DM.

Nevertheless, both options follow the same structure (see fig. 4.1). A beam combiner will allow the simultaneous use of the NGS/SCI and LGS sources. Subsequently, a group of lenses will be used to collimate the light of the NGS/SCI sources, ensuring the proper beam size to fully illuminate the DM pupil. The next element is a physical mask adjacent to the DM that serves the purpose of reproducing the telescope aperture and the obstruction from the secondary mirror. The final group of lenses will focus the light onto the output focal plane. It is also planned to use goniometric stages for rotation of the LGS sources and of the DM pupil. The required rotation of the DM and LGS sources is in the range of 60 degrees with respect to the AOM.

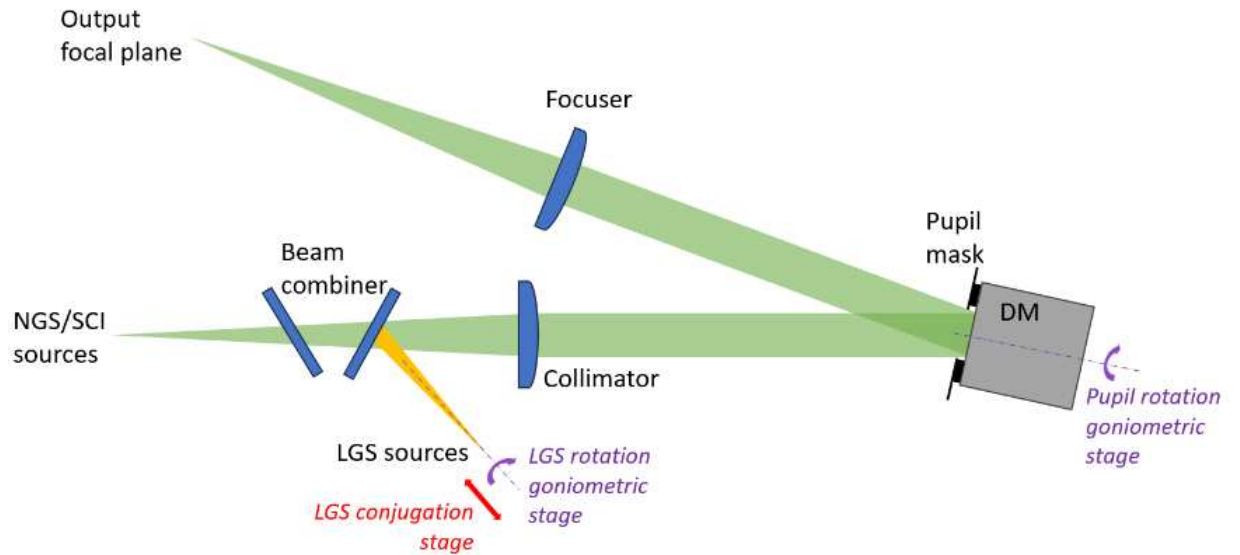


Figure 4.1: Schematic view of the VTB optical design.

As mentioned above, the driving element for the design development is the DM. From an optical design perspective, the size of the DM has a significant impact because it influences the size of the other optical elements, the total track length and the incidence angle on the DM. The optical design layout for the case with DM277 is shown in fig. 4.2a, whereas fig. 4.2b displays the layout for the VTB with the DM820.

The ALPAO DM277 is a smaller DM with a pupil size of 24.5 mm with a 1.5 mm pitch between actuators. The total number of actuators is 277. Its smaller size allows the VTB to remain quite compact, which is an advantage. The lenses are relatively small, with the largest being the beam combiner, which has a clear semi-diameter of 60 mm. The folding angle of the DM is 20 deg.

Meanwhile, the ALPAO DM820 has a pupil size of 45 mm with a 1.5 mm pitch between actuators. The total number of actuators is 820. This increases the size of

the lenses by a factor of ~ 1.4 . However, given that the lenses are slightly further from the pupil, it allows for a narrower folding angle, which helps to reduce the projection effects of the pupil mask on the DM. The angle in this case is equal to 16 deg. All the lenses used in both design options have standard spherical surfaces.

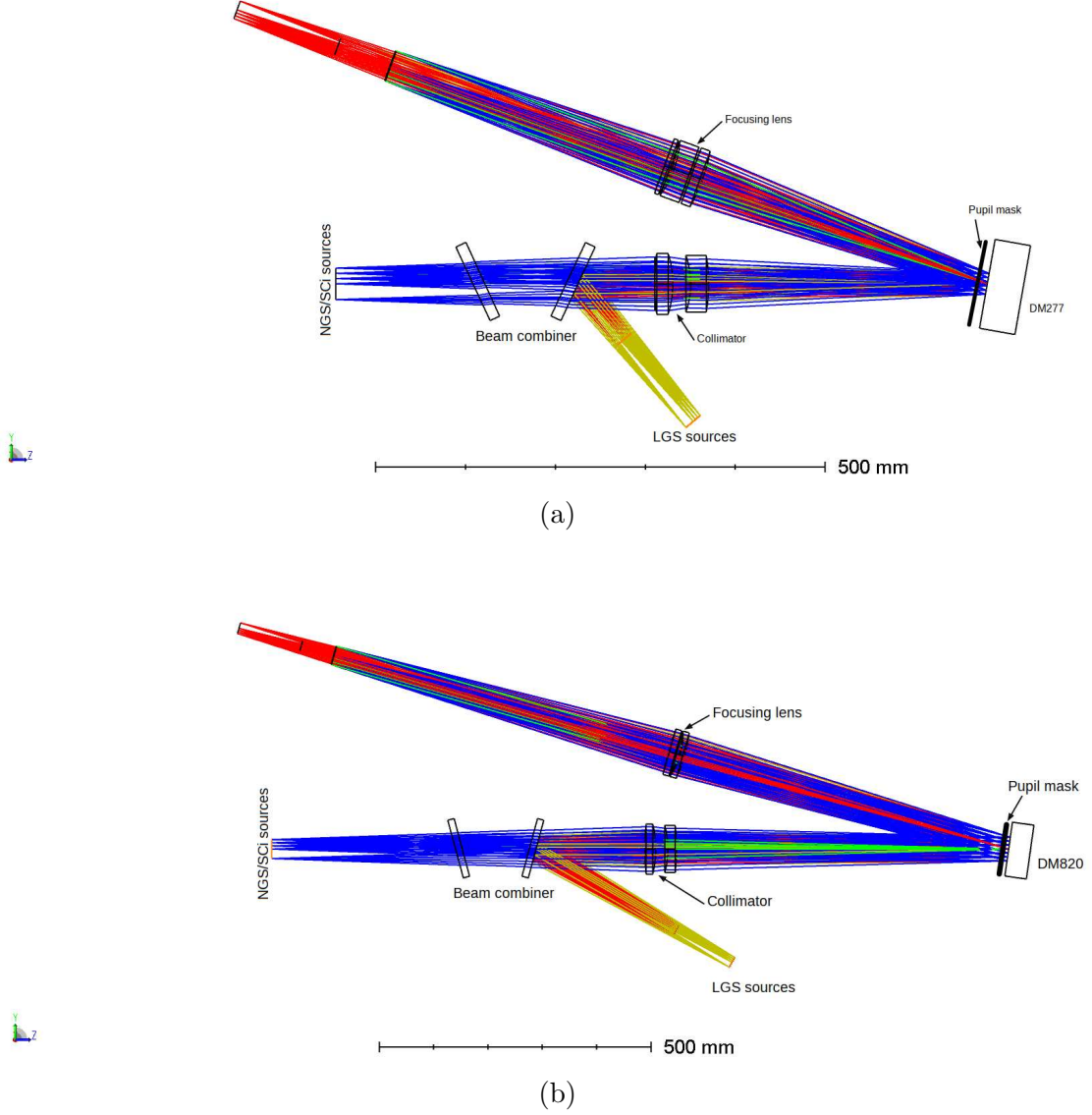


Figure 4.2: Optical design layouts of the VTB. (a) ALPAO DM277; (b) ALPAO DM820.

Figure 4.3 illustrates the optical performance in terms of RMS wavefront error. The plots depict wavefront errors (WFE) as a function of field across all the wavelengths specified above. Overall, the ALPAO DM820 delivers better WFE performance across the field in all the configurations. A particularly significant reduction in RMS WFE is achieved at infrared and sodium wavelengths, the latter being used for the LGS sources.

Table 4.1 summarises the performance of the VTB for each DM considered. The average wavefront errors computed for both designs are polychromatic and calcu-

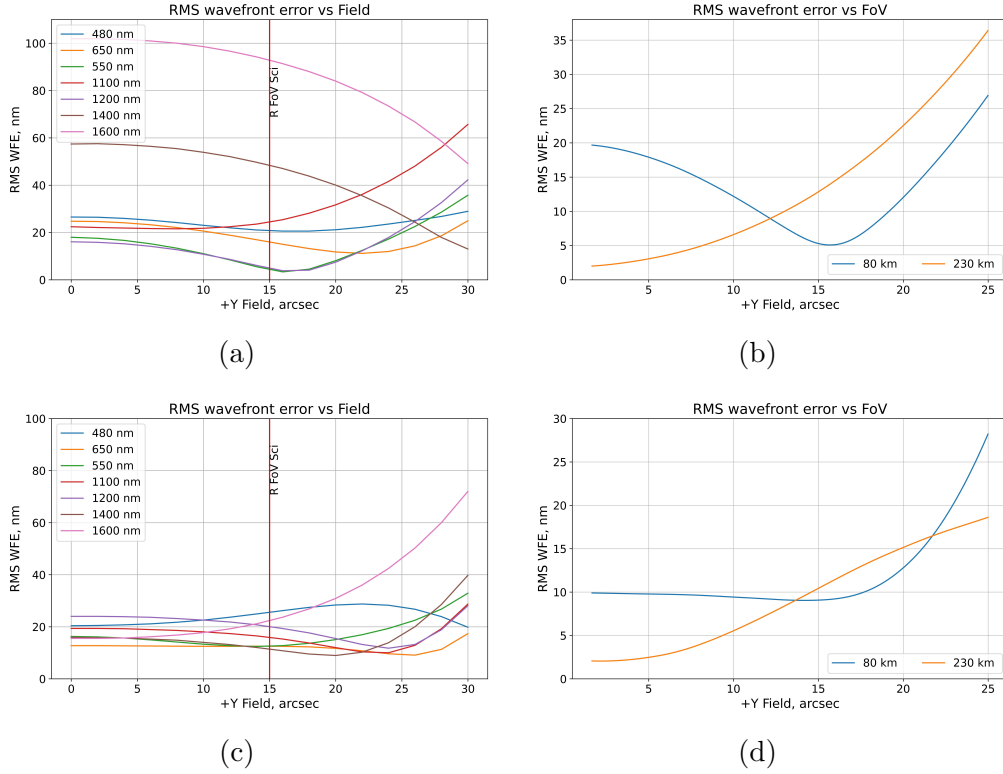


Figure 4.3: The RMS wavefront error of the VTB, utilising ALPAO DM277 (a) and (b), and ALPAO DM820 (c) and (d).

lated over the full field of view corresponding to each configuration. The second parameter taken into account for the comparison is the maximum distortion, estimated at the maximum field of view. The wavelengths at which the distortion is maximum are 480 nm for the SCI configuration, 1100 nm for NGS, and 589 nm for LGS configurations. The last parameter we compare is the focus extraction (back focal distance of the focusing lens), which is critical due to the space limitations of the location where the VTB will be installed.

Configuration Parameter	SCI	NGS	LGS@80km	LGS@230km
Average WFE, nm rms	27.455/ 27.583	64.505/ 31.439	14.160/ 12.290	13.735/ 9.287
Max distortion, %	0.171/ 0.052	0.147/ 0.032	-0.105/ -0.0082	-0.0077/ 0.007
Focus extraction, mm	320.713/ 641.382	321.737/ 642.061	502.568/ 823.237	383.514/ 704.183

Table 4.1: Comparative table of the optical design options of the VTB. Black numbers - DM277; red - DM820

Although the optical solution with the ALPAO DM820 provides better performance, both designs remain diffraction-limited. The main advantage of using the smaller DM277 is its compact size, which meets the limited space requirements and helps reduce overall costs.

The availability of the ALPAO DM277 and of the software to control it on-site

led to the final selection of this design option. Given that the main purpose of the VTB is to test and verify the performance of the AOM, it is also important to have an easy way to align it in the laboratory settings. For this reason, two steering mirrors were incorporated in the optical layout and the distance from the last optical element was kept ≥ 20 cm. The radii of curvature and thicknesses were slightly adjusted due to the increase in focal extraction. The final optical design layout is presented in Fig. 4.4.

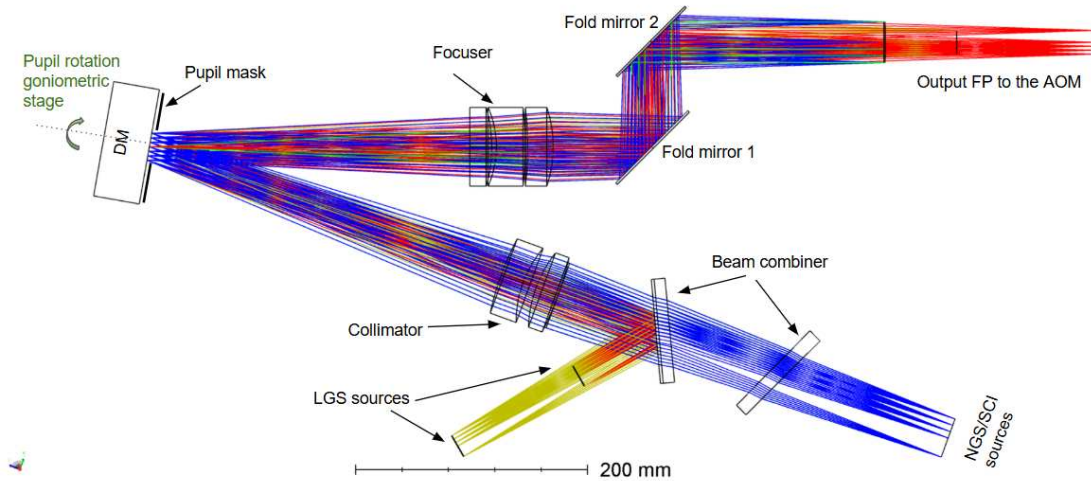


Figure 4.4: Optical design layout of the VTB including two steering mirrors.

Optical components of this design include two plates made of fused silica, together creating the beam combiner, an air-spaced doublet made of S-FPL51 and N-KZFS4 glasses that collimates the light of the infinity-conjugated sources, and three lenses made of S-FPM3 and N-KZFS4 to focus the beam. Table 4.5 reports the optical prescription data for the VTB design.

The position of the pupil mask is defined by the lateral shift s of the reflected beam footprint. This shift occurs due to the tilt of the DM, and can be defined as

$$s = \theta \cdot d, \quad (4.1)$$

where θ is the deflection angle operated by the mirror, in radians, and d is the distance between the reflecting surface and the stop.

If we impose the condition of s to be smaller than 1% of the pupil diameter D , we get that the distance to the pupil mask should be smaller than

$$d < \frac{0.01D}{\theta} \quad (4.2)$$

Considering the ALPAO DM277 pupil size of 24.5 mm, the distance to the mask should be $d < 1.4$ mm.

The focal extraction from the last optical element, the Fold mirror 2, is required to be at least 20 cm for the calibration sources considered. These data are reported in Table 4.2.

	Surface Type	Comment	RoC, mm	Thickness, mm	Material	Coating	Semi-Diameter, mm	Mech Semi-Dia, mm	Tilt about X, deg
0	STANDARD		Infinity	0.00E+00			17.45	17.45	0.00
1	COORDBRK		Infinity	1.57E+02			0.00	0.00	0.00
2	COORDBRK	Element Tilt	Infinity	0.00E+00			0.00	0.00	-25.00
3	STANDARD	Beam Combiner L1S1	Infinity	1.20E+01	F_SILICA	I.98	60.00	60.00	0.00
4	IRREGULA	Beam Combiner L1S2	Infinity	0.00E+00		I.98	60.00	60.00	0.41
5	COORDBRK	Element Tilt:return	Infinity	9.50E+01			0.00	0.00	25.00
6	COORDBRK	Element Tilt	Infinity	0.00E+00			0.00	0.00	25.00
7	IRREGULA	Beam Combiner L2S1	Infinity	1.20E+01	F_SILICA	I.98	60.00	60.00	0.27
8	STANDARD	Beam Combiner L2S2	Infinity	0.00E+00		I.98	60.00	60.00	0.00
9	STANDARD	Beam Combiner L2S2	Infinity	0.00E+00	MIRROR	I.05	60.00	60.00	0.00
10	COORDBRK	Element Tilt:return	Infinity	0.00E+00			0.00	0.00	-25.00
11	COORDBRK		Infinity	9.00E+01			0.00	0.00	0.00
12	STANDARD	Collimator L1S1	2.53E+02	2.00E+01	S-FPL51	I.98	30.00	34.00	0.00
13	STANDARD	Collimator L1S2	-1.12E+02	1.36E+01		I.98	30.00	34.00	0.00
14	STANDARD	Collimator L2S1	-1.00E+02	2.00E+01	N-KZFS4	I.98	30.00	34.00	0.00
15	STANDARD	Collimator L2S2	-2.71E+02	0.00E+00		I.98	30.00	34.00	0.00
16	STANDARD		Infinity	2.74E+02			25.32	25.32	0.00
17	COORDBRK		Infinity	0.00E+00			0.00	0.00	10.00
18	STANDARD	ALPAO DM277	Infinity	0.00E+00	MIRROR	OTECTED_SILV	11.80	11.80	0.00
19	COORDBRK		Infinity	0.00E+00			0.00	0.00	10.00
20	STANDARD		Infinity	-2.76E+02			11.80	11.80	0.00
21	STANDARD	Focuser L1S1	2.18E+04	-1.90E+01	S-FPM3	I.98	30.00	34.00	0.00
22	STANDARD	Focuser L1S2	1.23E+02	-4.00E+00		I.98	30.00	34.00	0.00
23	STANDARD	Focuser L2S1	8.37E+01	-2.50E+01	N-KZFS4	I.98	30.00	34.00	0.00
24	STANDARD	Focuser L2S2	2.79E+02	-2.00E+00		I.98	30.00	34.00	0.00
25	STANDARD	Focuser L3S1	2.80E+02	-2.20E+01	S-FPM3	I.98	30.00	34.00	0.00
26	STANDARD	Focuser L3S2	1.06E+02	-8.50E+01		I.98	30.00	34.00	0.00
27	COORDBRK		Infinity	0.00E+00			0.00	0.00	-45.00
28	STANDARD		Infinity	0.00E+00	MIRROR	I.05	44.00	44.00	0.00
29	COORDBRK		Infinity	9.00E+01			0.00	0.00	-45.00
30	COORDBRK		Infinity	0.00E+00			0.00	0.00	45.00
31	STANDARD		Infinity	0.00E+00	MIRROR	I.05	42.00	42.00	0.00
32	COORDBRK		Infinity	-2.00E+02			0.00	0.00	45.00
33	STANDARD		2.09E+03	0.00E+00			17.47	17.47	0.00

Figure 4.5: Optical design prescription data of the VTB.

Sources	Focal extraction, mm
SCI	200.274
NGS	201.392
LGS@80km	382.129
LGS@230km	263.075

Table 4.2: Focal extraction of the VTB for all configurations.

4.1.1 Preliminary throughput estimation

The throughput of the VTB is required to be not less than 20% for the visible and the LGS sources. Given the small number of optical components, this does not seem to pose many challenges.

The estimation of the throughput accounts for the light loss due to:

- Transmissivity/reflectivity of coatings;
- Internal absorption of the glasses.

There are no cemented components present in the design. The ALPAO DM277, that is already available on-site, has a protected silver coating with a reflectivity of $> 96\%$ in the 500-2000 nm wavelength range. Assuming uniform, ideal anti-reflection coatings for the lenses with a transmission of 98% and the coating of the mirrors with a reflectivity of 95%, we derive:

- SCI: 61.7%

- NGS: 61.5%
- LGS: 62.2%

The throughput curve for the VTB working wavelength range, including real coating models, will be obtained at later stages.

4.2 Manufacturing tolerances

Manufacturing tolerances of the optical elements of the VTB were obtained via a preliminary sensitivity analysis that allows the identification of the most critical components affecting the performance. The sensitivity analysis defined the maximum allowable errors of parameters. Using these values, a Monte Carlo simulation was conducted to estimate the overall impact of the tolerances on the wavefront error in each configuration.

The toleranced parameters are:

1. Radius of curvature: evaluated as a deviation from the nominal radius of curvature in mm for curved surfaces and as “fringes” (as measured in a double-pass interferometric test at 633 nm) for flat surfaces.
2. Center thickness of lenses.
3. Wedge: an angular error with respect to the nominal optical axis of the element. Only one surface is considered wedged with respect to the other.
4. Surface figure error: evaluated as an irregularity of a surface in “fringes”.
5. Refractive index: measurement error of the actual refractive index.
6. Abbe number: an error on the Abbe number.

After introducing the errors, each Monte Carlo realization was re-focused.

Table 4.3 reports the list of tolerances for each surface/element, while Table 4.4 reports the distribution of the WFE obtained from the Monte Carlo simulations. The statistics are based on 500 Monte Carlo realizations for each configuration.

Summary: Verification Test Bench

The VTB is going to be a support tool to verify MAVIS performance during the MAIT phase. Its presence will allow testing not only of the optical outputs but also of the RTC performance.

This chapter describes the optical design of the VTB, which uses the ALPAO DM277 to replicate the DSM of the VLT UT4. The design is minimalistic with

Surface	RoC, mm	RoC, fringes	Center thickness, mm	Wedge, arcmin	Figure error, fringes	Refractive index	Abbe number
Beam splitter L1S1	-	5	0.05	1	1	$5 \cdot 10^{-4}$	0.47
Beam splitter L1S2	-	5	-		0.038		
Beam splitter L2S1	-	5	0.05	1.1	0.038	$5 \cdot 10^{-4}$	0.47
Beam splitter L2S2	-	5	-		1		
Collimator L1S1	0.2	-	0.05	2	1	$5 \cdot 10^{-4}$	0.49
Collimator L1S2	0.2	-	-		1		
Collimator L2S1	0.2	-	0.05	1	1	$5 \cdot 10^{-4}$	0.27
Collimator L2S2	0.2	-	-		1		
Focuser L1S1	0.2	-	0.05	2	1	$5 \cdot 10^{-4}$	0.52
Focuser L1S2	0.2	-	-		1		
Focuser L2S1	0.08	-	0.05	0.9	1	$5 \cdot 10^{-4}$	0.27
Focuser L2S2	0.2	-	-		0.8		
Focuser L3S1	0.2	-	0.05	2	1	$5 \cdot 10^{-4}$	0.52
Focuser L3S2	0.09	-	-		0.8		
Fold mirror 1	-	1	-	-	0.3	-	-
Fold mirror 2	-	1	-	-	0.3	-	-

Table 4.3: List of the manufacturing tolerances for each element/surface.

Configuration	Unit	Best	10th	50th	80th	90th
SCI	nm	27.0	36.6	47.5	54.8	60.3
NGS	nm	20.8	23.9	26.4	28.3	29.7
LGS@80km	nm	11.1	15.6	21.7	27.0	31.6
LGS@230km	nm	8.6	12.8	16.3	19.5	21.4

Table 4.4: Distribution of the WFE obtained from the Monte Carlo simulation. We report the best case along with the different percentiles of the distribution.

primary components being the collimator and the focuser. This approach helps maintain the required throughput that is expected to be over 20%.

The VTB is planned to be integrated on site and ready for AOM testing in 2028.

Conclusions

In a period of rapid astronomical developments and discoveries, the demand for increasingly advanced instrumentation has become critical. Ground-based facilities can still effectively complement space missions by employing AO to correct for atmospheric turbulence. Achieving high-quality correction, however, requires not only an optimized design but also the precise fabrication of all system components, often pushing industrial partners to the limits of their capabilities.

This thesis was dedicated to the development of MAVIS, a new instrument for the VLT. On it as an example, we explored several key aspects in developing an MCAO assisted instrument. A well-structured modular design represents a fundamental step in constructing a highly functioning MCAO system. For MAVIS, modularity and flexibility were essential requirements, and these goals were successfully achieved. MAVIS consists of multiple sub-systems and modules that can be individually integrated and aligned, thereby simplifying both assembly and verification.

Verification of the optical design was the next critical stage. This process made it possible to identify potential issues and implement corrective measures. A major part of this work was devoted to distortion analysis. Two important outcomes were the definition of calibration frequency and the redesign of the ADC, which was originally introducing significant distortion. These represent concrete steps toward fulfilling the stringent astrometric performance requirements of the instrument.

We also demonstrated that image uniformity, scattering and ghosts remain within the specifications, and therefore do not compromise the imaging capabilities of MAVIS. The only out-of-specification ghost, originating from the LGS dichroic, was successfully mitigated by introducing a shallow curvature to the component. Because dichroics are critical elements in any MCAO system, they were studied in detail. The performance of coating designs proposed by different manufacturers was evaluated using dedicated software developed for this purpose, enabling the selection of the most suitable solution for MAVIS.

Finally, before installation on the telescope, it is essential to validate instrument performance in a representative environment. For this purpose, we designed the Verification Test Bench for MAVIS. The VTB emulates the characteristics of the VLT Nasmyth focal plane and includes the DM to replicate the telescope's DSM. It will be used in the laboratory settings during the MAIT stage of MAVIS. After the

testing, MAVIS will be transported to the VLT, with the first light expected in 2031.

In conclusion, the development of an advanced AO instrument, and an MCAO system in particular, requires careful consideration of numerous aspects. While this thesis has primarily addressed design and optical analysis, other critical components – such as integration, instrument control, RTC, PSF reconstruction, and data processing etc. – must also be developed in close coordination. Only by ensuring that each element performs to its highest standard can we guarantee that an instrument like MAVIS will achieve its scientific goals and contribute to future breakthroughs in astronomy.

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Appendix A

Software and Scripts developed

1. "Zernike" polynomials for elliptical apertures

GitHub: <https://github.com/AOtools/aotools/main/aotools/functions>

This class of methods is now part of the AOTools library, initially developed by Matthew Townson. The class I wrote, `ell_zernike.py`, together with its test function, is publicly available.

The class allows the simulation of individual Zernike modes or the construction of complex maps. It also provides a fitting function for existing aberration maps.

2. MSF distortion simulation

GitHub: https://github.com/alphaCassi/OpticalDesignAnalyses/MSF_simulation

This pipeline consists of three Python scripts that provide a full end-to-end simulation of MSF-originated distortions in an optical system, together with their calibration.

`raytrace.py` is a standalone Python application that interfaces with Zemax OpticStudio and performs ray-tracing of an optical system to derive distortion maps.

`zemax2mavisim.py` is a short script for re-formatting the data obtained with Zemax to the proper input for the calibration class.

`Calibration_pipeline_allrot_WithNoise_E2E.py` is a user script to calibrate distortions present in a system using MAVISIM library developed by Jesse Cranney and Stephanie Monty (<https://github.com/smonty93/MAVISIM>).

3. Plate scale variation analysis pipeline

GitHub: <https://github.com/alphaCassi/OpticalDesignAnalyses/PlateScale>

This pipeline was written specifically for the analysis of plate scale variations of MAVIS, but further was optimised for the use of any MCAO system. The analysis is based on the subaperture study by Negro 1984.

It provides functionality to generate NGS asterisms, create interaction matrix, derive DM commands, and compute plate scale variations in a system.

4. **Dichroic coating analysis pipeline**

GitHub: https://github.com/alphaCassi/OpticalDesignAnalyses/Tools/dichroic_spectra_analysis.py

It is a Python class that enables a comprehensive analysis of the coatings applied to optical components. Although it was written and used specifically for the MAVIS dichroics, it is equally applicable to the analysis of any desired coating.

A detailed description of its functionality is provided in Section 3.4.