

Performance assessment of the AOC system on a 1-m telescope: stellar mode characterisation and planetary mode development

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ABSTRACT

The Adaptive Optics at Calern (AOC) system aims to bring AO correction to 1-m class telescopes, which typically lack such capabilities, enhancing their high-angular resolution imaging performance. It offers both stellar (8.5 arcsec FoV) and planetary (30.5 arcsec/80.5 arcsec FoV) modes, guiding either on point sources or extended objects (such as Jupiter or Saturn). In the latter case, it introduces a filtering of the high-altitude turbulence, similar to ground-layer AO averaging, because high-altitude turbulence will be different around the edges of the planet, distorting the planetary disk, but not necessarily shifting the overall centroid. This work focuses on the ongoing characterisation and optimisation of the system, from near-infrared to visible wavelengths. We are developing both simulation tools and diagnostic/evaluation tools, and comparing simulations, telemetry, and on-sky data, aiming at refining wavefront control and improving robustness for both stellar and planetary observations.

Keywords: adaptive optics, 1-m class telescopes, planetary wavefront sensing, system characterisation, numerical modelling

1. INTRODUCTION

The Adaptive Optics at Calern (AOC) system is an adaptive optics (AO) bench currently being developed at the C2PU (Centre Pédagogique Planète Univers) facility of the Calern Observatory, Observatoire de la Côte d’Azur (OCA), near Nice (France). It is installed on the 1.04-m Epsilon (East) telescope at the F/35 Coudé focus, and aims to provide wavefront correction in both the visible and near-infrared domains.

AOC is designed as a flexible AO platform capable of operating on both unresolved (stellar) and extended (planetary) sources. It follows a standard closed-loop AO architecture in which the incoming distorted wavefront is measured, reconstructed, corrected by a deformable mirror (DM), and the resulting image is recorded for scientific analysis. The system is based on a 10×10 Shack-Hartmann wavefront sensor and a 97-actuator DM arranged in a Fried geometry. The optical beam is split into multiple channels dedicated to wavefront sensing, science imaging, and diagnostics, enabling simultaneous performance monitoring and scientific observations.

In this paper, we present an updated characterization of the AOC system and its recent developments since the initial description in Buralli et al. (2022)¹ and Abe et al. (2024).² We focus in particular on improvements in control strategies, system modelling, and on-sky performance in both stellar and planetary observing modes.

2. SYSTEM DESCRIPTION

2.1 AOC Overview

The telescope beam is redirected into a coudé path by mirrors M3 and M4 before entering the system. The remainder of the optical path is shown in the system bench view in Fig. 1 described in the following. After M4, it passes through a pupil derotator, which compensates for the pupil rotation introduced by the coudé configuration.

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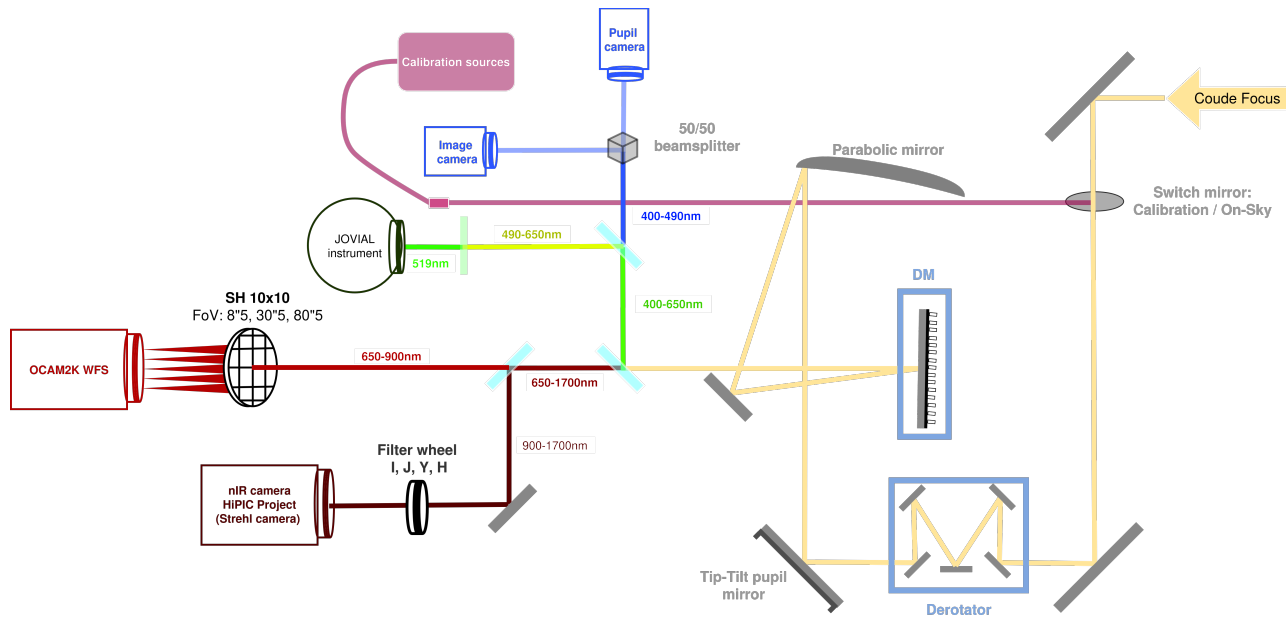


Figure 1: AOC bench view

Because the telescope's central obstruction is non-circular and asymmetric (see Fig. 2), the pupil is derotated instead of the field. This choice maintains a stable and repeatable alignment between the telescope pupil and the wavefront sensor (WFS), ensuring that the pupil configuration established during internal calibration is preserved during on-sky observations. After the derotator, a parabolic mirror relays the beam onto a motorised pupil tip-tilt mirror, in focal plane, which stabilised the pupil on the DM during both calibration and on-sky observations. This is achieved using a pupil camera operating in the 400–490 nm band, which provides continuous feedback to a slow servo loop. The acquired pupil image is thresholded and binarised, and its photometric centroid is computed. Any residual offset from the reference position is corrected in real time by adjusting the pupil mirror, while manual repositioning remains possible when required.

The optical path is structured to distribute the incoming light between the different subsystems. This is achieved using a set of dichroic beam splitters that separate the beam into several spectral channels. The 650–900 nm band feeds the 10×10 Shack–Hartmann wavefront sensor and its OCAM²K EMCCD camera, operating at 1.5 kHz (or 2.2 kHz in 2×2 binned mode), with a pixel size of 24 μm, allowing fast temporal sampling of the turbulence. The correction itself is provided by an ALPAO DM97-15 with 97 electro-magnetic actuators disposed on a 11×11 square-grid pattern, hence following Fried geometry together with the 10×10 WFS. The sensor configuration can be adapted to the observing case through three interchangeable microlens arrays, all with a pitch of 300 μm and focal lengths of 2, 5.1, and 18.8 mm, respectively, providing sub-image fields of view of 8.5 arcsec, 31.5 arcsec, and 80.5 arcsec, respectively, for different types of AO guide objects. This flexibility allows the system to switch between a narrow-field stellar mode, optimized for point sources (see Fig. 2c), and wider-field planetary modes for extended objects (see Fig. 2d).

The 900–1700 nm band is sent to the Ninox near-infrared camera for science imaging (HiPIC project³ – see paragraph 2.1.1) and is also used as a diagnostic tool to evaluate system performance (see Sec. 4). In parallel, the corrected images are acquired with a Ninox SWIR 640 infrared camera (part of the HiPIC project, see paragraph 2.1.1) with a 15 μm pixel size, enabling AO performance evaluation through quantities such as the Full-Width at Half-Maximum (FWHM) and Strehl ratio during stellar observations.

At the same time, shorter wavelengths (400–650 nm) are used, with part of the light directed toward the pupil camera for alignment and the remainder toward the JOVIAL⁴⁵ instrument.

Finally, the calibration unit, used to measure the system interaction matrix, can generate either a point source using single-mode or multimode fibers, or an extended source with an adjustable size up to dimensions comparable to planetary targets such as Jupiter. The illumination can be monochromatic (633 nm laser) or

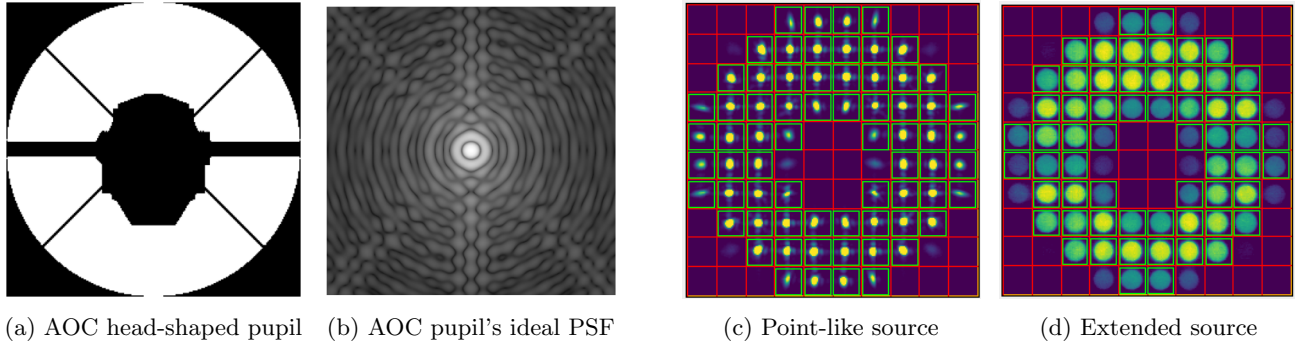


Figure 2: AOC pupil (a) and corresponding theoretical ideal PSF (b), and Shack-Hartmann subapertures for point-like (c) and extended (d) sources.

broadband ('IR Light Source' 500–4500nm), and a dedicated 3D-printed mask reproduces the pupil.

2.1.1 Applications: HiPIC and JOVIAL

The AOC bench is designed as a test bench for instrumentation, including future developments toward fibre-fed systems after the adaptive optics stage. It is currently used as a shared platform for two scientific instruments, HiPIC and JOVIAL, enabling their operation downstream of the adaptive optics correction. The corrected beam is distributed between these instruments, allowing simultaneous wavefront correction and science observations.

HiPIC³ (High angular resolution Post-adaptive optics Imaging at Calern observatory) is dedicated to high-resolution imaging and post-AO reconstruction methods in low-Strehl regimes, including deconvolution, lucky imaging, and speckle techniques across visible and near-infrared bands (I, Y, J, H filters). While JOVIAL is a Doppler imaging instrument based on an interferometric concept, aimed at measuring velocity fields in planetary atmospheres and contributing to ground-based studies of atmospheric dynamics and oscillations.⁵

2.2 Interface Development

In terms of software, AOC is driven by a parallelized C++ main loop combined with a Python graphical interface, as already described in Abe et al. (2024).² The maximum frame rate is 1504 Hz, but we usually run the loop at ~ 1428 Hz (0.7ms) due to the time taken for the built-in ALPAO SDK method to execute (we measured the purely computation part of the loop to run faster than $150 \mu\text{s}$). In order to improve this DM control latency, we are developing our own routines in order to bypass the current SDK. We acquired from ALPAO the so-called "LED-Boxes" hardware that emulate the presence of a physical DM to safely develop our own, faster DM actuation routine that completely bypasses the original software SDK through direct access to the DM controller. The DM settling time is reported to be about $220 \mu\text{s}$ and the total DM response time is about $800 \mu\text{s}$, so we expect this delay to be substantially reduced with these developments.

Several graphical tools allow configuration of active/inactive subapertures, threshold tuning, and visualization of DM-related buffers (low-order, high-order, flat) and static components. Static aberration modes can also be injected asynchronously during correction to tune PSFs at the output. Logging of the WFS measurements, commands and DM state are done in real-time using multi-buffering and data-packing, and dumped on a fast 4 GB NVMe SSD every 3.5 s.

We extended the existing graphical interface with additional diagnostic and visualization tools (see Fig. 3). The goal is not only to enable real-time control of the AO system, but also to provide immediate access to system diagnostics. The goal being to facilitate on-the-fly characterization and troubleshooting during experiments, to monitor the impact of parameter changes, identify instabilities, and refine calibration procedures.

A key addition is the SVD Tool (Fig. 3, left), developed to investigate alternatives to the interaction matrix acquired immediately before closing the loop. The tool allows the user to load and compare instantaneous,

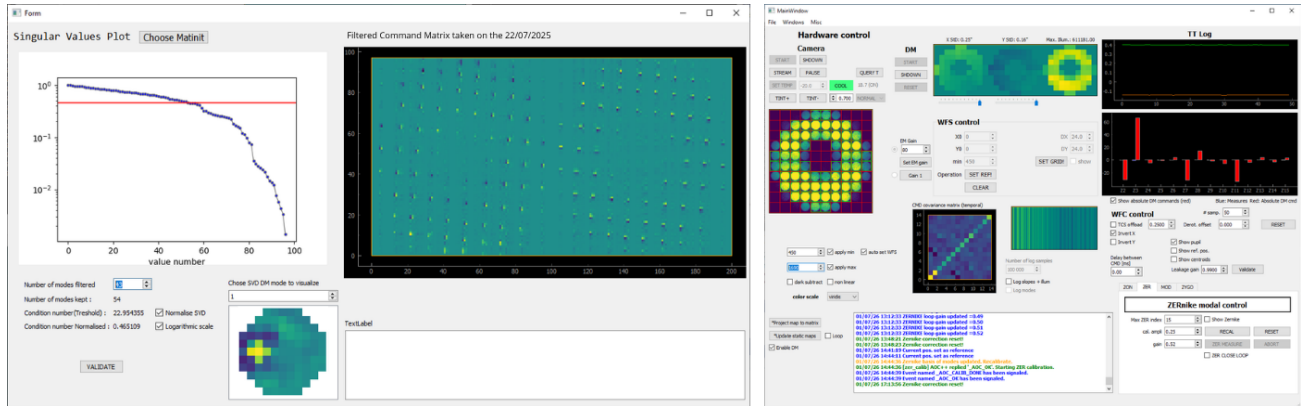


Figure 3: Left: SVD_Tool interface. Right: AOC main control interface.

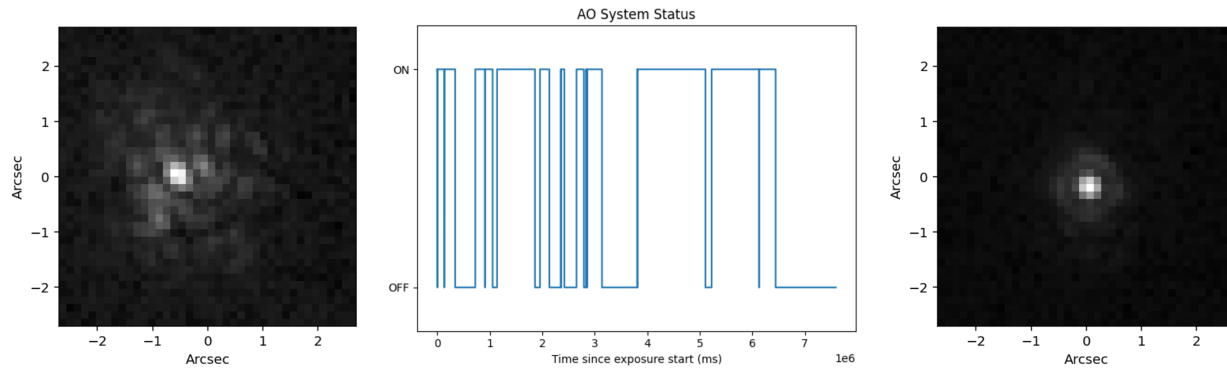


Figure 4: Instantaneous PSF comparison from Vega observations on 2025-07-22. Left: AO off; right: AO on. The images are not normalized to the same value between the two states. Center: AO status during the night.

averaged, or synthetic interaction matrices, and to visually choose the SVD filtering used to compute the command matrix. The motivation is that successive interaction matrix measurements exhibit noticeable variations, likely due to residual bench turbulence, small alignment drifts, or mechanical instabilities. Rather than relying systematically on the most recently acquired matrix, the tool makes it possible to test whether averaging several measurements to reduce random fluctuations, or using synthetic matrices derived from a calibrated model, leads to a more robust and repeatable reconstructor. The tool both optimises the reconstructor and supports diagnostics, with future extensions enabling controlled DM/turbulence playback, interaction matrix measurements, and NCPA estimation using Zernike perturbations.

A post-processing tool was developed to synchronize the near-infrared camera data with the wavefront sensor telemetry. Since the two systems run on separate computers without direct communication, the synchronization is performed offline. This makes it possible to identify the AO status (on/off) of each science frame (Fig. 4, center), enabling reliable frame selection for Strehl ratio estimation, PSF reconstruction, and temporal analysis.

3. MODELLING AND OPTIMISING THE SYSTEM

We aim to model the system as accurately as possible using an iterative approach between simulations and experimental data (see Sec. 3.1) to better understand performance and limitations. The numerical model is built from measured parameters, in particular the DM influence functions (see Sec. 3.2), and includes key effects such as pupil-to-DM mismatch, where the projected pupil is smaller than the full DM area, leading to different actuator usage than expected. Measured closed-loop transfer functions are also included to reproduce temporal behaviour and stability limits (see Sec. 3.4). Within this framework, we explore control parameters such as SH sub-aperture selection, SVD filtering, and loop gain optimisation (see Sec. 3.5).

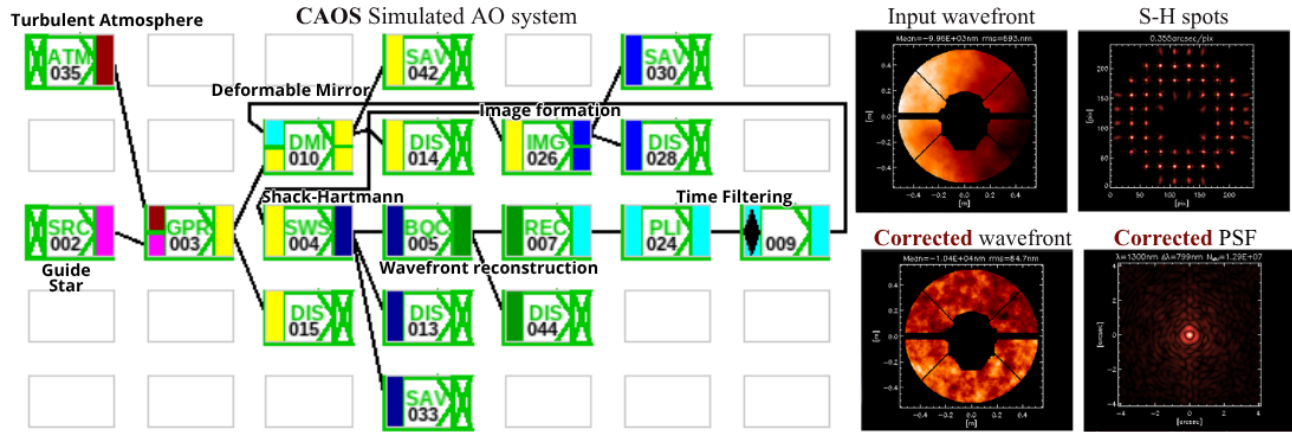


Figure 5: Overview of the CAOS simulation framework and example outputs.

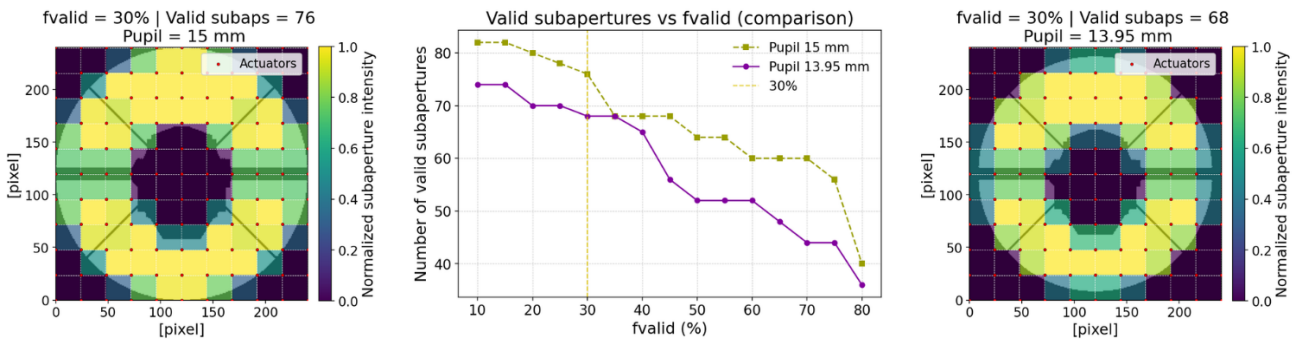


Figure 6: Effect of f_{valid} on the number of valid Shack-Hartmann sub-apertures for both pupil sizes.

3.1 Physical and Numerical Model of the System

The AO system is simulated using the CAOS Software Package.⁶ The model includes the main components (Sec. 2): a 11×11 DM, a 10×10 Shack-Hartmann sensor, and science/diagnostic cameras with detector sampling. Temporal delays (Sec. 3.4) and control parameters are also included. The goal is to reproduce the real system as closely as possible to enable direct comparison with experiments, identify discrepancies, and guide optimisation. An iterative simulation-experiment loop is used to refine the model and quantify effects such as pupil mismatch (Sec. 3.3). Numerical parameters are listed in Table 1, with key ones tuned as described in Sec. 3.5.

3.2 Influence Function Measurement

The DM influence functions were re-measured in the laboratory using a Zygo interferometer, without the 13.5 mm mask used in the manufacturer data, in order to characterise the full active surface (15 mm) including edge actuators. These measurements provide a more realistic DM model for simulations and are also used to build interaction matrices and derive modal bases (e.g. KL modes) for on-sky control.

3.3 Pupil Projection onto the DM

The DM has a 15 mm active diameter, but bench measurements show that the telescope pupil is actually undersized on the DM, with an effective projection of about 13.95 mm. This reduction modifies the Shack-Hartmann geometry: edge and partially vignetted sub-apertures receive less flux, changing the set of valid sub-apertures used for reconstruction. In the simulations, this is controlled via the f_{valid} threshold, which defines the minimum illumination required per sub-aperture (Fig. 6).

Because the interaction matrix depends on the illuminated pupil, the SVD spectrum is also modified: a smaller pupil leads to a faster decay of singular values, reflecting reduced sensitivity of higher-order modes. As a

Table 1: Physical and numerical modelling for the simulations of AOC in 'stellar mode'.

AO guide star parameters	
spectral type	A0
V-magnitudes	0–16
Turbulent atmosphere modelling	
Fried parameter r_0 (at 500 nm)	7 cm
number of turbulent layers	4
ground layer velocity	3.5 m/s
ground layer C_N^2 profile relative percentage	69%
higher layers velocities	4.5, 9.4, 22.1 m/s
higher layers C_N^2 profile relative percentages	10, 4, 17%
size of the turbulent layers	7.28 m $\equiv$ 1806 px
wave-front outer-scale $\mathcal{L}_0$	30 m
simulation method	FFT-based, 4 sub-harmonics
Shack-Hartmann wavefront sensor	
central sensing wavelength	775 nm
bandwidth	250 nm
sub-aperture configuration	10 $\times$ 10
valid minimum illumination ('fvalid')	0.3
$\Rightarrow$ number of subapertures	68
Wavefront sensing camera (OCAM 2)	
number of pixels per sub-aperture	24 $\times$ 24
pixel size	0.356''
$\Rightarrow$ sensing FoV	8.545''
exposure time (frequency)	0.667 ms (1.5 kHz)
noises	photon noise only
Deformable mirror (ALPAO DM-97)	
number of actuators (considered ones)	97 (87)
configuration	square grid (Fried geometry)
influence functions (IF)	measured in lab' (Zygo interferometer)
stroke	5 μ m
size of projected pupil onto DM actuator grid	13.95 mm onto 15 mm
Wavefront reconstruction & control	
condition number (truncated SVD)	25
$\Rightarrow$ number of SVD modes reconstructed	85
time-filter type	pure integration + leak factor
closed-loop gain	0.25
leak factor	0.99
Global parameters	
telescope diameter	1.04 m
total transmission (QE included)	1
global AO delay time	2 ms (3 frames)

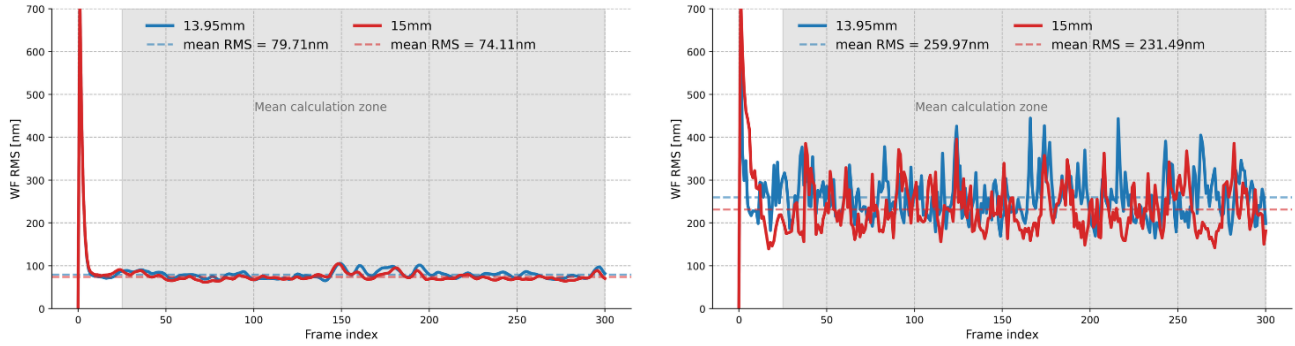


Figure 7: Simulated phase RMS of the corrected wavefront for the two pupil sizes: 13.95 mm (blue) and 15 mm (red). Left: source magnitude 0; right: source magnitude 13, for $f_{\text{valid}} = 30\%$.

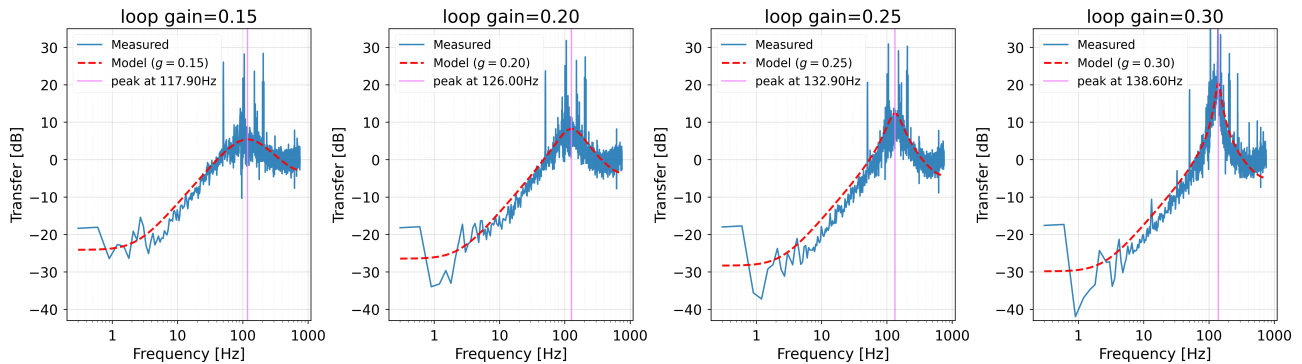


Figure 8: Closed-loop transfer function for different loop gains (0.15, 0.20, 0.25, 0.30), highlighting the effect of loop delay on system stability and bandwidth.

result, a fixed SVD threshold does not preserve the same number of controlled modes between configurations, with more modes becoming poorly constrained in the reduced-pupil case. In this context, singular values represent the sensitivity of each mode to the wavefront sensing process: lower values correspond to modes that are less well observed and therefore less reliably reconstructed after inversion.

This effect translates into a measurable performance difference in simulations: the 13.95 mm pupil systematically yields slightly higher residual errors than the full 15 mm configuration (Fig. 7), both in low and high magnitude regimes. For a magnitude 0 source, the mean residual RMS is 79.7 nm for the 13.95 mm pupil, compared to 74.1 nm for the 15 mm configuration. For a magnitude 13 source, the residual RMS increases from 231 nm (15 mm pupil) to 260 nm (13.95 mm pupil).

3.4 Transfer Function Analysis

The system transfer function is derived from Shack–Hartmann telemetry acquired under photon-noise-limited conditions in both open loop (for normalisation) and closed loop (zonal control). From the WFS slopes and interaction matrix, actuator commands are reconstructed. Each actuator signal is windowed, Fourier-transformed, and averaged to obtain a mean command spectrum. The transfer function is then obtained as the ratio between closed-loop and open-loop spectra.

This measured response is compared to a discrete integrator model with a 1% leak and a pure delay (Fig. 8). The delay is tuned to reproduce both the high-frequency attenuation and the overshoot of the measured curves. The analysis indicates an effective delay of about three frames in the control loop, consistently observed across loop gains. This latency is a major contributor to the temporal error budget and limits the achievable bandwidth. The delay originates from detector readout, computation, data transfer, and DM response, with camera readout and processing being the dominant, unavoidable, latency. Reducing the latency from three to two frames (one for acquisition, one for processing and actuation) should be a realistic target.

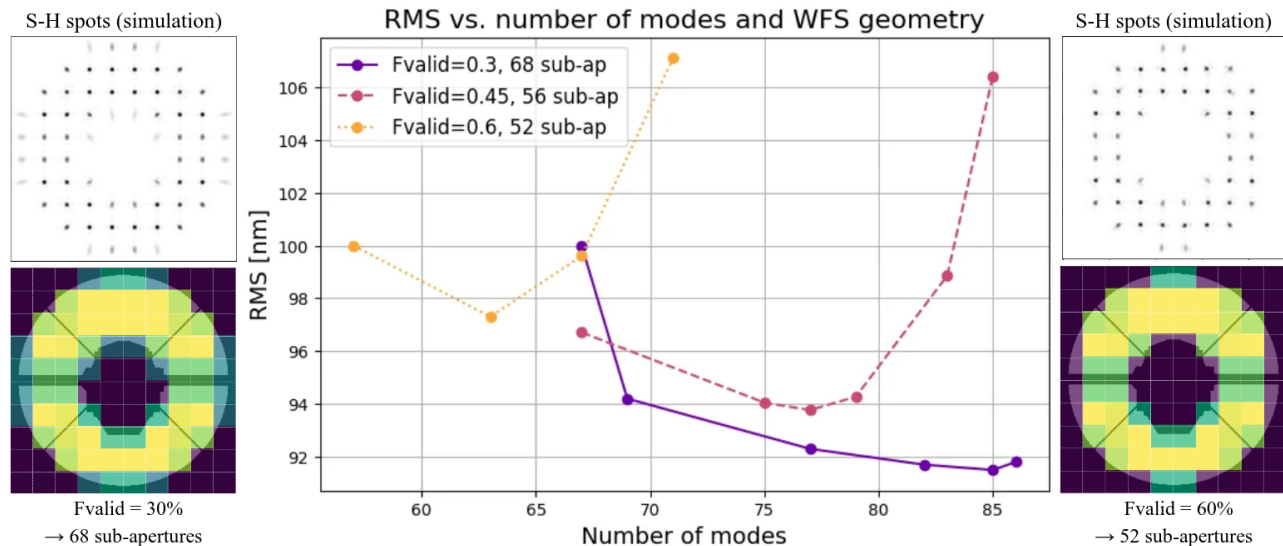


Figure 9: Center: Optimisation of the number of reconstructed modes and Shack-Hartmann geometry selection through the f_{valid} parameter. With two examples of f_{valid} value (Left: 30%, Right: 60%). Bottom: percentage of illumination of the valid sub-apertures. Top: chosen sub-aperture SH spots.

Finally, non-modelled vibrations appear near the loop amplification peak, visible in the SH signals. These disturbances degrade stability, highlighting the need to identify and mitigate mechanical vibration sources.

3.5 Simulation-Based Optimisation

Several key parameters were optimised through numerical simulations to improve correction performance and understand current system limitations, in particular the Shack-Hartmann geometry selection (f_{valid}), the number of reconstructed modes, and the loop gain.

Because edge sub-apertures are partially illuminated, especially with the reduced pupil described in Sec. 3.3, f_{valid} directly affects both the number of usable measurements and the SNR of the wavefront sensing. This optimisation was performed at magnitude 0 using the baseline parameters in Table 1, but becomes even more critical at low flux. The current study uses SVD-based modes derived from measured influence functions, with future extensions planned toward Karhunen-Loève (KL) modes for improved turbulence reconstruction. Residual phase analysis shows an optimal configuration around $f_{\text{valid}} = 30\%$ with 85 modes, with better performance when a larger set of sub-apertures is retained, enabling control of more actuators.

The loop gain was also optimised (Fig. 10, left). Due to the delay discussed in Sec. 3.4, high gains amplify noise and reduce stability. The optimal value at magnitude 0 is 0.25, balancing correction efficiency and stability. Finally, the simulated Strehl ratio versus magnitude (Fig. 10, right) was computed using photon noise and ideal transmission only, and does not include static aberrations (Sec. 4.3). This optimisation is therefore representative of the high-flux regime.

Further work will extend this optimisation to faint targets and refine centroiding and weighting strategies based on SNR and sub-aperture illumination.⁷

4. RESULTS OBTAINED IN STELLAR MODE

In this section, we present the on-sky results obtained in March and July 2025 (in stellar mode), highlighting the evolution of the correction performance following optimisations of the system control (see Sec. 4.1). We measure Strehl ratios in order to evaluate our system performance. A detailed analysis of mode optimisation and command tuning is provided in Sec. 4.2. Eventually, we discuss the static PSF contribution, its impact on the correction quality, and possible optimisation strategies in Sec. 4.3.

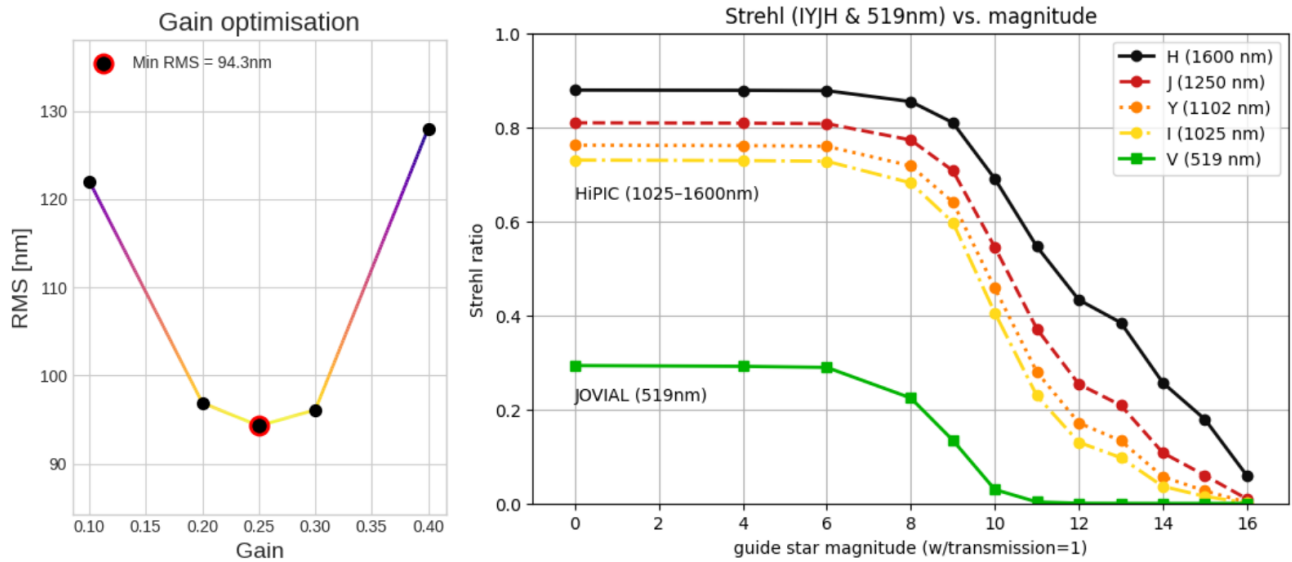


Figure 10: Simulated Strehl ratio as a function of source magnitude after optimisation of the reconstruction and control parameters.

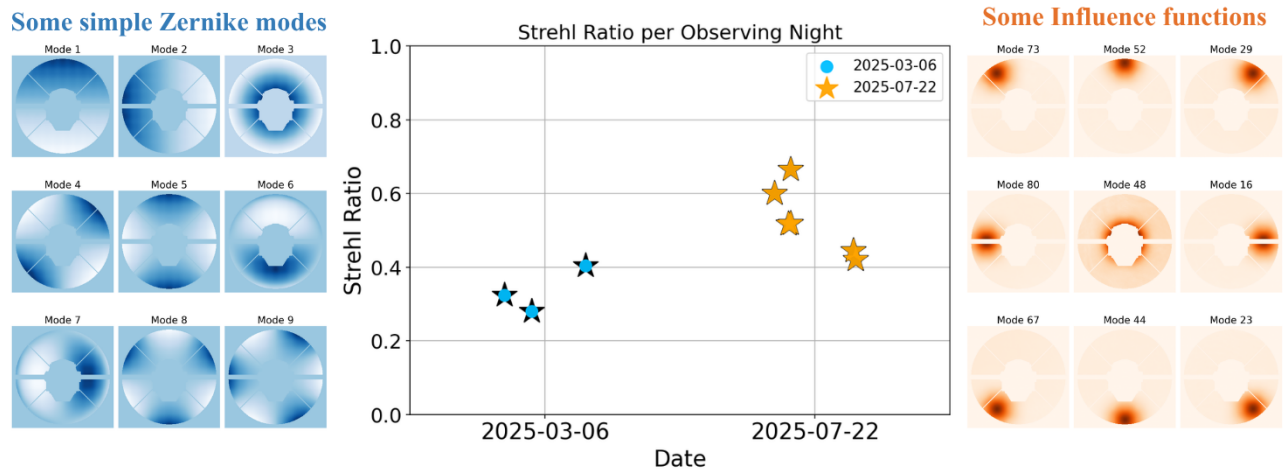


Figure 11: Average H-band Strehl ratio obtained during the March 2025 and July 2025 observing campaigns, together with the corresponding correction modes.

4.1 Image Quality in Stellar Mode

This section presents H-band on-sky performance from two observing campaigns carried out in March and July 2025, respectively on Arcturus (6 March, 5 ms exposures) and Vega (22 July, 10 ms exposures).

Between the two runs, the control strategy and system alignment were improved. In March, the correction relied on 14 Zernike modes projected onto the 11×11 DM grid, without SVD filtering. In July, a zonal approach was adopted using full actuator-based interaction matrices, with 17 modes filtered through SVD. This configuration currently provides the best performance, while alternative modal bases are under investigation (Sec. 4.2). The corresponding evolution in average H-band Strehl ratio is summarized in Fig. 11.

The mean PSF Strehl ratio (from dark-subtracted, simply stacked images) increases from $\sim 40\%$ in March to $\sim 66\%$ in July. This improvement is mainly attributed to the updated control strategy and system refinements, with a secondary contribution from more favorable atmospheric conditions.

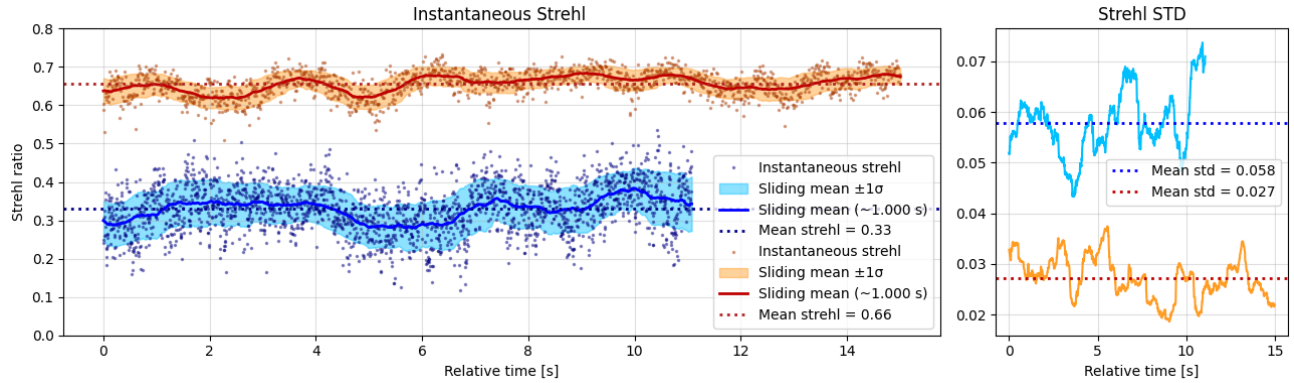


Figure 12: Instantaneous Strehl ratios for different observing runs.

To better assess atmospheric effects, the instantaneous Strehl ratio was analysed frame by frame for representative sequences from both campaigns. Figure 12 shows the temporal evolution together with a running mean and a $\pm 1\sigma$ interval. In March, the Strehl averages 0.33 with $\sigma \approx 0.058$, while in July it reaches 0.66 with reduced fluctuations ($\sigma \approx 0.027$). The July sequence also exhibits slower temporal variations, consistent with more stable seeing conditions.

The observed Strehl fluctuations can be compared to weak scintillation theory (Yura & Fried, 1998):⁸ $\sigma_S^2 = (\sigma_{\delta\phi}^2)^2 \left(\frac{d}{D}\right)^2$. Using the Maréchal approximation ($S \approx e^{-\sigma_\phi^2}$), the July conditions ($S \approx 0.65$, $\sigma_\phi^2 \approx 0.43 \text{ rad}^2$) and assuming $d/D \approx 0.1$, the expected Strehl fluctuations are on the order of a few percent. This is consistent with the measured value ($\sigma \approx 2.7\%$), despite the neglect of static aberrations (Sec. 4.3). Overall, the observed behaviour agrees with the simplified theoretical trend.

4.1.1 AO-Off PSF Analysis and Seeing Proxy Estimation

In open-loop (AO-off), image quality metrics can be used as a proxy for atmospheric conditions, in particular through the PSF FWHM. Table 2 reports representative measurements from the 06 March 2025 and 22 July 2025 observing nights.

Table 2: FWHM values in pixels and arcseconds for selected observations.

DATE (d/m/y)	TARGET	FWHM (pix)	FWHM (arcsec)
03/06/25	Arcturus	13.56	1.83 ± 0.08
03/06/25	Arcturus	11.84	1.60 ± 0.06
03/06/25	Arcturus	14.28	1.93 ± 0.07
07/22/25	Vega	10.63	1.43 ± 0.05
07/22/25	Vega	9.81	1.32 ± 0.05
07/22/25	Arcturus	8.90	1.20 ± 0.04

An approximate Fried parameter r_0 can be inferred from the FWHM using $r_0 \approx 0.98\lambda/\epsilon_0$, where ϵ_0 is the measured angular resolution. This provides only a first-order, optimistic estimate, since the outer scale L_0 is not accounted for, effectively biasing ϵ_0 .⁹ Despite this limitation, the estimates are useful for relative comparison between nights and performance tracking. Future work will compare these values with external turbulence monitors such as ANATOLIA¹⁰ and with estimates derived from our WFS telemetry.

These atmospheric proxies can also inform adaptive control strategies, in particular gain scheduling based on r_0 , τ_0 , and guide-star flux. This relies on real-time estimates (from slope variance and flux, with $\tau_0 = 0.31r_0/\bar{v}$) and precomputed simulation-based lookup tables. Local turbulence sources (e.g. dome or bench seeing) could also be characterised separately to disentangle environmental and instrumental effects.¹¹

4.2 Toward Modal Control

As introduced in Sec. 4.1, the system was initially controlled in March using a reduced set of 14 Zernike modes. These modes were directly projected onto the DM actuator grid (11×11), without explicit use of the system influence functions. While this provided a first operational correction, it did not fully exploit the DM's capability.

In July, the control strategy was revised toward a purely zonal formulation, in which the correction is directly handled in actuator space. The interaction matrix D contains the wavefront sensor measurement response $\mathbf{m}$ for a given actuator $\mathbf{a}$ with $\mathbf{m} = D \mathbf{a}$. When inverting the interaction matrix to generate the control matrix D^+ , any number of modes can be filtered, either in the SVD inversion or by filtering eigenmodes of $(D.D^T)^{-1}$ in the Moore–Penrose inversion. These are equivalent and can be called the system modes. We can then compute the actuator voltage vector from a set of wavefront sensor measurements ($\mathbf{a} = D^+ \mathbf{m}$).

Current work focuses on constructing improved modal bases derived from the system influence functions, in order to better match the physical response and improve robustness to noise and ill-conditioning. A first approach is the construction of Karhunen–Loève modes via a double diagonalisation procedure,¹² which provides an optimal ordering in terms of turbulence statistics and system response.

Alternative bases are also being investigated, including Zernike modes adapted to the system influence functions, DM eigenmodes, system modes derived from the interaction matrix, etc. All these bases are derived from the measured influence functions introduced in Sec. 3.2. In particular, geometrical covariance matrices can be diagonalised to generate orthogonal sets of mirror modes. A similar approach applied to statistical covariance matrices leads to turbulence-optimised system modes. Within this framework, modal control naturally separates well-constrained and poorly constrained components of the system. The latter correspond to the null space of the combined WFS–DM response (e.g. piston, tip–tilt, waffle modes, and high-order weakly sensed modes), which can be removed or attenuated through SVD filtering.

Overall, modal control will offer improved noise rejection and robustness by filtering weakly observed modes, but its performance strongly depends on the choice of basis. The transition from zonal to modal control is therefore currently being explored in simulation, with experimental validation planned in future work.

4.3 Static PSF Estimation and Error Budget

NCPA and other static aberrations introduce an intrinsic performance limit, independent of atmospheric turbulence or closed-loop correction. Quantifying this contribution is therefore essential to interpret the on-sky performance.

The static PSF was characterised in the H band using the Ninox science camera and the internal calibration source. The DM reference shape was manually optimized by combining actuator offsets and low-order Zernike corrections through the control interface to obtain a PSF as close as possible to the diffraction limit. This procedure also serves as a first step toward a future automated static optimization loop.

Comparison with the theoretical diffraction-limited PSF yields a static Strehl ratio of approximately 70% (Fig. 13), corresponding to a residual wavefront error of about 150 nm RMS, consistent with independent phase-retrieval estimates (e.g. Gerchberg-Saxton). This value represents the intrinsic optical quality of the current system. This measurement can also be compared to the numerical simulations. For example, the simulated H-band Strehl of 88% for a magnitude-0 source (Fig. 10) becomes an expected on-sky Strehl of about $0.88 \times 0.70 \approx 62\%$ once the measured static limitation is included, in good agreement with current observations.

Future work will focus on reducing this static error through automated calibration, characterising the static PSF in each observing band (I, Y, J, H filters), and investigating more advanced NCPA estimation techniques such as phase diversity (e.g. COFFEE¹³). The present measurement was obtained in April 2026 and therefore serves only as an order-of-magnitude reference for the 2025 observing campaigns.

Finally, residual non-atmospheric dynamic effects may still be present in the current measurements, in particular due to air flow induced by the Ninox camera cooling system. These contributions have not yet been quantified and may introduce an additional unmodelled error term in the budget.

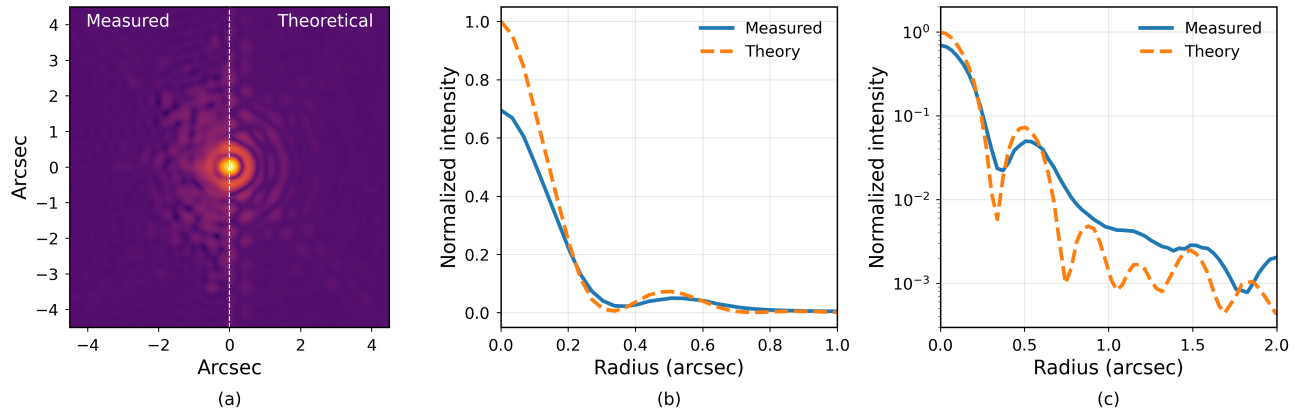


Figure 13: Static PSF in H-band: (a) comparison between theoretical and measured PSF, (b) linear radial profile, (c) logarithmic radial profile.

5. PLANETARY MODE DEVELOPMENT

As explained in Sec. 2, the system can operate on both unresolved and extended sources. This is possible because the Shack-Hartmann wavefront sensor computes photocentres within each subaperture image rather than relying on a point-like reference. However, for an extended object, different regions of the field probe different atmospheric paths. The correction therefore no longer corresponds to a single line of sight through the atmosphere, and only part of the turbulent volume is compensated. This aspect is discussed further in Sec. 5.2.

5.1 Preliminary results

Although the correction is inherently more local than in stellar mode, it still provides a significant improvement, particularly for low-order aberrations such as tip-tilt. In fact, the image is at least very well stabilised, as illustrated in Fig. 14, which is a stack of 5000 individual 0.5 s exposures of Saturn acquired in band H on September 11th, 2025. Despite the total integration time of about ~ 1 h, the planet remains remarkably stable in the field.

No direct atmospheric measurements are available for that night. However, using the method described in Sec. 4.1.1, AO-open-loop observations of Aldebaran acquired the same night, just before starting to observe Saturn, yield a typical FWHM of about 11 pixels in H band (0.01 s exposures), corresponding to a *rough* estimated Fried parameter of $r_0 \approx 5$ cm at 500 nm. Although approximate, this suggests moderately poor seeing conditions under which the AO system nevertheless maintained stable image quality. Because the target is extended, the Strehl ratio is not necessarily the most relevant performance metric. Image sharpness, contrast, encircled energy, or feature detectability could provide a more meaningful assessment of correction quality. An exception arises when an unresolved point source is present in the field. In Fig. 14, Titan is visible next to Saturn, due its orbital motion during the integration time produces a noticeable trail, but it is resolved, preventing its use as a Strehl reference. In observations including an unresolved satellite, however, its Strehl ratio could provide a local estimate of the AO performance, provided anisoplanatic effects are taken into account.

These preliminary observations demonstrate that the system can successfully stabilize and partially correct extended targets, providing a promising basis for future optimisation of the planetary mode.

5.2 Wide-Field Wavefront Sensing Perspectives and Discussion

One of the directions opened by this work is the possibility of exploiting the full Shack-Hartmann subaperture images rather than only the centroid measurements currently used by the AO loop. The motivation is to move beyond a purely 2D wavefront correction problem and recover information about the 3D structure of atmospheric turbulence. Instead of reducing each subaperture image to a single centroid value, the full subaperture intensity patterns can be analysed to search for correlations between different regions of the field. In the case of an extended object such as Jupiter, different subapertures provide slightly different views of the same planetary features. By

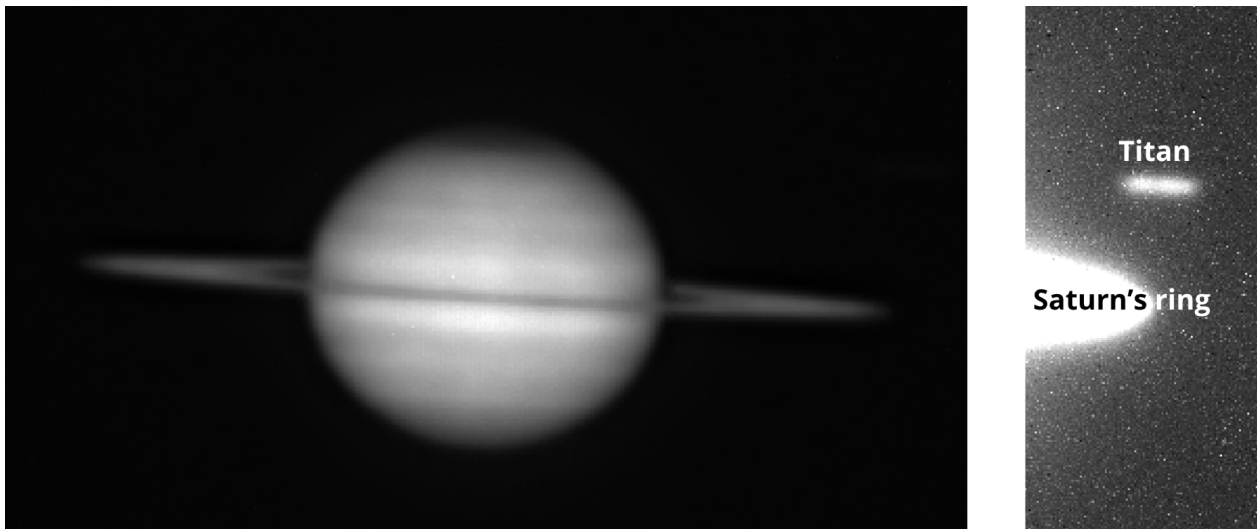


Figure 14: Simple stack of 5000 exposures (0.5 s each) of Saturn acquired in H band (with the application of an “unsharp mask” of 6 pixels radius) on September 11th, 2025

comparing corresponding regions (e.g. the limb), it may be possible to identify signatures of turbulence at different altitudes.

This idea is closely related to SLODAR techniques,¹⁴ which use correlations between spatially separated lines of sight to reconstruct the vertical distribution of turbulence. Here, the extended nature of the target provides the angular diversity that is normally obtained from double stars. Correlating subapertures observing different parts of the object could therefore, in principle, allow the estimation of turbulence layer altitude and strength, by tracking relative distortions of identifiable features across the field.

In this framework, low-altitude turbulence affects the entire field similarly, producing mainly global tip-tilt-like motions, while high-altitude turbulence introduces differential distortions between different lines of sight. For example, opposite limbs of a planet experience nearly the same ground-layer perturbations but different high-altitude phase screens, leading to measurable differential displacements or shape distortions. Another complementary observable is scintillation. High-altitude turbulence produces not only phase distortions but also intensity fluctuations due to propagation effects, whereas low-altitude turbulence mainly induces geometric image motion. Combining phase- and intensity-based diagnostics could therefore help disentangle contributions from different atmospheric layers.¹⁵

Ultimately, the objective is not only to improve adaptive optics correction, but also to use the wavefront sensor as an atmospheric diagnostic tool. Such measurements could provide an independent estimate of the turbulence profile that could be compared with external instruments such as ANATOLIA.¹⁰

6. CONCLUSION AND PERSPECTIVES

We have presented improvements and upgrades to the AOC system. In stellar mode, the delivered H-band Strehl ratio was improved from $\sim 40\%$ to $\sim 66\%$, as a result of improvements in the dynamic correction using zonal control and a first attempt to optimise the static PSF. Loop parameters were optimised using numerical simulations in a back and forth manner with the real system, in which we have also started developing diagnostic tools to improve usability and assess performance. We have made good progress with the characterisation of the system, but we still need to resolve some issues such as mechanical vibrations from unknown sources which unfortunately are right at the overshoot of the transfer function. This overshoot is large, due to the 3-frames temporal delay which we hope to reduce in the near future. We also plan to improve faint end performance using modal control and enhance the system’s limitations by refining the static PSF. Those improvements will be characterised by new and better diagnostic tools. In the longer term, the wide field performance is a fundamental challenge, as explained in Sec. 5.2, with preliminary work reported in the companion paper Schmider et al. (2026).⁵ Our aim is

to provide a framework to explain the averaging of high layer turbulence and quantify the resulting performance in terms of a ground-layer AO approach. A by-product will be vertical turbulence profiling through the SLODAR formalism.

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