Wavefront Sensing Workshop 2026

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Book of Abstracts

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PROVIDENCE : a 2.5m Adaptive Telescope for testing new WFS concepts

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PROVIDENCE will be an ambitious optical research platform primarily dedicated to the observation of. It is a 2.5m adaptive telescope optimized for High Angular Resolution. Installed at the Observatoire de Haute Provence, the project targets dual applications, covering satellite and debris observation, astronomical observation, innovative instrumentation and cross-disciplinary issues around environmental and atmospheric characterization, laser focusing and optical telecoms (QKD and deep space communications). PROVIDENCE will offer 7 different focii (two Nasmyths, one cassegrain and four coudé rooms) allowing operational and research instrumentation. In particular, PROVIDENCE will be the perfect tools to test on-sky new wavefront sensor concepts.

In this presentation, we give technical details on this station, flowing down from its science and prograùatic objectives to the technical specifications and functionalities. Currently at the study and prototyping stage, the station will be ready for the observation of the near-Earth asteroid APOPHIS in April 2029.

Topics:

Laboratory and on-sky demonstration

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Optical gain compensation for pyramid WFS on extended source in harsh conditions

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During the past decades, the pyramid wavefront sensor (P-WFS) high sensitivity has been theoretically formalized and demonstrated for on-sky operations. Current adaptive optics (AO) systems and first-generation instruments of the ELT will extensively rely on the P-WFS to provide extreme performance on fainter and fainter targets in order to improve sky coverage and AO loop speed. However, the sensitivity of the P-WFS is strongly affected by the observing conditions, such as the turbulence but also the spatial extension of the source if applicable. Indeed, AO loop operations are envisaged not only on stars, but also on minor bodies of the Solar System such as asteroids or trans Neptunian objects (TNO). Observation of artificial satellites in Earth orbit is also possible from ground-based observatories. This former application is particularly challenging since it requires to observe at low elevations, with a huge apparent wind speed due to satellite's movement.
For these astronomical and space awareness applications on extended sources, a P-WFS allows to

close the AO loop on fainter targets, but at the detrimental cost of non-linearities. The Gain Scheduling Camera (GSC) is a support to the P-WFS enabling to measure optical gains and to compensate for them in real time during AO operations. Early 2026, we demonstrated on the PAPYRUS AO bench, installed in France, the possibility to close the AO loop on extended objects with optical gain compensation within the reconstructor. We show that the compensation allows for better performance on extended objects, improving the scientific outcome on raw images or for post-processing techniques such as deconvolution. This optical gain compensation technique will be implemented for the future PROVIDENCE telescope, with space awareness applications, to be installed in France by the end of 2028. We report the expected performance of such a system. These challenging developments will help to gain in maturity of the P-WFS operating in harsh conditions, making it more robust to variable operating conditions.

Topics:

Laboratory and on-sky demonstration

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AI4AO: an AO python package for machine learning

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Artificial intelligence for adaptive optics (AI4AO) is a python package made for machine learning experiments in adaptive optics. Inspired by the Object-Oriented Python Adaptive Optics (OOPAO) package, based on numpy/cupy, AI4AO implements fully differentiable end-to-end AO simulations in Pytorch. Leveraging auto-differentiation, this approach is extremely powerful to optimize and tune digital twins of existing AO instruments, to then, for example, train phase reconstructors fully in simulation that can be seamlessly deployed on the real instrument.
The package includes an atmospheric phase screen generator that can produce thousands of independent samples per second, making it possible to generate the dataset on-the-fly while training.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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Estimating differential pistons for the Extremely Large Telescope using defocused images and deep learning

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Differential piston aberrations, commonly known as petaling, represent a critical limitation for the optical performance of the Extremely Large Telescopes (ELT). If left uncorrected, petaling severely degrades the core of the point spread function (PSF), restricting high-contrast imaging capabilities and reducing the spatial resolution of a segmented primary mirror to that of a single sub-aperture petal.

In this presentation, we present an evolution of our deep-learning framework dedicated to estimating differential piston modes. By replacing our previous sub-PSF approach with a method exploiting defocused dual-wavelength focal-plane images, we successfully enhance both the capture range performance and the overall versatility of the wavefront sensor.
First, the network can concurrently estimate all five differential piston modes of a 6-petal pupil from a single image frame, introducing native robustness against pupil rotation. Under realistic ELT turbulence residuals (25% Strehl ratio baseline with 13-frame averaging), the network achieves a wavefront error of approximately 25 nm RMS, demonstrating very close agreement with historical frameworks (23 nm RMSE).
Second, by incorporating a dual-wavelength input configuration ($\lambda 1$ = 1.5 μm and $\lambda 2$ = 1.8 μm), the network expands its operational bounds well beyond the classical $[-\pi, \pi]$ phase ambiguity. Robust linear estimation is maintained up to a range of $[-5\pi, 5\pi]$. Beyond the synthetic wavelength limit (Λ = 9.0, μm), the system continues to exhibit a coarse linear behavior, with no clear evidence of classical phase wrapping.
Finally, we outline our roadmap for experimental validation on the High-Contrast Module (HCM) testbed at IPAG using the Zernike wavefront sensor as a reference baseline, paving the way for eventual on-sky deployment on the EKARUS adaptive optics R&D platform at the Asiago Observatory.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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Advancing METIS focal plane wavefront sensing: ALF results and other promising architectures

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The Mid-infrared ELT Imager and Spectrograph (METIS) will enable high-contrast thermal infrared imaging, including vortex coronagraphy, for direct exoplanet detection. However, water vapor-induced chromatic turbulence in the N-band and variable non-common path aberrations significantly degrade performance and limit companion detectability.

To address these challenges, especially the dynamical nature of those turbulence, we developed the Asymmetric Lyot wavefront sensor (ALF). ALF encodes even pupil aberration modes into observable intensities using an asymmetric Lyot stop, with supervised learning solving the non-linear inversion.

First, we optimize the asymmetric mask by maximizing the Fisher information, and validate our finding by end-to-end simulation. Then, we analyse the operational range, the control stability, and the closed-loop performance. Finally, we demonstrate how ALF enables the detection of temperate planets.

Beyond ALF, we explore two new methodological avenues. First, we replace our previous ResNet-18 models with a modulated U-Net architecture, conditioning a single network on magnitude and optical setup to handle multiple regimes without retraining. Second, we present PO4NCPA, a model-based reinforcement learning framework that uses sequential phase diversity to infer phase corrections from focal plane images without prior system knowledge. We show that it can robustly compensate static and dynamic NCPAs, making it a promising framework for real-time training and correction.

Topics:

Wavefront sensors for high-contrast imaging

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Toward a bio-inspired AO system

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Future adaptive optics instruments used in space observation from the ground, both in astronomical and space defense domains, require wavefront sensors capable of operating at ever higher temporal frequencies while maintaining high sensitivity in order to operate under photon-starved conditions. This trade-off between sensitivity, temporal bandwidth and measurement range motivates the exploration of new sensing technologies beyond conventional frame-based detectors.

Event-based cameras represent a new generation of bio-inspired sensors whose detection principle relies on intensity variations rather than absolute intensity levels. Unlike conventional frame-based cameras, their pixels operate asynchronously and respond to logarithmic changes in illumination, mimicking the functioning of the human retina. The output signal consists of a stream of events of the form (x, y, t, p), where x and y correspond to the pixel coordinates, t is the timestamp, and p is the polarity of the intensity change. This sensing paradigm enables low latency ($\approx 100\,\mu$s), microsecond temporal resolution, and a wide dynamic range ($> 125\,$dB). Beyond their sensing capabilities, their fully asynchronous operation also opens the way to new adaptive optics control strategies.

The objective of this talk is to investigate and demonstrate the feasibility and scientific relevance of using event-based cameras for wavefront sensing in high-resolution adaptive optics through a combined theoretical, numerical and experimental approach. This work proposes a paradigm shift in wavefront sensing. Initially designed to measure an instantaneous wavefront, wavefront sensors based on event-driven detection are now able to provide access to the temporal evolution of the wavefront within a single measurement. This new capability opens new perspectives for adaptive optics.

To fully exploit these properties, we first develop a physically accurate theoretical model of the event-based sensor, with a particular focus on the origin of the detector noise and the effective contrast threshold governing event generation. Based on this understanding, we introduce dedicated wavefront reconstruction algorithms specifically designed for event-driven measurements. Their performance is then quantitatively compared with conventional frame-based wavefront sensors under a wide range of parameter combinations. Finally, these models and algorithms are integrated

into a complete closed-loop adaptive optics simulation, allowing us to evaluate both the potential benefits and the current limitations of event-based wavefront sensing for future high-performance AO systems.

Topics:

Frontier of wavefront sensors

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AI4AO and RAMA: an open on-sky testbed for scintillation-robust wavefront sensing and AI-based control

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The development of new wavefront-sensing and control strategies increasingly requires flexible platforms that can bridge the gap between numerical simulations, laboratory experiments, and on-sky validation. The AI4AO programme aims to develop and experimentally assess advanced wavefront-sensing and control approaches for adaptive optics, with a particular focus on machine-learning methods, non-linear wavefront reconstruction, and predictive control.

A central component of this programme is RAMA, an open and modular adaptive-optics testbed installed on the ONERA 60-cm telescope. RAMA is designed to enable the rapid integration and on-sky evaluation of new wavefront sensors and associated control algorithms. Its current configuration includes a visible non-modulated pyramid wavefront sensor, providing a relevant platform for investigating both the high sensitivity and the strongly non-linear behaviour of this sensor.

One of the main objectives is to study the impact of atmospheric scintillation on pyramid wavefront sensing, particularly under conditions relevant to free-space optical links. Beyond this analysis, we aim to develop and experimentally validate dedicated wavefront-sensing concepts that remain robust under strong scintillation. We will also investigate machine-learning approaches for extending the linearity range of the non-modulated pyramid, accounting for variations in optical gain and amplitude fluctuations, and improving the robustness of wavefront reconstruction. In parallel, predictive control strategies are being developed to reduce temporal errors by exploiting the spatial and temporal structure of atmospheric turbulence.

This contribution will present the overall objectives of the AI4AO programme, the RAMA architecture and experimental roadmap, and the first results obtained through numerical simulations, laboratory experiments, and on-sky tests. The longer-term goal is to establish RAMA as an open platform for the adaptive-optics community, supporting the comparative evaluation of emerging wavefront-sensing and control techniques under representative observing conditions.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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GAPS: a dedicated phasing test bench for the Natural Guide star Wavefront Sensor Prototype for the Giant Magellan Telescope

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The Giant Magellan telescope adaptive optics system will use two different diffraction-limited imaging modes. One of them is the Natural Guide Star Adaptive Optics mode (NGAO). NGAO uses 7 Adaptive Secondary Mirror (ASM) segments to provide wavefront correction and a single natural guide star coupled with a post focal wavefront sensor called the Natural Guide Star Wavefront Sensor (NGWS). The NGWS has two different channels: the main one featuring a high spatial sampling pyramid sensor dedicated to the fast frame rate correction of atmospheric turbulence and the second one featuring a Holographic Dispersed Fringe Sensor dedicated to phasing correction of the seven segments of the GMT at a low frame rate. To address the risk of phasing errors, GMTO and the Arcetri adaptive optics group have collaborated to build the GMT Adaptive optics and Phasing Sensors testbed (GAPS). GAPS features a GMT telescope simulator with seven segments actuated in piston, tip, and tilt (PTT); a 2k-actuator Deformable Mirror (DM) that serves as a proxy for the ASM; and a full scale prototype of the NGWS. Both the PTT mirror and the DM are used conjointly to emulate wavefront disturbances (including atmospheric turbulence and quasi-static phasing errors) and wavefront correction. In this contribution, we report the results of preliminary experiments demonstrating coarse and fine phasing control with or without atmospheric disturbance.

Topics:

Laboratory and on-sky demonstration

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Low-Cost Atmospheric Turbulence Monitoring Using Smartphone CMOS Sensors and Machine Learning

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Atmospheric turbulence significantly degrades the resolution of ground-based astronomical observations. While traditional wavefront sensors effectively measure these optical aberrations, their high cost limits accessibility for educational and independent research institutions. This study proposes an alternative, low-cost framework utilizing commercially available smartphone CMOS sensors coupled with machine learning to monitor atmospheric turbulence. We captured real-time observational footage of stellar scintillation and speckle patterns under various seeing conditions. Instead of relying on direct hardware-based wavefront measurements, the raw video data is processed using sequential image stacking and computational phase approximation techniques. Subsequently, a machine learning model is trained on these observational datasets to estimate turbulence parameters and reconstruct the optical degradation effects. Preliminary results demonstrate promising performance in characterizing local seeing conditions, effectively correlating raw CMOS sensor data with

atmospheric behavior. By replacing expensive optical hardware with computational algorithms, this methodology provides a low-cost and accessible framework for astronomical atmospheric monitoring and adaptive-optics education. This approach offers a scalable solution for resource-limited observatories to conduct meaningful atmospheric site characterization.
Keywords:
Atmospheric turbulence, CMOS sensors, Machine learning, Adaptive optics, Astronomical seeing.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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Explainable Machine Learning for Photonic Lantern Piston Sensing

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In addition to the continuous wavefront errors corrected by conventional adaptive optics systems, segmented pupils introduce spatially discontinuous phase errors. These errors manifest as “piston” modes representing phase steps between different pupil segments. Piston errors scatter light and degrade wavefront quality, compromising the high-contrast imaging and spectroscopy performance of instruments such as ANDES and HARMONI. Consequently, accurate, real-time piston sensing is critical for the Extremely Large Telescope (ELT) and future segmented-aperture telescopes.

In this context, we explore a wavefront-sensing concept that couples a photonic lantern to a low-resolution spectrograph. The electric field at the lantern’s single-mode outputs, which encodes piston information across the pupil, is dispersed to extract wavelength-dependent features. This enables accurate sensing of pupil piston modes while overcoming phase-wrapping ambiguities. Previous studies have addressed the highly nonlinear response of photonic lantern wavefront sensors using neural-network reconstructors: here we investigate alternative methods in the real of exaplaiable machine learning techniques, such as symbolic regression and polynomial fitting. These machine-learning techniques discover explicit analytical expressions that directly map spectral features to piston coefficients. Once identified, these closed-form mathematical expressions are computationally lightweight and fully transparent compared to opaque deep-learning models, providing a clear path toward formal verification and real-time deployment in telescope control loops.

Framed within the ANDES SCAO prototyping work package, this study directly addresses the broader co-phasing requirements of current and next-generation segmented telescopes. We detail our simulation pipeline—which models atmospheric propagation, photonic lantern injection, multi-mode-to-single-mode propagation, dispersion, and polynomial fitting or symbolic regression —and report on performance metrics by comparing the symbolic reconstructor against a conventional multilayer perceptron (MLP).

Topics:

Wavefront sensors using photonics and integrated optics

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PetalBench, the INAF Arcetri test bench for segmented telescope's wavefront sensors.

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We present the commissioning status and first experimental results of the INAF Arcetri Observatory's Petalbench, a new wavefront sensing testbench developed within the STILES project funded by the Italian PNRR programme. The facility has been designed and developed as a flexible platform for the laboratory validation and characterization of wavefront sensors dedicated to segmented telescopes and adaptive optics applications. The optical layout includes a custom seven-segment PetalMirror with a fixed central segment and six independent piston tip tilt (PTT) petals. The facility includes internal metrology for alignment, phasing and the possibility to inject controlled perturbation residuals. We report the ongoing characterization of the long and short-term stability, precision and accuracy of the segmented mirror, providing quantitative assessment of its suitability for high-precision wavefront sensing experiments. The readiness of the facility will be highlighted presenting the integration and first measurement result obtained with the CIAO CIAO wavefront sensor, developed, designed and integrated at INAF Arcettri's AO laboratory.

Topics:

Laboratory and on-sky demonstration

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Water-Vapor Seeing in the Mid-Infrared: Insights from VLTI Data for ELT/METIS High-Contrast Imaging

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The dynamic fluctuations in atmospheric water-vapor (WV) content play a critical role in determining the quality of ground-based wavefronts at infrared wavelengths. While adaptive optics (AO) can effectively correct atmospheric turbulence in the visible and near-infrared, the strong chromaticity of water-vapor-induced phase fluctuations introduces an additional and wavelength-dependent limitation, particularly in the mid-infrared.
In this study, we use high-temporal-resolution infrared interferometric observations from the Very Large Telescope Interferometer (VLTI), we estimate variations in atmospheric water-vapor column density through a detailed analysis of K-band fringe-tracker measurements from the GARVITY instrument. We examine the dependence of the RMS differential WV column density (σ_Σ) on precipitable water vapor (PWV), airmass, seeing, and wind speed across multiple VLTI configurations.

Among these parameters, PWV shows the strongest correlation with σ_{Σ}. We further explore the influence of the vertical PWV distribution on this relationship. The wavefront error associated with this phenomenon on ELT scale is approximately 15~nm RMS in the L-band and 175~nm RMS in the N-band, relative to the K-band. Our analysis shows that, following single-conjugate adaptive optics (SCAO) correction in the near-infrared, the residual wavefront error induced by water-vapor seeing can become a dominant component of the wavefront error budget for METIS, particularly in the N band (8–13 μm).

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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The extragalactic SOUL of the LBT's adaptive optics

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In the era of reliable, powerful, and affordable sodium (Na) Laser Guide Stars (LGS), the role of Natural Guide Star (NGS) wavefront sensing is often seen as relegated to high-contrast observations and the detection of low-order modes that are invisible to LGS wavefront sensors. While these are undoubtedly the primary roles for NGS wavefront sensors (WFSs) today, fully exploiting the faint-end regime of NGS Adaptive Optics (AO) systems can yield significant additional astrophysical returns under certain conditions. This is demonstrated by the Large Binocular Telescope (LBT) AO system, where sodium LGS is unavailable; here, instruments fed by the SOUL systems are currently being successfully utilized for both high-contrast and extragalactic observations.
In this work, we present the optimization and tuning of the SOUL pyramid WFS, which provides AO correction using reference stars as faint as Grp = 17 and flux levels down to 1 e^-/pixel/frame. The lessons learned from SOUL demonstrate that other NGS Single Conjugate Adaptive Optics (SCAO) systems—originally designed for bright-end regimes—can expand their scientific scope to include extragalactic targets through appropriate system tuning, with minimal to no impact on the hardware design. We show how this strategy applies directly to the ANDES instrument for the Extremely Large Telescope (E-ELT). More generally, all E-ELT SCAO systems feature a similar architecture to SOUL, utilizing pyramid WFSs and the M4 deformable mirror as a corrector. Consequently, these findings are highly relevant beyond the ANDES AO system alone, especially given that early science on the E-ELT will rely on SCAO corrections while awaiting the commissioning of MORFEO, the telescope's only AO system equipped to exploit sodium LGS.

Topics:

Laboratory and on-sky demonstration

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Development of a Space-Based Metal-Mirror Telescope Prototype with Active Optics Correction

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Conventional space telescopes use low coefficient of thermal expansion (CTE) materials such as Zerodur, Silicon carbide (SiC), Beryllium, and ULE glass to maintain optical surface quality under launch loads and thermo-mechanical disturbances. Although effective, these materials are heavy and expensive. Space based telescopes require high optical performance with minimum system mass and cost, motivating the use of lightweight metal mirrors with active optics correction to achieve diffraction-limited imaging. The aim of the project is to demonstrate the feasibility of active optics for lightweight metal-mirror telescopes and provide a scalable approach for future space-based imaging missions.

This work presents the optical design and end -to-end simulation of an active optics correction system integrated with a small aperture (~200 mm) metal-mirror telescope system designed for high-resolution Earth observation. Optical sensitivity, tolerance and thermal analyses were carried out to evaluate the effects of temperature variations and alignment errors on the optical performance. Both focal-plane wavefront sensing and Shack–Hartmann wavefront sensing were implemented and experimentally evaluated in the laboratory for wavefront estimation and correction using a deformable mirror. The goal is to demonstrate diffraction-limited imaging performance from a native optical system with an initial wavefront error of approximately λ/5–λ/10.

Topics:

Laboratory and on-sky demonstration

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Wavefront control for photonic lantern optimization

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We present a new photonic pathway toward high-contrast wavefront control by applying the DrWHO empirical optimization framework to a photonic lantern (PL). Classical DrWHO implementations rely on separate science and wavefront sensors, limiting performance due to non-common path aberrations, chromatic effects, and synchronization issues. Replacing the focal-plane detector with a photonic lantern feeding a single detector provides simultaneous spectral and spatial information, enabling high contrast at ~0.5λ/D angular separations. In this architecture, single-mode fibers act as directional spatial filters: concentrating stellar light into one fiber makes the remaining fibers sensitive to off-axis planetary signals. DrWHO iteratively learns the WFS state that maximizes a chosen metric, either for blind searches - by driving stellar light into one fiber - or targeted detection, by optimizing the coupling of stellar and planetary flux across selected fibers. This photonic approach, enhances sensitivity to narrowband emission such as Hα and supports sub-λ/D detection of accreting protoplanets. We will also present 1:1 mapping from the WFS and the PL, showing their complementarity for wavefront control.

Topics:

Wavefront sensors using photonics and integrated optics

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Prototyping Results of the Relay-Optics-Free Shack–Hartmann Wavefront Sensor for the GMT Laser Tomographic Adaptive Optics

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The Giant Magellan Telescope Laser Tomographic Adaptive Optics (GMT-LTAO) system requires six Shack-Hartmann sensors for its wavefront sensing system called the Laser Tomography Wavefront Sensor (LTWS). To minimize the system size and complexity, we have developed a "relay-optics-free" configuration, where a custom-designed microlens array (MLA) is positioned directly in front of the CMOS detector. By removing the detector's protective window and utilizing a very short back-focal length (0.105 mm), this design eliminates the need for conventional relay optics, thereby reducing optical losses and mechanical volume. In this paper, we present the design and prototyping results of this configuration. We successfully implemented a specialized mechanical interface for the C-BLUE 2 camera to achieve high-precision alignment and conducted a dry-nitrogen purging procedure to enable stable operation at low temperatures without condensation. Our experimental results demonstrate that the spot grid alignment is determined solely by the MLA's manufacturing precision. While a spatial gradient in the spot size and subaperture pixel scale was observed, indicating a slight tilt between the MLA and the detector plane, the overall performance meets the fundamental requirements for the GMT-LTAO. These results validate the feasibility of the relay-optics-free architecture as a robust and compact solution for next-generation adaptive optics systems.

Topics:

Laboratory and on-sky demonstration

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Simulation based investigation and validation of a Outer-Scale (L0) diagnostic using IFU observations.

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Atmospheric turbulence cannot simply be described using Fried's parameter (r_0) alone. Additionally, the atmospheric wavefront outer scale (L_0) is required to set the scale of the largest turbulent eddies. L_0 predominantly influences the low-spatial-frequencies (mainly, tip-tilt) which conventional wavefront

sensors (Shack–Hartmann, pyramid) are poorly equipped to constrain directly, since their subaperture/pupil sampling saturates well below L_0. Yet L_0 governs tip-tilt anisoplanatism and the achievable sky coverage of wide-field and laser-guide-star-assisted tip-tilt sensing architectures, making it a key input for wavefront sensor and AO system design and even more so for upcoming extremely large telescopes whose scale approaches that of L_0.

\vspace{7pt}

Garcia-Lorenzo et al. (2024, A&A 687, A40) proposed a focal-plane, WFS-free route to L_0: comparing the wavelength-dependent image quality in seeing-limited integral-field spectroscopic (IFS) data against a first-order von Karman/Tokovinin prediction, applied to VLT/MUSE. Discrepancies between measurement and prediction were attributed to seeing uncertainty and dome-induced turbulence, but real data alone cannot isolate genuine physical effects from systematics intrinsic to the method itself. We therefore present a simulation-based stress test of this technique using OOPAO-generated turbulence with known injected r_0 and L_0, propagated through fibre-IFU-like spatial sampling and inverted with the same pipeline used on real data. We study the degeneracy between r_0 and L_0, the effects of IFU spatial binning, the properties of the Moffat profile used to fit the PSFs, and any systematic effects introduced by OOPAO's simulated turbulence that deviate from theoretical or empirical expectations. We also plan to extend these methods to analyse KOALA IFU data from the Anglo-Australian Telescope in the near future.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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The MORFEO MCAO Control Strategy

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MORFEO (Multiconjugate adaptive Optics Relay For ELT Observations) is the MCAO system designed for the Extremely Large Telescope, featuring a complex architecture with three deformable mirrors, over 6000 actuators, and 12 wavefront sensors. As the project consolidates its Final Design baseline, the control strategy relies on a specialized split-tomography approach tailored to address the unique scaling and opto-mechanical challenges of a 39-meter aperture.

The MORFEO control architecture distributes the wavefront sensing tasks across three distinct sensor networks. High-order turbulence is tomographically reconstructed using six Laser Guide Stars (LGSs). However, because sodium layer altitude variations induce a focus aberration that severely scales with the telescope diameter, average and differential field focus are completely filtered from the LGS measurements to avoid large wavefront errors. Consequently, tip-tilt, plate scale, and focus are exclusively controlled by fast, low-order Natural Guide Star (NGS) sensors operating in the infrared.

To complement this, a low-bandwidth truth-sensing loop utilizes three visible-band Reference NGSs to detrend non-common path aberrations and LGS sensing artifacts, such as spot truncation and sodium profile variations. These truth-sensing corrections are applied directly as modal offsets to prevent cross-talk within the main tomographic reconstructor. The control baseline is further enriched by dedicated strategies for specific ELT challenges, including an optimized Infinite Impulse Response filter to reject severe M2 windshake on tip-tilt modes, and out-of-focus focal plane sensing (LIFT) to explicitly track telescope petal modes.

Finally, to maximize sky coverage, the NGS loops must handle stars of varying magnitudes, resulting in disparate, asynchronous frame rates ranging from 10 Hz to 1000 Hz. To fuse these signals without injecting transient step commands into the actuators, MORFEO implements a robust multirate sensor fusion framework based on complementary filtering that seamlessly integrates asynchronous measurements while naturally driving the steady-state differential tracking error to zero.

Supported by end-to-end simulations, this comprehensive control architecture provides a robust, implementation-ready baseline capable of meeting the stringent requirements of MORFEO.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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Practical deep holographic Fourier-plane wavefront sensors

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This work presents our advances in developing an optical computing framework for deep holographic Fourier-plane wavefront sensors, including the numerical design of pyramid-like Fourier filters, their holographic recording, their implementation in an adaptive optics bench, the acquisition of experimental sensor data, the training of companion neural net reconstructors, and their validation in closed-loop operation. The results demonstrate that holographically recorded Fourier-plane filters can operate as functional wavefront-sensing elements and can be successfully combined with learned modal reconstruction for adaptive optics applications, no matter the chosen initial Fourier-plane geometry. An important outcome of this study is that the proposed deep holographic sensors were able to estimate aberrations and sustain stable closed-loop correction under severe aberration regimes, making them a suitable candidate for compact adaptive optics systems aimed for small telescopes, leading to cost-effective, modulation-free, Fourier-based wavefront sensors for a myriad of applications.

Topics:

New technique, design, and concept

33

Toward MCAO Applications of SLM-Based Wavefront Sensing

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MATTO (Multi-conjugate Adaptive Techniques Test Optics) is a testbench designed to develop and validate next-generation multi-conjugate adaptive optics (MCAO) technologies, new wavefront sensors (WFSs), and advanced reconstruction algorithms. Currently in its AIT phase at the INAF Astronomical Observatory of Padova, MATTO features a highly modular design capable of simulating a broad range of atmospheric conditions, guide-star configurations, and wavefront sensor choice. In particular, physical WFS optics across all six channels in its sensing module are replaced with Spatial Light Modulators (SLMs) to enable easy switching between WFS configurations.
This contribution focuses on the implementation and the operational performance of SLM-based wavefront sensing in a MCAO framework Focusing our initial evaluations on the four-faced Pyramid WFS simulation, we present the optical performance, practical advantages, and physical constraints of using SLMs, comparing our results with existing implementations of this technique. Furthermore, we demonstrate that we can reproduce a Pyramid modulation by taking direct advantage of the dynamic capabilities of SLMs. This approach can overcome the need for tip-tilt steering mirrors in the sensing channels, but it requires precise temporal synchronization between SLM frame updates and the exposure windows of the WFS cameras. We show how we achieved this synchronization by exploiting DAO4MATTO, a custom real-time controller built upon the Durham Adaptive Optics package that provides low-latency data exchange. Finally, we detail the ongoing integration of these SLM-based WFS units into a wide-field MCAO framework for mini-MATTO, a scaled-down precursory version of the testbench. We will summarize the current achievements and outlining key technical steps ahead.

Topics:

Laboratory and on-sky demonstration

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Characterization and experimental results from the Ingot WFS ELT- scale bench

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Extremely Large Telescopes (ELTs) rely on Sodium Laser Guide Stars (LGSs) to achieve high sky coverage and uniform Strehl ratios across wide fields of view. However, traditional Shack-Hartmann wavefront sensors (WFSs) suffer from severe LGS spot elongation, reaching more than 20 arcsec at furthest subaperture from the laser launcher at the ELT. This forces the use of mitigation strategies like subaperture masking and spot truncation, inevitably degrading measurement sensitivity and losing valuable photons. The Ingot Wavefront Sensor (I-WFS) addresses these limitations by matching the 3D geometry of the sodium beacon image at the focal plane, fully recovering the beacon flux while achieving the higher wavefront sensitivity of a pupil-plane sensor.

Over the past years, the I-WFS project has progressed from end-to-end simulations and alignment optimization to experimental laboratory validation. Recently, an upgraded optical testbed was implemented and aligned to closely replicate the F/5 beam of the ELT MORFEO LGS-WFS module. The setup allocates a dedicated path for a parallel Shack-Hartmann channel, which will be integrated in the near future to allow direct comparison with the I-WFS. This Ingot WFS ELT- scale bench is now fully operational with an Alpao DM292 and a dynamic fluorescent Rhodamine-6G LGS source capable of reproducing time-evolving mesospheric sodium density profiles.

Here, we present the latest experimental results from this testbench: we report on the characterization of I-WFS linearity and dynamic stroke across Zernike modes, evaluate wavefront reconstruction using distinct interaction matrix approaches, and demonstrate a path towards a stable low-speed closed-loop convergence. Finally, we start outlining control strategies designed to decouple optical wavefront aberrations from sodium layer profile variations, establishing key operational prerequisites for future on-sky validation.

Topics:

Laboratory and on-sky demonstration

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EKARUS: first light and commissioning of an AO R&D platform at Asiago Observatory

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EKARUS is the newly installed adaptive optics platform at Asiago Copernico telescope in Italy, led by ONERA/LAM and INAF, in collaboration with Durham University. The objective of EKARUS is twofold: serving as a platform for teaching AO to young astronomers and driving the research and development of new technologies for the next generation AO instruments.
In its current configuration, the visible channel (600 nm–900 nm), built around a double pyramid wavefront sensor, a modulator, and a 24×24 ALPAO DM468 deformable mirror, was successfully tested on-sky last August. The bench has been designed to be modular and accessible for remote on-sky testing. Future development stages will add a second SCAO stage operating between 900–1600 nm, multiple visitor ports, and dedicated modules, including a pupil-fragmentation unit for ELT-like segmentation tests and a coronagraph arm for XAO studies. This talk will present the project status, preliminary first-light results, and upcoming integration plans.

Topics:

Laboratory and on-sky demonstration

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Performance of attention-based deep learning models in Shack-Hartmann wavefront sensor measurements

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We present a performance study of attention-based deep-learning reconstruction for Shack-Hartmann wavefront sensors (SHWFSs) using simulated Subaru Telescope pupil data. A dataset of 3.5 million open-loop turbulent phase and SHWFS image pairs was generated across 8×8, 16×16, 20×20, and 32×32 subaperture configurations, including photon noise, background, and detector read noise. A Vision Transformer (ViT) that operates directly on the full SHWFS image was evaluated against a convolutional U-Net and a linear maximum-a-posteriori reconstructor.
Across all sampling configurations, the ViT achieved the lowest overall residual phase variance. Its advantage was particularly evident in the high-order modal regime, where it delivered approximately 1.5 times lower median residual variance per mode than the U-Net for the 32×32 case. These results indicate that attention-based reconstruction can exploit global pupil-scale correlations and information contained in the full subaperture intensity distribution, beyond the localized spot-position information used by conventional approaches. The U-Net remained competitive, but showed reduced accuracy for global high-spatial-frequency phase structure.
Alongside this empirical comparison, we are developing an analytical framework to characterize the observed modal performance. Our goal is to compare the learned reconstruction behavior with the conventional SHWFS limits in a common physical framework. This effort aims to make the observed high-order gains interpretable in terms of measurement performance and relevant adaptive-optics correction regimes. Our results indicate that attention-based SHWFS reconstruction is a promising approach for future Subaru AO telemetry processing and next-generation adaptive-optics systems such as ULTIMATE-Subaru.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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Wavefront Sensor Data Fusion for Extreme Adaptive Optics

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The ultimate question “Are we alone in the universe?” is leading scientists and technicians to develop extreme adaptive optics (ExAO) systems for ground observatories, in an effort to reach the equally extreme contrast levels required for the direct imaging of exoplanets. The high contrast performance of such systems is, however, limited to favourable observing conditions: namely, good seeing and bright targets. In this contribution, we explore the potential of employing multiple wavefront sensors (WFS) in single-conjugated, extreme AO to increase the limiting magnitude at which high performance can be achieved. In particular, we study, in simulation, the optimal configuration of two WFS in terms of the number of subapertures and sampling frequency, for different source brightness levels. We then compare different methods to optimally combine the WFS’ signals at different frame rates. We focus on the pyramid WFS, as it offers excellent sensitivity to both phase and amplitude aberrations, as well as flexibility in changing its sensitivity/dynamic range (modulation radius) and the number of subapertures.

Topics:

Wavefront reconstruction, prediction, AI, and simulation

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HOGS 2026 Update on Current Status and Future Development of Wavefront Sensing for Satellite Free-Space Optical Communications and Quantum Key Distribution

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Satellite-to-ground optical links are a key enabling technology for future quantum networks. The performance and availability of these links can be improved with adaptive optics (AO) by compensating for atmospheric wavefront distortions. However, the effectiveness of an AO system is ultimately limited by the wavefront sensing and reconstruction process, particularly under challenging operating conditions. These include strong optical turbulence at urban ground station sites, increasing demand for daytime operation, and satellite passes at low elevation angles.

To better understand and anticipate system performance under these conditions, representative simulation and laboratory environments are required alongside telescope-based experiments. Such platforms provide a controlled and repeatable means to recreate operational scenarios, investigate performance limitations, and assess the impact of atmospheric conditions on wavefront sensing and correction.

We present the current status and future development of wavefront sensing activities within the Hub Optical Ground Station (HOGS) at Heriot-Watt University. The work combines numerical simulation tools, laboratory validation capabilities, and ground-station development activities aimed at supporting the testing and verification of wavefront sensing technologies for satellite quantum key distribution and free-space optical communication systems. Together, these capabilities provide a pathway for identifying operational regimes that may limit AO performance and guide future system development.

Topics:

Novel wavefront sensor needs and beyond astronomy

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Development and Performance Testing of the ELT AO Simulator for LOR

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The Extremely Large Telescope (ELT) will use advanced Adaptive Optics (AO) systems to improve the image quality at visible and infrared wavelengths. One of the AO modules developed for the ELT is MORFEO, which uses Multi-Conjugate Adaptive Optics (MCAO) to provide atmospheric correction. Within MORFEO, the Low-Order and Reference (LOR) module performs Natural Guide Star (NGS) wavefront sensing and provides information required for the AO correction.

In this work, the LOR AO Simulator is developed by modifying the Deformable Mirror Simulator (DSMSim), which was originally designed as a hardware test tool for the ERIS instrument at ESO's Very Large Telescope. The simulator is adapted to reproduce the main optical conditions required for the LOR WFS, including an f/17.7 input beam and operation in visible and infrared wavelengths.

The work mainly includes modification of the optical setup, alignment, beam characterization, calibration, and initial performance testing of the LOR WFS. The developed simulator will be used for further testing and validation of the LOR module before its integration with MORFEO.

Topics:

Others

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Accreting Protoplanets At Extreme Contrasts and Angular Separations with Subaru/FIRST-PL

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High-Contrast Imaging (HCI) of exoplanets at small angular separations is restricted by residual speckle noise and focal-plane mask constraints. To circumvent these limitations, telescope light can be injected into a Photonic Lantern (PL)—a waveguide that adiabatically tapers a multi-mode input into multiple single-mode output fibers. This maps spatial phase and amplitude distortions at the input directly to intensity variations across the output channels, enabling simultaneous wavefront control and spectroscopy at small angular separations. We demonstrate the capability of the 19-port FIRST-PL/SCExAO system as both a wavefront sensor and spectrograph in a search for Hα from accreting exoplanets. We accomplish this by applying the Direct Reinforcement Wavefront Heuristic Optimization (DRWHO) algorithm to steer the wavefront sensor reference convergence point, maximizing overall coupling efficiency while steering starlight at 656.3 nm into 5 ports and reserving 14 ports almost exclusively for planetary light. This sidesteps the need to physically separate planetary light from starlight at the focal plane, allowing direct measurement of planetary Hα flux in the isolated planet ports. We demonstrate DrWHO as a robust method for wavefront steering on post-processed data, achieving an improvement in light injection, and further discuss strategies for applying this technique on-sky for wavefront control and Hα detection. This work paves the way for leveraging PLs to search for protoplanetary signatures deeply embedded in circumstellar disks in the habitable zone of their star, nominally inaccessible by conventional adaptive optics systems.

Topics:

Wavefront sensors using photonics and integrated optics

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Adaptive Optics for Evanescent Wave Coronagraph (EvWaCo)

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From Starlight to Chip: Why Photonics Needs Wavefront Control

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Introduction to Center for Optics and Photonics at NARIT

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