"To change or not to change": Exploring the Potential of Event-Based Detectors for Wavefront Sensing

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Abstract

Event-based image sensors respond to the brightness changes in the scene; they operate differently than traditional frame-based sensors, as they only detect changes rather than registering the overall illumination during a fixed exposure time. These sensors produce an asynchronous stream of spatial-temporal events data, which includes information on the location, timestamp, and polarity of triggered events (positive vs negative change). Compared to frame-based sensors, event-based sensors offer benefits such as high temporal resolution, low latency, high dynamic range, and low power consumption. The use of event-based cameras has been explored in the fields of computer vision, navigation, and space situational awareness applications; however, their potential in Adaptive Optics and wavefront sensing has not been thoroughly investigated. We will present the numerical modelling of a Shack-Hartmann wavefront sensor equipped with an event-based detector, demonstrating its ability to estimate spot displacement with remarkable speed and sensitivity in low-light conditions. This study will also present the results of end-to-end simulations with AO tools, conducted to evaluate the performance of the event-based wavefront sensor in various scenarios, including different levels of turbulence and varying light conditions.

24-hour continuous vertical monitoring of atmospheric optical turbulence using the 24hSHIMM

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Abstract

In this talk we will show the first example of fully continuous, 24-hour vertical monitoring of atmospheric optical turbulence. This is achieved using a novel instrument, the 24-hour Shack-Hartmann Image Motion Monitor (24hSHIMM). Optical turbulence is a fundamental limitation in free-space optical communications and ground-based astronomy. Continuous 24-hour monitoring of the optical turbulence conditions enables support for solar and astronomical telescopes with a single instrument, early indication of the quality of night by continuous measurements through twilight, and continuous data assimilation for turbulence forecasting tools to enhance their accuracy, leading to more effective scheduling of operations. The instrument is built around an off-the-shelf 30cm telescope and mount and utilises a Shack-Hartmann wavefront sensor observing a single star in the short-wave infrared to obtain continuous measurements of key optical turbulence parameters. Slope and intensity measurements from the wavefront sensor are combined to estimate a four-layer vertical optical turbulence profile. With the addition of a wind speed profile derived from meteorological forecasts and measurements from a local anemometer, the 24hSHIMM estimates the coherence length, time, angle and Rytov variance. The instrument is portable and can operate at any time of the day or night in any location, providing the field with a versatile atmospheric turbulence monitor to support the next generation of solar telescopes and astronomical ELTs.

A Constellation of Bright Orbiting Beacons for Imaging and Characterizing Rocky Earth-size Exoplanets Orbiting Sun-like stars with Ground-Based Telescopes

Marois christian [1], Johnson adam [2], Thompson william [2], Lardière olivier [1], Jackson kathryn [1], Veran jean-Pierre [1]

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Abstract

Detecting and characterizing Earth-size exoplanets by imaging around Sun-like stars to search for life signatures is a formidable challenge, requiring advanced coronagraph designs and picometer-level wavefront control to reach 1E10 contrast at a few lambda/D separation. While a dedicated highly-stable space observatory may be required to achieve such extreme observations, I will present a new concept to achieve an intermediate sky-limited ~1E8 visible-band contrast on ground-based 8 to 30-m class telescopes. The idea consists of using a constellation of orbiting ~30-cm beacons located on highly eccentric ~100,000-km orbits to allow for hour-long observations of nearby Sun-like stars. These beacons will surround the science target and generate extremely bright unresolved off-axis guide stars for ~in-band >10 KHz adaptive optics, with a goal to reach closed-loop Angstrom-level residuals on the science target. A sequence of images during the constellation transit will be post-processed and combined to reach 1E10 contrast inside the generated "dark hole" in a narrow ~1% bandpass, allowing for targeted color imaging to identify key biomarkers in the planet's atmosphere. With up to ~5x greater aperture compared to a future space observatory, ground-based 30-m class observatories could expand the imaging discovery of rocky planets closer to stars (i.e. discovering warmer inner planets, or observing later type stars), or probe systems up to 5x further away, significantly increasing the star sample size to search for and characterize Earth-size exoplanets. I will present the concept, discuss its various challenges, and showcase current projects and upcoming laboratory experiments at the NEW EARTH Laboratory to develop the technologies needed for such "extreme" instruments.

A Constellation of Bright Orbiting Beacons for Imaging and Characterizing Rocky Earth-size Exoplanets Orbiting Sun-like stars with Ground-Based Telescopes

Garcia-Rissmann aurea [1], Carrasco rodrigo [1], Diaz ruben [1], Font joan [1], Garrel vincent [1], Gomez-Jimenez manuel [1]

1 - Gemini Observatory/NSF's NOIRLab(Chile)

Abstract

As part of the plan for AO-related upgrades envisioned for the Gemini Observatory a feasibility study has been started aiming to integrate GeMS with Flamingos-2 operations. This latter, hereafter referred to as F2, is a wide-field near-infrared imager, long-slit and multi-object spectrograph with a percentage of Gemini South instruments demand currently ranging around 15-20%. The integration with GeMS can open the possibility

for an AO-corrected beam to feed spectroscopic modes, thus significantly increasing the sensitivity as well as the spectral and spatial resolutions of F2 observations covering J, H and K bands. First steps towards this goal include a characterization of the current GeMS performance with the Gemini South Adaptive Optics Imager (GSAOI) for measuring the centroid stability under nodding & sky offsets and EE/FWHM uniformity across the FoV. A discussion of the main aspects and challenges to be addressed in this feasibility study will be presented, such as the need to integrate new calibration sources in the AO path for spectroscopy, a revisit of the non-common path aberrations calibration strategy, thermal background mitigation, among others. Results from preliminary GeMS+F2 operational settings and on-sky tests will also be presented.

A geometrical approach for the calibration of Wave-Front Sensors

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Abstract

The study of Fourier Filtering Wave-Front Sensors (FF-WFS) is very active in the AO community to identify/design a WFS that provides the best compromise between sensitivity and dynamical range. This research area benefited from the theoretical work developped in Fauvarque et al (2016) to serve different applications such as optical gains tracking (Chambouleyron et al 2020). This theoretical formalism is based on the idea that the knowledge of the impulse response function of a given FF-WFS allows to characterize fully its performance, making it a very fast and powerful tool of performance prediction. In this communication, we propose to revisit this concept to a very simple application : the computation of interaction matrices. The method proposed consists of calibrating the system using a unique signal that represent the response of the system to the actuation of a single actuator. This defines the « generalized impulse response » of the system and depends on the DM influence function shape. The second ingredient consists in properly locating this response geometrically in the WFS space to match the proper DM/WFS registration. Strong hypothesis are used to proceed in such a way (uniform response of the actuators, edge effects neglected, ...) that can be taken into account adopting a hybrid calibration scheme. The advantage of such method is to reduce drastically the computation cost of the interaction matrix computation. This is of particular interest for the ELT AO instruments as all of them have considered the use of pseudo synthetic interaction matrices as their baseline with regular updates during the operations to track eventual mis-registrations errors. An analysis of the performance and validity of the method for different systems will be presented, including ELT scale systems. An experimental validation on a real AO system using the ESO-GHOST bench and/or an on-sky validation using the PAPYRUS instrument at Observatoire de Haute Provence are expected.

A Holographic Dispersed Fringe Sensor to Disambiguate Segment Piston for GMT

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3 - University of Arizona(United States)
4 - Flat Wavefronts(New Zealand)

Abstract

Diffraction-limited observing modes of the Giant Magellan Telescope will require ensuring that its doubly segmented optical design remains phased over the duration of a scientific exposure. The natural guide star wavefront sensor (NGWS) for the GMT will consist of two channels: a highly-sensitive pyramid wavefront sensor and a holographic dispersed fringe sensor (HDFS) designed to disambiguate phase wrapping that can occur in a pyramid wavefront sensor. The HDFS uses a phase mask in the pupil plane to selectively interfere GMT segment pairs in the subsequent focal plane. Multiplexed diffraction gratings over each segment are oriented so that the spectra of segment pairs are superimposed and interfere with each other. This results in a series of dispersed interference fringes that encode the segment piston differences. The dynamic range of the HDFS is ± 12 waves wavefront. This paper will present the design of the HDFS channel of the NGWS and give an update on the development and testing of a lab prototype.

A low-cost, high-speed,very high-order Shack-Hartmann sensor for testing TMT deformable mirrors

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Abstract

The Thirty Meter Telescope will use a sophisticated adaptive optics system called NFIRAOS. This system utilizes two deformable mirrors conjugate to 0 km and 11.2 km to apply a Multi-Conjugate Adaptive Optics (MCAO) correction over a 2 arcminute field of view. DM0 and DM11 have 63 and 75 actuators across their respective diameters. To study the behavior of these mirrors, we have developed a low-cost, very high-order Shack-Hartmann Wavefront Sensor (WFS). We will use our WFS to calibrate the flatness of the DMs and measure the influence functions of the actuators. NFIRAOS is cooled to reduce the thermal emissivity of optical surfaces visible to the science detectors, so we will also measure the behaviour of the DMs in both warm and cold environments. As the cold chamber is prone to vibrations, a WFS is preferred to a phase-shifting interferometer. Our design was driven by the need to be able to evaluate the DM surface between the actuators, which led to the requirement of at least 248 sub apertures across the diameter. The largest commercially available Shack-Hartmann WFS has only 128 sub-apertures across the diameter, which is not enough to properly sample these DMs. Furthermore, the designed sensor is able to record the wavefront at 50 FPS (50 times per second) at full resolution. To fabricate this WFS, we used a commercial off-the-shelf CMOS detector, camera lens, and lens let array, which kept the total cost less than 20K USD. Here we present the design and performance characteristics of this device.

A new fibered NIR spectrograph for novel wavefront sensing techniques on SCExAO

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Abstract

The advancement of astrophotonics, especially for wavefront sensing, is one of the key goals of the high-contrast instrument SCExAO. We are now demonstrating the use of photonic lanterns in the focal plane as a wavefront sensor (PLWFS), as well as nulling interferometry with GLINT, or more conventional high-contrast high-resolution spectroscopy with REACH-IRD. For the PLWFS project, after successful demonstrations using narrow bandwidth light, we are moving to polychromatic tests using a newly developed NIR spectrograph using First Light Imaging's C-RED ONE camera. The diffraction limited spectrograph, providing a resolution of 200 to 600 over 1 to 1.8 um (y- to H-band), was designed to be compatible with any other fibered modules like GLINT and REACH, and can adapt to a large variety of single mode fiber bundles. A photometric mode is also available and can be used for injection optimization. The opto-mechanical design was challenging due to the small amount of space available inside SCExAO, in front of the camera already used for polarimetric differential imaging, but also due to the camera itself with its cold stop, filter stack and recessed detector. We will present here the opto-mechanical design of the spectrograph, as well as the first lab and on-sky results.

A novel approach to interaction matrix calibration at THEMIS: accuracy analysis and extension to a temporal model

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Abstract

Performance and stability of a closed-loop Adaptive Optics (AO) system are strongly related to the ability of the controller to model the response of the wavefront sensors to commands sent to the deformable mirrors. In most AO systems, this is modelled by the so-called Interaction Matrix (IM) which has to be calibrated. While most AO systems calibrate the IM on an internal source, implementing the deformable mirror (DM) in the telescope requires more and more systems calibrate the IM on sky. But this difficulty brings advantages. For example, the calibration can take into account source specificities such as the elongation of laser guide stars or the structure of the solar granulation. Furthermore, if the calibration is done at the system full speed, temporal effects can also be calibrated, such as the temporal response of the DM. This is the strategy followed on THEMIS AO, relying on original solutions for its wavefront sensing, its control, and its calibration, each one based on an inverse problem approach. We present in this work the interaction matrix calibration and we analyze the quality and features that can be obtained from this original approach. In THEMIS AO, the IM is calibrated during open-loop observations of the sun granulation using a

binomial random distribution of perturbation commands. The properties and benefits of this approach are analyzed. The uncertainties on the obtained IMs perfectly follow the theory. Data are compared to theory in Fig. 1 (left) showing noise decrease as $(\varepsilon \sqrt{nt})^{-1}$ with nt the number of measurements and ε the ratio between the standard deviations of the perturbation and of the turbulence. For THEMIS AO, residual calibration errors suggest that a time dependent model of the IM is needed. To account for the temporal response of the DM in the controller, our calibration approach has thus been extended to fit an IM model consisting in a sequence of matrices. We show that, in practice, 2 components are sufficient and that the second IM matrix is well approximated by the first one times a simple factor. Figure 1 (right) shows the relative contribution of the 2-component IM fitted on THEMIS calibration data. Our time dependent IM model thus amounts to applying the static IM matrix to the current commands plus a fraction (11% here) of the previous commands. THEMIS calibration approaches and results are of importance for other high-frequency AO systems, particularly for High-Contrast AO systems.

A Novel Wavefront Sensor for Solar Adaptive Optics Based on Integrated Photonics

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Abstract

In this work, a novel kind of wavefront sensor (WFS) for adaptive optics in solar physics based on integrated photonics is proposed. Shack-Hartmann and plenoptic sensors are limited to pupil sampling of approximately 8 cm because they need a solar granulation image with a minimum contrast to be able to compute displacements. To overcome this limitation and effectively use existing deformable mirrors with thousands of actuators, a novel wavefront sensor is proposed, which will be able to obtain wavefront phase differences of the beam with higher pupil sampling. The proposed wavefront sensor can increase the resolution and the speed with respect to the other sensors as the incoming wavefront is obtained by passing the wavefront through optical fibres to the integrated photonics wavefront sensor (IP-WFS) and directly measuring the phase differences without the generation of images. In the same way as Shack-Hartmann and plenoptic sensors, the proposed IP-WFS delivers data about the phase differences on the incoming wavefront to subsequently use this information to calculate the deformable mirror actuation. Consequently, the integration of the proposed IP-WFS in the current systems of adaptive optics can be performed without having to make drastic modifications to the existing instruments.

A PSF estimation method using gaussian mixtures

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Abstract

It is well known that one of the main challenges of adaptive optics (AO) corrected images post-processing is the missing of information about the Point Spread Function (PSF) of the optical system. Typically, the PSF is not always available and therefore it is necessary to estimate the PSF from the scientific images or the AO system telemetry. In this work we address the PSF estimation and deconvolution using a finite gaussian mixture.

A pupil-plane LGS Wavefront sensor for the next-generation telescopes: the Ingot WFS

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2 - ADONI - Laboratorio Nazionale di Ottica Adattiva(Italy)

Abstract

We present a well-known concept of pupil-plane WFS, proposed 20 years ago, but developed recently to cope with some typical limitations and problems of using LGS, especially on 40m-class telescopes. The main advantages will be to overcome the truncation problem, to be sensitive to the island effects and, not as a secondary aspect, to be optomechanically compatible with the vast part of the existing WFS-LGS system and doable with a smaller format detector. We called it "Ingot", looking at its final design, even if we started from a more complicated initial 6 faces concept and here we describe the possible combinations and configurations. We also focus on the characterization of the LGS in the focal volume and the optical/geometrical description of the Ingot WFS. Then we provide a first order comparative analysis with other approaches, by using some relationships to quantify its sensitivity. Finally, we describe the project and the progress of each work-package, in terms of numerical simulations, lab activity and preparation for validation.

A simulator-based autoencoder approach for focal-plane wavefront sensing: application to the SCExAO instrument

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2 - Montefiore Institute of Electrical Engineering and Computer Science
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Abstract

High-contrast imaging instruments are today primarily limited by non-common path aberrations appearing between the scientific and wavefront sensing arms. These aberrations can produce quasi-static speckles in science images that are difficult to distinguish from exoplanet signatures. With the help of recent advances in deep learning, we have implemented convolutional neural networks (CNN) to estimate pupil-plane phase aberrations from point spread functions (PSF). The approach we propose here is to introduce into the deep learning architecture a differentiable simulator of the instrument. To do so, we create an autoencoder-like architecture, with a deep CNN as the encoder and the simulator as the decoder, while the latent space represents phase aberrations. Because this unsupervised learning approach reconstructs the PSFs, it is not required to know the true wavefront aberrations in order to train the models. Following our earlier work based only on simulated data, we now assess how our method performs on laboratory and on-sky data using the SCExAO instrument installed at the Subaru Telescope. Our simulator-based autoencoder approach is particularly motivated for on-sky applications because the ground truth is not available in this case. By taking into account prediction uncertainties and prior information, we also apply a variational inference approach and investigate how it can improve the robustness of the models.

A Test bench for future MCAO techniques validation

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3 - Università degli Studi di Padova(Italy)

Abstract

We present MATTO (Multi-conjugate Adaptive Techniques Test Optics), a wide field AO testbench, under development at the Astronomical Observatory of Padova. It is conceived as a wide field AO facility, aimed to serve as a test bench for the study and development of MCAO techniques, under a wide range of conditions. As the test bench is devised to be used in the future to reach proof of concept of new techniques, it is conceived to be flexible, thus it is divided into independently-configurable modules. The first is a reference source module, including a number of opto-mechanical groups producing atmosphere-perturbed reference beams. Both natural and artificial references (characterized by different light spectra and geometries) can be simulated. A telescope simulator module then combines the light coming from the references, mimicking the geometry of the beams in the lower atmosphere. The MCAO correction module is designed to simulate a wide variety of compensation schemes, thanks to the combination of three large DMs, allowing conjugation at any equivalent distance. Finally, a sensing module can simulate a wide variety of wavefront sensors, including both pupil plane and focal plane techniques, and mimic optical phase-modifiers (e.g. roof, pyramid, ...). A flexible setup allows positioning of sensing and perturbing elements in different optical positions. We here present the conceptual scheme and opto-mechanical design, together with the control approach under development.

Accuracy and Computational Efficiency of Various Methods for Atmospheric Turbulence Structure Function Computation

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Abstract

Structure functions are a measure of the variations in air density and thus refractive index and wavefront phase caused by atmospheric turbulence. They are often used to verify numerically generated phase screens for use in numerical simulations or with, for example, spatial light modulators. The usual method of calculating the structure function of such a screen in principle requires the comparison of each pixel with every other pixel, a computationally complex and time-consuming process. This paper will compare alternative methods for calculating the structure function of numerically generated atmospheric turbulence. Specifically, it evaluates the efficiency and accuracy of the methods and highlights the strengths and limitations of each. The study aims to help researchers select the appropriate method for their specific needs, choosing between faster computation, or higher accuracy.

Adaptive optics for high contrast and very large array optical interferometry without WFSs and DMs using integrated photonics devices and a digital signal modulated satellite beacon

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1 - National Research Council Canada(Canada)
2 - National Research Council Canada(NRC-Advanced Photonics & Electronics)(Canada)

Abstract

For high contrast imaging, atmospheric turbulence may be sensed and corrected at very high bandwidth without WFS or deformable mirrors using phase correcting integrated photonics devices and advanced signal processing. This method employs a satellite loitering near a science object to send a time-coded reference laser to telescopes on the ground. It permits coherently combining arrays of optical telescopes to give unprecedented micro-arcsecond resolution in the near infrared to obtain image and spectral data cubes of extrasolar planets. The method is also useful for satellite communications. The overall system employs radio astronomy techniques developed for clock distribution, to sense and correct phase, and radio interferometry procedures to produce high resolution images. One of the tallest poles in high-contrast AO is the frame rate. Our simulation models estimate correction bandwidth might be 1-2 orders of magnitude faster than current high contrast AO. We have designed and measured a 32 channel astrophotonics phase sensing and correcting device, which is low-cost and compact due to its telecommunications heritage. We are developing a prototype AO system to test the concept, first on a lab bench and then using a telescope pointed at sources on a tower. We present simulations and prototype testing and what we have learned about limitations that merit continued technology developments.

Adaptive Optics Infrastructure Development for High-contrast Science at Keck Observatory

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2 - UCSC(United States)
3 - UCI(United States)
4 - MICROGATE(Italy)
5 - Caltech(United States)

Abstract

W.M. Keck Observatory (WMKO) has endeavored to continually improve the capabilities of the Keck adaptive optics (AO) systems since first Keck AO science over two decades ago [1]. We present the Keck AO infrastructure developments to enhance the high-contrast imaging capability and fully benefit from the next-generation high-contrast science instruments implemented or under development (i.e., SCALES [2] and HISPEC [3]) for Keck II AO. One of the development goals is to set a pathway towards detecting exo-Earths with ELTs. This paper focuses on three ongoing developments, namely, (1) the new real-time controller (RTC [4]), (2) a new near-infrared pyramid wavefront sensor (PyWFS), (3) the High order Advanced Keck Adaptive optics (HAKA) project [5], and (4) the residual wavefront controller (rWFC [5]) developments, to enhance the high-contrast imaging capability at WMKO. The new RTC, with its high performance and flexible capabilities, will enable the implementation of future algorithms and next-generation AO capabilities. We will present the on-sky performance of the new RTC commissioned on the Keck AO systems. The new near-infrared PyWFS would improve the performance of future high-contrast imaging instruments, such as the SCALES and HISPEC, and enable new AO observing capabilities, such as LGS with NIR low-order wavefront sensing. We present the design of the new near-infrared PyWFS. The HAKA project would upgrade the existing 349-actuator DM with a state-of-the-art 2900-actuator deformable mirror (DM) fabricated at ALPAO. We present the status of HAKA, including the design of the integration of the high-order DM with the new RTC, and the expected on-sky performance. Uncorrected residual wavefront errors limit the ultimate performance of AO systems, especially the raw contrast for high-contrast imaging studies. The recently proposed new AO subsystem, a residual wavefront controller (rWFC), to monitor the performance of the AO control loops and the image quality of the AO science instruments and apply the necessary changes to the telescope and AO parameters would minimize the residual wavefront errors. We present a scheme to integrate the rWFC with the operational software, including the new RTC. The benefits of reducing or eliminating the residual wavefront errors has broad implications for optical astronomy besides high-contrast imaging. The lessons learned through the technology development will have implications for the ELTs. Testing these techniques on a segmented telescope will be extremely useful for teams developing high-contrast AO systems for all ELTs and future segmented space telescopes. References: [1] Wizinowich, P. et al., "Keck's Current and Future Roles as an ELT AO Pathfinder", 2023 (this conference) [2] Skemer, Andrew J.; Stelter, R. 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Adaptive Optics system-box for the QKD transportable ground station at IAC

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Abstract

Free space optical communications implementing QKD protocols demand sensors with very high signal to noise ratio, compatible with the reduced size of a single-mode fiber core. The use of adaptive optics allows high data throughput links, by correcting the aberrations generated by atmospheric turbulence. In this paper we present the design of an adaptive optics (AO) system-box to correct for daytime and nightime atmospheric turbulence. The system will be small enough to be implemented at the Nasmyth focus of a transmitter/receiver 70cm-aperture telescope used as a Transportable Optical Ground Station in urban sites or LEO links scenarios or in the OGS at Teide Observatory 1 meter-aperture telescope. The setup will correct for aberrations based on a plenoptic wavefront sensor camera. The optical performance of the system will be analysed, together with simulations of turbulence to estimate the increase on the coupling from free-space to SMF.

Adaptive Optics Telemetry Format

Gomes tiago [1 2], Correia carlos [2 3], Bardou lisa [4], Fusco thierry [5 6], Kulcsar caroline [7], Morris tim [4], Morujão nuno [2 8], Neichel benoit [5], Osborn james [4], Garcia paulo J V [1 2]

1 - Faculdade de Engenharia da Universidade do Porto(Portugal)
2 - CENTRA - Center for Astrophysics and Gravitation(Portugal)
3 - Space ODT - Optical Deblurring Technologies(Portugal)
4 - Durham University(United Kingdom)
5 - Aix-Marseille Université(France)
6 - DOTA
ONERA
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7 - Institut d'Optique Graduate School(France)
8 - Departamento de Física e Astronomia
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Abstract

Context:There is a growing volume of AO telemetry data being generated in facility-class ground-based VIS/NIR observatories, which has highlighted the need for a standardized data exchange format to enable performance analysis and AO R&D; involving extensive telemetry mining, processing, and curation. Aims:In this paper, we present the Adaptive Optics Telemetry (AOT) data exchange format, designed to facilitate the sharing of AO telemetry from visible/infrared ground-based observatories. The AOT format is built on the Flexible Image Transport System (FITS) and aims to provide a clear and consistent means of accessing data across multiple systems and configurations, including classical natural and single/multiple laser guide-star AO systems. Methods: AOT was designed with two main use-cases in mind 1) atmospheric turbulence parameters estimation and 2) Point-spread function reconstruction (PSF-R). To support this format, a Python package that enables data conversion, reading, writing and exploration of AOT files was developed. Results: The AOT format has a well-defined file structure, including data fields, descriptions, data types, units, and expected data dimensions. A supporting Python package has been made publicly available. To demonstrate the format's versatility, we packaged data from four different 8-meter class telescopes of vastly different configurations.

Advances with the WIVERN laboratory experiment for testing novel laser-based wavefront sensing techniques

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Abstract

WIVERN is a testbed for laboratory experiments in laser-based wavefront sensing. It emulates laser uplink from a 8m telescope with 0.8 arcsec seeing and laser back-scattering from up to 20 km. Currently there are three wavefront sensing capabilities designed into the experiment. The first two are from a wide-field of view (1.0 arcmin) Shack Hartmann wavefront sensor observing a constellation of point sources at infinity (reference targets, for conventional, star-oriented wavefront sensing), or observing an image from emulated atmospheric Rayleigh/sodium back-scattering (for wide-field correlation wavefront sensing). The third is based on the PPPP concept. For both back-scattering experiments (correlation or PPPP) a laser beam can be launched from the pupil through the phase screens, scattered from a plane, and then returned through the pupil and onto the WFS. For the correlation wavefront sensing, the signal is developed as with conventional LGS, on the return path to the telescope, using contrast in the projected pattern to detect motion. Meanwhile for PPPP, the beam projected is as wide as the pupil and the intensity distortions from wavefront propagation are produced on the outwards propagation, with back-scattering emulation simply to retrieve the signal back at the telescope. Other sub-systems designed are the laser projection replicating a pupil launch, a 7x7 pupil-conjugate deformable mirror (DM), and a wide-field camera for PSF analysis. The SH WFS camera is a First Light C-Blue ONE which can measure images of 1100x1100 at upto ~500 Hz (using the DAO software, see the presentation by Cetre et al in this meeting for more information). This acquisition speed is only necessary for statistical and machine-learning analysis, but is useful for RTC development. Currently the DM is not installed and the system is used for wavefront-sensing experiments. We report in this meeting our latest progress in the correlated wavefront sensing using a laser of low coherence which generates high-contrast speckles; this is used for the correlation analysis. The aim of WIVERN Is wide-field wavefront sensing and our results report on progress with enabling multiple sub-regions within each sub-aperture. We also discuss ideas for enabling the PPPP mode for which we've encountered unanticipated design issues.

Amplitude & phase adaptive optics with a digital micro-mirror device for exoplanet high-contrast imaging

Carlotti alexis [1], Baccar salma , Leboulleux lucie , Curaba stéphane , Delboulbé alain , Jocou laurent , Moulin thibaut , Gluck laurence , Sztefek marie-Helene

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Abstract

Oncoming exoplanet spectro-imagers like the Planetary Camera and Spectrograph (PCS) for the Extremely Large Telescope (ELT) will aim for a new class of exoplanets, including Earth-like planets evolving around M dwarfs i.e., as close as 0.02" with contrasts around 10-8. This goal can be achieved using coronagraphs. Classical coronagraphs are not optimal, however: 1) they usually impose a planetary photon loss, which is particularly problematic when the instrument includes a high spectral-resolution spectrograph, 2) some aberrations such as the missing segments of the ELT are dynamic and not compatible with a static coronagraph design, 3) the coupling of the exoplanet light into a fiber for spectroscopy only requires the electric field to be controlled on a small target-dependent region of the detector. Such instruments would benefit from an adaptive tool to modulate the wavefront in both amplitude and phase. We propose to combine in the pupil plane a deformable mirror (DM) to control the phase and a digital micro-mirror device (DMD) i.e., an array made of millions of micro-mirrors able to switch between two positions, to provide a binary amplitude control. If the DM is already well-known in the field in particular for adaptive optics applications, the DMD has so far not been fully considered. At IPAG, we have assembled a testbed called CIDRE (Coronagraphy for DiRect Imaging of Exoplanets) to develop, test, calibrate, and validate the combination of these two components with a Lyot coronagraph. Since mid-2022, the testbed is operational and has entered its scientific exploitation phase albeit without the Lyot coronagraph yet, to test dynamic amplitude apodization coronagraphs (so-called Shaped Pupils). We will present the set up, and the results obtained with the CIDRE testbed.

An Adaptive Optics Community Response to Astro2020

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Abstract

In the recent Astro2020 Decadal Report, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" Adaptive Optics (AO) was identified as a crucial technology for a variety of reasons. These included an emphasis on high-contrast imaging and AO systems as being part of future technology development

especially with application to the two US ELT projects. Instrument upgrades were also identified for existing 4-10m class telescopes which would incorporate upgrades to existing AO systems. As noted in the Report: "the central role of AO instrumentation and the importance of further development are rapidly growing, with novel concepts pushing toward wider areas". "Visible AO has high potential scientific return by opening up an entire wavelength regime to high angular resolution studies. The goal is to exploit the smaller diffraction limit (~λ/D) of telescopes in the optical, yet both the coherence length and time decrease at shorter wavelengths (~λ6/5), requiring wavefront sensing at high spatial and temporal frequencies that are currently technologically challenging. This is an important developing area for the 2020s - 2030s.". "Such investments in AO systems development is a key risk mitigation strategy for ELTs, whose full resolution and sensitivity potential can only be realized with AO, and which is recognized as the most important technical risk for both GMT and TMT". The last US Community AO Roadmap, held in 2008, served to identify and prioritize AO related research topics which could be referenced in proposals submitted to various NSF/AST instrumentation programs. We will hold a workshop to develop a 2023 Community Response document to provide feedback and suggested priorities to various funding agencies, such as NSF, NASA, and DoE, as to the AO R&D; priorities to meet the technical and science objectives outlined in Astro2020 for ground-based AO, both stand-alone and in support of space missions. This NOIRLab sponsored workshop will be held in May 2023 and will comprise ~ 40 attendees broadly representing the US Community in terms of science and technology, along with agency representation. We will report on the outcome of this workshop outlining the identified R&D; priorities.

An analytical approach to model the second-stage Adaptive Optics correction for SPHERE

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Abstract

SAXO+[1] is the name of the proposed second-stage adaptive optics module to increase the performance of the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE[2]) at the Very Large Telescope (Chile). This upgrade aims at improving the raw contrast (up to 10-5, goal 10-6) close to the optical axis, enabling the observation of fainter and redder targets. In order to define the main requirements for the second-stage module design, a few trade-offs need to be carried out. We propose in this paper the use of an analytical approach, based on spatial PSD analysis, to study some error terms affecting the SAXO+ system and to directly compute the AO residual phase screens. For this purpose, a second-stage correction filter in the spatial frequency domain has been implemented in PAOLA[3], a software tool for the analytical modeling of AO systems. The results are then validated by comparing them to the output of a full end-to-end simulation tool, COMPASS[4], running with the same input parameters. [1] F. Vidal et Al, Adaptive Optics Systems VIII (2022) [2] J.-L. Beuzit et al., Astronomy & Astrophysics 631, A155 (2019) [3] L. Jolissaint, J. Europ. Opt. Soc. Rap. Public. 5 , 10055 (2010) [4] F. Ferreira et al., 2018 HPCS, Orléans, France, pp. 180-187 (2018)

An innovative SLM technology for fast achromatic and unpolarized wavefront correction

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Abstract

Spatial Light Modulators (SLM) are commonly used for wavefront correction or wavefront shaping. They feature unrivaled resolution (up to 3840x2160) in a compact form factor. However, despite the ongoing progress in performances, Liquid-crystal-based LCOS-SLM currently require polarized light, have limited speed, and a significant chromatic effects due to the phase wrapping required in most applications. This paper presents a new concept of photothermal spatial light modulator (PT-SLM) for wavefront shaping solving the major difficulties of LCOS-SLM. While keeping the main advantages of the SLM technology the new concept of PT-SLM vastly improves the optical transmission and the wavelength range of the SLMs structure, is insensitive to polarization and suppresses the diffraction artifacts resulting from the predefined pixel grid of the digital SLM. The first proof of concept results are presented, and the performance characteristics of the design are analyzed experimentally and theoretically.

An overview of the key science drivers and expected scientific performance of the combined GNAO + GIRMOS system

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Abstract

In the era between JWST and future 30m class telescopes (ELTs), current 8m class observatories can offer a critical opportunity for novel adaptive optics (AO) systems to lay the groundwork for future 2nd generation ELT instrumentation. Furthermore, these novel AO systems can achieve this feat while still providing exceptional science complimentary to JWST. One such AO system is the future combined Gemini

North Adaptive Optics (GNAO) + Gemini InfRared Multi-Object Spectrograph (GIRMOS) instruments. GNAO will offer both narrow and wide-field AO capabilities, which will feed GIRMOS. GIRMOS offers observations with a near-infrared (NIR) imager and/or four NIR integral field unit (IFU) spectrographs, where each IFU has its own deformable mirror. The workhorse mode of GNAO+GIRMOS will be multi-object adaptive optics (MOAO) IFU spectroscopy, where its main scientific goal is to survey the high redshift universe in a manner that will only be superseded by future 30m class telescopes. An additional goal of the combined instrument is to demonstrate the key capability of AO + MOAO technology on 8m telescopes, such that they can provide the critical experience and technology necessary to develop a future 2nd generation MOAO instrument on ELTs. In this work, I will present the key science we wish to achieve with GNAO + GIRMOS, including current pilot studies with existing instruments, and discuss their scientific and technical relevance with respect to current and future instrumentation. In addition to an overview of several key imaging and spectroscopic science cases, I will also present the expected performance delivered to both the imager and IFU focal planes; this performance is based on extensive modelling of the AO systems, imager and IFU spectrographs, and allows us to establish an effective integration time calculator for the combined GNAO + GIRMOS system.

Analytical tolerancing of high-contrast imaging performance under AO on the ELT

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Abstract

High-contrast imaging (HCI) from the ground will provide complementary data to space-based missions looking for habitable exoplanets. While third-generation instruments like PCS on the ELT will be optimized for the search for temperate Earth analogues, several first-generation instruments will already be equipped with coronagraphs for HCI observations, like HARMONI, METIS and MICADO. Supported by AO, these instruments will perform high-contrast observations at unprecedented angular resolution, enabled by the 39-meter aperture of the ELT. These observations, however, are very sensitive to wavefront errors (WFE). In particular the 798 segments of the primary mirror need to be well-phased to limit the contrast degradation in the image. Recent studies on WFE stability for space-based, segmented telescopes have used an analytical approach to quantify the segment-based WFE tolerances imposed by the HCI system. We present a similar analysis on a ground-based telescope, the ELT, and adapt it to account for the dominating aberration factors on the ground. The major focus of our analytical study is the HCI performance under segmentation errors when working with AO-corrected images. Apart from segment-induced phase aberrations, we also investigate segment-based amplitude aberrations with an analytical tolerancing model, which can be induced by combinations of missing segments or their varying reflectivity.

Analyzing the AO Operational Behavior of Non-sidereal Tracking on the Thirty Meter Telescope using SysML

Miles john [1]

1 - Thirty Meter Telescope(United States)

Abstract

TMT has embarked on an ongoing effort towards modeling the functional and physical architecture, behavior, requirements, and parametric relationships through system-level simulation of observation workflows, using OMG's Systems Modeling Language (SysML), to validate use-case scenarios and verify timing requirements early in the life-cycle phase. This paper presents preliminary results for non-sidereal tracking scenarios, especially for fast targets where the on-instrument wavefront sensors must hand off from one guide star to another. Operational modes and behavior are modeled using activity diagrams. Scenarios are captured primarily using sequence and activity diagrams. Verifiable requirements are formally captured using constraints on properties. This type of modeling can be particularly useful when investigating the effect of parallelizing or re-ordering sequence tasks.

Analyzing the AO Operational Behavior of Non-sidereal Tracking on the Thirty Meter Telescope using SysML

Miles john [1], Trancho gelys , Wang lianqi , Boyer corinne , Herriot glen , Andersen david , Ellerbroek brent , Karban robert

1 - TMT International Observatory(United States)

Abstract

TMT has embarked on an ongoing effort towards modeling the functional and physical architecture, behavior, requirements, and parametric relationships through system-level simulation of observation workflows, using OMG's Systems Modeling Language (SysML), to validate use-case scenarios and verify timing requirements early in the life-cycle phase. This paper presents preliminary results for non-sidereal tracking scenarios, especially for fast targets where the on-instrument wavefront sensors must hand off from one guide star to another. Operational modes and behavior are modeled using activity diagrams. Scenarios are captured primarily using sequence and activity diagrams. Verifiable requirements are formally captured using constraints on properties. This type of modeling can be particularly useful when investigating the effect of parallelizing or re-ordering sequence tasks.

ANAtOLIA : a high-performance mobile station for atmospheric characterization for Astronomical Observations and Optical Communications

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Abstract

ANAtOLIA (Atmospheric moNitoring to Assess the availability of Optical LInks through the Atmosphere) is a project funded by the European Space Agency (2M€) and aims to ground-sites selection and assess their availabilities for optical links through the atmosphere. Astronomical observations and space-to-ground optical communications are limited by clouds, aerosols and atmospheric turbulence. Therefore, we developed in the framework of the ANAtOLIA project, an innovative and efficient instrumentation and methods to accurately measure, analyze, characterize, and ultimately predict critical atmospheric parameters for the purposes of the selection of the astronomical and OGS (Optical Ground Station) sites and the evaluation of their availability. The main mission objectives of ANAtoLIA are to design, manufacture, procure and assembly a self-standing and autonomous ground support equipment, comprising cloud, aerosol and turbulence monitoring to deliver precise measurements of the atmosphere transmission. ANAtOLIA is a compact mobile station consisting of the GMT monitor (Generalized Monitor of Turbulence), Reuniwatt Sky Insight camera and Cimel CE318-T photometer, which is operational 24h a day, 7 days a week in any site around the world with minimal infrastructure. After two years of instrumental specifications, design, development and on sky tests, we started recently installation of the ANAtOLIA station on selected ground sites in ESA member states to record continuously local clouds, aerosol information and atmospheric turbulence conditions during a 24 month campaign. The data collected with these ANAtOLIA monitors will be correlated with data available from other sources of cloud coverage and atmospheric conditions (e.g., MSG, MODIS, local meteorological sites). The main goal of these correlations is to improve knowledge of the optical link availability for selected OGS sites and to carry out a long-term validation of the optical link availability prediction methods.

AO-COCKPYT: a semi-analytical model for Single Conjugate Adaptive Optics based on Fourier filtering Wave-Front Sensors

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Abstract

The future Single Conjugate Adaptive Optics (SCAO) systems on the ELT will be equipped with the Pyramid Wave-Front Sensor (WFS), considered now as the reference Wave-Front Sensor (WFS) for SCAO. Recent studies show that the non-linearities of the Pyramid sensor is a real challenge. The goal of the new Python code 'AO-COCKPYT', is to evaluate Fourier-Filtering WFS (FF-WFS) sensitivity in presence of residuals (aka Optical Gain) . The code is based on the Convolutional Model (Fauvarque, 2019) and yields a closed loop modal and/or Fourier-based error budget and residual Wave-Front (WF) statistics. In this presentation, we analyze the validity and limitations of the AO-COCKPYT model by comparison to OOPAO end-to-end results. We find that the agreement is very good for moderate residuals (typically < 1 rad): in these cases, AO-COCKPYT makes accurate predictions and permits to compute optimum modal controller gains when used with a Least-Square WF reconstructor. For larger residuals, cross-talk in the WFS response to modes is the main limitation especially for the emblematic Petal modes. In this case, we propose a Minimum Variance (MV) approach to WF reconstruction using AO-COCKPYT sensitivity estimation to refine the WFS model. OOPAO simulations show that in cases when sensitivity to Petal modes is seriously hampered but not null, an MV-based correction of slow quasi-static Petal error is possible and can address partially issues linked to the Low wind effect. Finally, we show how AO-COCKPYT is applied to various ELT Pyramid-based system configurations, from K-band to R-band SCAO WFS. We also apply AO-COCKPYT to the new Bi-O-edge WFS in the frame of Planetary and Camera Spectrograph (PCS) simulations.

AO3K at Subaru: the facility adaptive optics goes extreme

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Abstract

The facility adaptive optics of the Subaru Telescope AO188 is getting some long-awaited upgrades: a new 3224-actuator deformable mirror from ALPAO (hence the name change to AO3K), an upgraded GPU-based real-time computer, a non-linear curvature wavefront sensor and a near-infrared wavefront sensor (NIRWFS) using First Light Imaging's C-RED ONE camera, closing the loop at up to 2 kHz. With these new features, AO3K will provide extreme-AO level of correction to all the instruments on the IR Nasmyth platform: The NIR-MIR camera and spectrograph IRCS, the high-resolution Doppler spectrograph IRD, and the high-contrast instrument SCExAO. AO3K will also support laser tomography (LTAO), delivering high Strehl ratio imaging with large sky coverage. The NIRWFS, using part of the light from y- to H-band, will dramatically increase the number of reachable targets for high-contrast imaging, for exoplanets characterization, as well as AGNs or the galactic center. It has two modes that can be used to drive the new DM: A double roof-prism pyramid WFS, and a focal plane WFS. The high Strehl will especially benefit SCExAO for high contrast imaging. The second stage ExAO will no longer have to chase large residual atmospheric turbulence, and will focus on truly high contrast techniques to create and stabilize dark holes, as well as coherent differential imaging techniques. We will finally be able to leverage the several high performance coronagraphs tested in SCExAO, even in the visible. AO3K will answer crucial questions as a precursor for future adaptive optics systems for ELTs, especially as a technology demonstrator for the HCI Planetary Systems Imager on the Thirty Meter Telescope. A lot of questions are still unanswered on the on-sky behavior of high actuator counts DMs, NIR wavefront sensing, the effect of rolling shutters or persistence. We present here the first lab and on-sky results of AO3K, giving us some insight on the great scientific results we hope to achieve in the future.

AOB-1: Phase A study for the Gemini North AO instrument, inovative concepts and expected perfomance.

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Abstract

AOB-1 is a LAM/ONERA/ASTRALIS Adaptive Optics (AO) facility currently designed to feed the GIRMOS instrument on the GEMINI North 8m class telescope located in Hawaii. This AO system can operate in two modes. A laser tomography AO (LTAO) mode using 4 LGS (laser guide stars) and [1-3] NGS (natural guide stars) for high performance over a narrow field of view (a few arcsec). The LTAO reconstruction will benefit from the most recent developments in the field, such as the super-resolution concept for the multi-LGS tomographic system, the calibration and optimization of the system on the sky, etc. The system will also operate in Ground Layer Adaptive Optics (GLAO) mode providing a robust solution for homogeneous partial AO correction over a wide 2' FOV. This last mode will also be used as a first step of a MOAO (Multi-object adaptive optics) mode integrated in the GIRMOS instrument. Both GLAO and LTAO modes are optimized to provide the best possible sky coverage, up to 60% at the North Galactic Pole. Finally, the project has been designed from day one as a fast-track, cost effective project, aiming to provide a first scientific light on the telescope by 2027 at the latest, with a good balance of innovative and creative concepts combined with standard and well controlled components and solutions. In this paper, we will present the innovative Phase A concepts, design and performance analysis of the two AO modes (LTAO and GLAO) of the AOB-1 project.

Architecting, Implementing and Observing with a Metasurface vector Zernike wavefront sensor on the Keck Telescope

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Abstract

The Zernike wavefront sensor is a member of the diffraction-limited wavefront sensor family with a few attractive properties. It is simple, robust, and easy to implement, at the expense of limited dynamic range. Here we extend previous demonstrations of the Zernike wavefront sensor in the follow ways: we implement a vector Zernike wavefront sensor in order to extend the otherwise limited dynamic range, and we demonstrate this vZWFS on sky. The vector Zernike dimple itself is made using metasurfaces – an optical surface comprised of sub-wavelength optical features. Here, we describe how this sensor is implemented on the Keck Telescope, in particular: 1) the optical design that enables the implementation, 2) the design and fabrication of the metasurface focal plane mask, 3) operations of the sensor on the bench and on sky. We will discuss how this work compares with performance models, and will describe implications of this work on future segmented aperture systems.

Assessing and improving the TMT LGSF optical performance with thermal CFD modeling

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Abstract

In order to maximize the laser guide star adaptive optics system's performance, the laser launch system needs to minimize the projected spot size at the sodium layer by both minimizing the output laser beam wavefront error and focusing the beam correctly in the sky. However, with the continuously changing thermal environment, including radiation cooling and intermittent laser heating of the lenses, it is not trivial to achieve the two goals. We have recently carried out unsteady thermal computational fluid dynamics (CFD) modeling of the laser guide star facility (LGSF) for TMT to assess its thermal behavior. The temperature distribution of the lenses and lens mounts are fed into the Code V optical design software to assess the induced focus and wavefront error, while the temperature gradient of the air is used to determine the beam jitter and tube seeing. The optical baffle length, thermal resistance between the lenses and lens mounts, as well as dry air flushing, have been treated as parameters and optimized as a result. In this paper, we will present the findings.

Assessing the photometric and astrometric capabilities of the ELT METIS imager on the centre of our Milky Way

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Abstract

Context: ESO's Extremely Large Telescope (ELT) will provide unprecedented performance in ground-based infra-red imaging and spectroscopy. Improvements in astrometry and photometry, derived from the expected increase in sensitivity and angular resolution, will empower challenging astronomical observations, such as imaging closed-packed stellar clusters. Aims: Before instrument completion, it is of utmost importance to assess its expectable astrometric and photometric accuracy, and evaluate its suitability for different observation targets. In this work, we analyse the mid-infrared ELT imager and spectrograph (METIS) instrument capabilities in L/M band imaging and attest its performance in observations of the centre of our galaxy. Methods: We utilise well established photometry packages to analyse synthetic images of the centre of the galaxy to estimate the astrometric and photometric accuracy of the instrument. The synthetic images are generated from a catalogue of objects using the ScopeSIM package, an astronomical instrument simulator, and OOPAO, an Adaptive Optics simulation suite, which allow us to closely model the optical system considered. Results: We compare the astrometric and photometric performance metrics obtained from the simulations with the ELT METIS L/M imager top-level requirements. Additionally, we assess the viability of the instrument in further constraining physical parameters of t

Astrometry with MAVIS: Pushing Past the Limits of Gaia to the Crowded Centres of Globular Clusters

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Abstract

High precision astrometry has entered a Golden Age, ushered in by the Gaia mission and surely culminating in the clearest 3D picture of the Milky Way to-date. The Gaia satellite has been revolutionary in many ways and yet, as a relatively small telescope, it is fundamentally limited in its study of both faint and crowded sources. The MCAO Assisted Visible Imager and Spectrograph (MAVIS) is an instrument being designed for the Very Large Telescope Adaptive Optics Facility. Equipped with MAVIS, the VLT will be the only 8m-class telescope, ground-based or otherwise, to operate at its diffraction limit (~0.02 arcseconds) in the optical (550 nm). Designed with astrometry in mind, MAVIS must deliver precision astrometry at the 150 micro-arcsecond level, with a goal of 50 micro-arcseconds, the same requirement as the 39m Extremely Large Telescope. To verify this requirement will be met, we have created the MAVIS Image Simulator (MAVISIM), an image simulating tool to explore MAVIS science cases ranging from stellar to extra-galactic science. MAVISIM accounts for three major errors introduced by adaptive optics, including PSF field variability, along with imager and detector characteristics. In this first test of MAVISIM, we have investigated both the astrometric capabilities of MAVIS and a key science case for the instrument, the presence of intermediate mass black holes (IMBHs) in globular clusters. In this talk I will present exciting results from MAVISIM showing that MAVIS will: i) meet its astrometric requirements and ii) be able to detect the kinematic signature of a central 1500 solar mass IMBH in the crowded central region of NGC 3201.

Atmospheric outer scale models: a mathematical analysis and a comparison on adaptative optics telematry data

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Abstract

In adaptive optics, to compensate for the distortion effects introduced along the propagation path between a light source and a receiver (telescope lens), it is important to estimate certain optical parameters of the turbulence, such as the outer scale L_0 and Fried's parameter r_0. The outer scale L_0 is however a model-dependent variable. In this work, a theoretical analysis of the mathematical derivation and a comparison of the puntual covariances and the covariances of the arrival angles averaged over square apertures of finite size (called general) for each of the spectral models considered: Von Karmán, Greenwood, Exponential and the classical Kolmogorov model. An important difference between these covariances is that the general covariance has an associated validity limit depending on the external scale and the diameter of the apertures. On the other hand, an empirical analysis has been carried out by fitting the theoretical models to data obtained from the telemetry of the Paranal AOF system. Empirical cross-sectional and longitudinal covariances are obtained from the AOF telemetry slope measurements. By fitting this set of empirical covariances we seek to estimate the turbulence parameters (r_0, L_0), the measurement error, \sigma_e, and the TT contribution of the laser guide star jitter, \sigma_{s_\phi}. The aim is therefore to determine which model provides the best fits under certain criteria of algorithm optimality, compilation times, among others. In conclusion, from the theoretical study it is possible to find an analytical solution for the puntual and general covariances for each model, except for the Exponential model. In figure (a) it is possible to see the behaviour of these covariances under certain fixed values of the optical parameters r_0 and L_0. From the study of the data, the Von Karmán and Greenwood models on the exponential and the Kolmogorov model are of particular interest. Figure (b) shows a general covariance fit of the Von Karmán model.

Atmospheric turbulence prediction for optical links optimization & Astronomical Observations

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Abstract

The prediction of the atmospheric and turbulence conditions are of great interest for the astronomical community and free space optical telecommunications. With the advent of the next generation of ELTs, the knowledge of atmospheric conditions several hours prior to observations has become essential. Besides the

importance of reducing the lost in cost of observations due to bad atmospheric conditions, it is important to specify a site that provides an optimal optical quality. Therefore, it is crucial to overcome the effects of atmospheric turbulence. In general, the challenge is to find ways to reduce the effects of turbulence on the optical beam propagating through the atmosphere. Adaptive Optics (AO) methods aim to reduce these effects. However, the use of AO alone cannot overcome all the effects of turbulence. Moreover, these AO corrections are more efficient if the predicted conditions are more advantageous, for both prediction and performance optimization. Hence, emphasizing the importance of developing a robust and efficient tool to predict atmospheric turbulence conditions a few hours in advance in order to optimize the planning of astronomical observations called "flexible scheduling". As well, in the field of free space optical telecommunications, the propagation of optical signals in the atmosphere is significantly influenced by weather conditions (clouds, fog, rain, etc.) and optical turbulence, which can cause signal losses. Optical ground stations must be installed at the most favorable sites, and it is necessary to have a tool to predict the best locations as well as the most favorable periods for laser links (transmission/reception). Based on the work that have been developed previously in our team, a numerical approach based on the Weather and Research Forecasting (WRF) model coupled with different optical turbulence models has been used. The results were compared to in-situ measurements and optical measurements from the Calern Atmospheric Turbulence Station (CATS). In order to improve the statistical model, an optimization of the prediction has been performed using local measurements to improve the turbulence model and better take into account the local specificities of a given site. This method known as "site learning", has been tested at the Calern Observatory site, France and has brought improvement to the predictions results. On the other hand, a new estimation method of the outer scale of turbulence from the profile of meteorological data has been developed to improve the theoretical model. This method has been applied to the Cerro Pachon Observatory site, in Chile. The results show good agreement with the measurements. Until now we have used weather forecast tools coupled with turbulence models to predict turbulence conditions. An approach using machine learning algorithms such as the Regression Ridge (ARR) and the Random Forest Algorithm (AFA), was also tested and showed good results on predictions. The goal is to build new models using advanced Machine Learning algorithms such as LSTM(Long short-term memory), to enhance the short term prediction.

Calibration and performances of a self-referenced Mach-Zehnder wavefront sensor for extreme adaptive optics

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Abstract

We describe our latest results obtained with the integrated Mach-Zehnder (iMZ), a wavefront sensor based on the Fourier filtering of one of the interferometer arms. This kind of sensor meets extreme adaptive optics requirements, high accuracy (< 10 nm at 5-10 cm spatial scale) and low computational load. As the iMZ performs an absolute measurement of the phase (and amplitude), the aberrations reconstruction is not affected by discontinuities in the pupil : the presence of large or small telescope spiders do not affect the iMZ measurements accuracy. For the same reason, the iMZ performs efficiently while measuring any segmented phase pattern such as the phasing errors on segmented telescopes (such as petal modes) or island effect aberrations. Our contribution will present recent results on the enhanced calibration method we have developed and validated experimentally to extract the phase from the iMZ signal, using several phase patterns introduced by a deformable mirror and the monitoring of the flux variation on the pinhole in the iMZ coronagraphic path. As the iMZ is based on the spatial filtering of the incoming beam, the quality of the phase retrieval strongly depends on the alignment of the optical beam with the pinhole. Here we present the method and results of the tip/tilt close loop correction using piezo mirror we have developed recently on the

XAO testbench at CRAL. The tip/tilt control is based on the centroïd measurement of the coronagraphic point spread function, measured behind of the pinhole and simultaneously with the wavefront sensor with very low non common path aberrations. Performances of the iMZ on turbulence residuals will be presented thanks to experimental results of phase measurements on turbulent phase screens introduced on the bench. We will also report our first laboratory results of real-time phase correction on turbulence residuals using a 12x12 deformable mirror. We finally present the phase modulation method and the unwrapping algorithm developed to increase the dynamical range of the sensor up to several microns, limited at ± lambda/4 without these strategies. The recent validation of those unwrapping techniques on experimental data will be presented.

Calibration Unit Design for High Resolution Infrared Spectrograph for Exoplanet Characterization (HISPEC)

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Abstract

The latest generation of high-resolution spectrograph instruments on 10m-class telescopes continues to push challenging science cases. Consequently, evermore precise calibration methods are necessary to enable bleeding-edge science methodology. We present the High-resolution Infrared SPectrograph for Exoplanet Characterization (HISPEC) Calibration Unit (CAL), designed to enable challenging science cases such as doppler imaging of exoplanet atmospheres, precision radial velocity, and high-contrast high-resolution spectroscopy of nearby exoplanets. CAL builds upon the heritage from the pathfinder Keck Planet Imager and Characterizer (KPIC) and utilizes four near-infrared (NIR) light sources encoded with wavelength information that are coupled into single-mode fiber. They can be used synchronously during science observations or asynchronously during daytime calibrations. A Th-Ar hollow cathode lamp and a series of gas absorption cells provide absolute calibration from 0.96 µm to 2.4 µm. A laser frequency comb (LFC) provides stable, time-independent wavelength information during observation and CAL implements a lower finesse astro-etalon as a backup for the LFC. Design lessons from instrumentation like HISPEC will serve to inform the requirements for similar instruments to go on ELTs in the future.

CATS: last upgrades, turbulence forecasting and additional instrumentation

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Abstract

The atmospheric turbulence measurement and characterization is an essential information for high-angular resolution imaging in astronomy, and for optical link (telecommunication, telemetry, time trans- fer, ...). Indeed, its impact on the light propagation decreases the resolution of astronomical images, and degrades the bit error rate of optical communication signals. In this framework, since 2015, the Calern Atmospheric Turbulence Station (CATS) monitors atmospheric conditions at the Calern observatory, during both daytime and nighttime from the ground to the top of the atmosphere. The station is fully autonomous and is equipped with a set of complementary instruments to continuously monitor optical turbulence. The Profiler of Moon Limb (PML) measures, from Sun or Moon limbs observation, the vertical profiles of the refractive index structure constant Cn2 with a high vertical resolution (~ 100m at ground level). The Gener- alized Differential Image Motion Monitor (GDIMM) monitors the integrated turbulence parameters (seeing, isoplanatic angle, coherence time, scintillation, outer scale) by observing bright stars. The equipment is controlled with a ground weather station providing the ground meteorological conditions (pressure, tem- perature, relative humidity, wind speed, wind direction and irradiance), and the nighttime cloud coverage is given by an all-sky camera. More recently, knowing the need of turbulence forecasting, we developed a system integrated in the CATS station to daily predict daytime and nighttime meteorological and optical turbulence conditions for the next 48h. We also have designed an instrumental platform attached to a drone and allowing to measures, with a high resolution, the weather conditions between the ground and an alti- tude of around 500m. Since 2022, we have also added an infrared AllSky imager measuring 24/7 the cloud conditions, and a photometer measuring aerosols conditions, important for optical telecommunications. In this paper we present the CATS station and its last upgrades, the instrumented drone, and the forecasting tool developed and tested on Calern Observatory (France).

Characterising the Atmosphere Turbulence with the SHIMM

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Abstract

The Shack-Hartmann Image Motion Monitor (SHIMM) is a portable, low-cost instrument, that can estimate atmospheric seeing, coherence time and a low-resolution three-layer turbulence profile. It is a development of the Differential Image Motion Monitor (DIMM), which is a commonly employed seeing monitor for astronomical observing sites across the world. However, the SHIMM employs a Shack-Hartmann wavefront sensor in place of the two-hole aperture mask utilised by the DIMM. This allows the SHIMM to provide an estimate of the seeing, unbiased by shot noise or scintillation effects. The SHIMM is comprised of off-the-shelf components making it easy to duplicate and therefore well-suited for comparisons of atmospheric conditions within and between different observing sites. Here the SHIMM design and methodology for estimating key atmospheric parameters will be presented, as well as initial field test results with comparisons to the Stereo-SCIDAR high-resolution profiling instrument. In addition, techniques developed for the SHIMM have been applied to adaptive optics telemetry data to retrieve important atmospheric parameters, making in-situ profiling possible.

Closed-Loop Until Further Notice: Comparing Predictive Control Methods in Closed-Loop

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Abstract

For future extremely large telescopes, error in adaptive optics systems at small angular separations will be dominated by the lag time of the correction, which can be anywhere from ~1-5 milliseconds; the natural solution is to apply a predictive correction to catch up with the system delay. Predictive control provides exemplary results in simulation (on the order of 5-10x improvement in RMS error), but shows only modest improvement on-sky (less than 2x in RMS error). This performance limitation is likely impacted by pseudo open-loop (POL) reconstruction, which requires assumptions about the response of the deformable mirror and accuracy of the wavefront measurements that are difficult to verify in practice. In this work, we remove the need for POL reconstruction by considering two closed-loop methods for predictive control: data-driven prediction using a reformulated empirical orthogonal functions (EOF) and the physically-motivated predictive Fourier control (PFC). We extend the EOF method to run in closed-loop, and verify its performance in this new framework. We examine the performance of both methods in simulation under varying turbulence profiles, including simulated single and multi-layer turbulence, and apply them to on-sky telemetry.

Combining statistical learning with deep learning for improved exoplanet detection and characterization

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Abstract

In previous works, we have developed the PACO algorithm [1, 2, 3] dedicated to the post-processing of A(S)DI observations for exoplanet detection and characterization by direct imaging at high contrast. PACO captures locally the spatial correlations of the nuisance component (i.e., speckles plus other sources of noise)

with a multi-variate scaled mixture of Gaussian models. It delivers reliable detection confidences with an improved sensitivity with respect to the classical processing methods of the field (e.g., cADI, PCA, TLOCI). However, it remains room for improvement, especially at short angular separations. I will present the "deep PACO" algorithm [4, 5, 6] that combines the statistics-based model of PACO with a deep learning model in a three steps algorithm. First, the data are centered and whitened locally using the PACO framework to improve the stationarity and the contrast in a pre-processing step. Second, a convolutional neural network is trained from scratch, in a supervised fashion, to detect the signature of synthetic sources in the pre-processed science data. Finally, the trained network is applied to the pre-processed observations and delivers a detection map. Photometry of detected sources is estimated by a second deep neural network. Both models are trained from scratch with custom data augmentation strategy allowing to generate large training sets from a spatio(-spectro)-temporal dataset. As a proof of concept, we applied our method on tens of datasets from VLT/SPHERE (both IRDIS and IFS instruments). We compared the proposed method against state-of-the-art algorithms of the field, including PACO. With ADI, the proposed method leads to a typical improvement by half a magnitude in terms of contrast with respect to the best comparative algorithm. The ultimate detection sensitivity driven by the fundamental photon noise limit can also be reached far from the star on some datasets. A joint processing of spatio-temporo-spectral observations obtained with ASDI allows to further improve the detection sensitivity. The future thirty meters class telescopes will enable exploring much deeper the inner environment of nearby solar-type stars than existing facilities. This goal raises three challenges from a data science point of view: (i) approaching the ultimate performance of the instruments by an optimal extraction of the signals of the sought objects, (ii) capturing a highly spatially structured nuisance component subject to strong temporal fluctuations, and (iii) building a model of the nuisance component from several datasets to bypass the limits of ADI at very short angular separations. Concerning points (i) and (ii), data-driven approaches combining statistical modeling with deep learning would be highly valuable to model the complexity of such observations. We are considering to adapt and to apply our method on simulated ELT high-contrast data (e.g., from ELT/HARMONI) as a future work. Concerning point (iii), I will discuss some methodological developments we have started in that direction. The methodology we are targeting differs from RDI in the sense that a highly non-linear model will be learned from the observations and will exploit several prior domain knowledge. [1] Flasseur+, A&A;, 618, A138, 2018. [2] Flasseur+, A&A;, 634, A2, 2020. [3] Flasseur+, A&A;, 637, A9, 2020. [4] Flasseur+, SPIE Adapt. Opt. Syst., 12185, 1154-1167, 2022. [5] Flasseur+, to be submitted to MNRAS the 3rd of March 2023, ArXiv link available soon. [6] Flasseur+, to be submitted to EUSIPCO conference the 6th of March 2023, ArXiv link available soon.

Commissioning Status of the MAPS Adaptive Optics System on the MMT

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Abstract

The MMTO Adaptive optics exoPlanet characterization System (MAPS) is a new facility instrument being commissioned for the 6.5 meter MMT observatory. Funded by NSF-MSIP, MAPS features a complete redesign of the electronics and actuators for MMT's adaptive secondary mirror, a new wavefront sensing system with optical and near-infrared pyramid wavefront sensors, and upgrades to the Arizona infraRed Imager and Echelle Spectrograph (ARIES). The project aims to characterize the atmospheric composition of up to 100 exoplanets over a 60-night observation campaign. MAPS achieved first light in October 2022 and demonstrated closed-loop operation using an on-sky interaction matrix in January 2023, marking the first empirical calibration of an AO system at the MMT. We report on the on-sky commissioning efforts, including on-sky calibration, system performance, software development, and lessons learned.

Comparison of atmospheric tomography basis functions for PSF reproduction.

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Abstract

Atmospheric tomography is a process used to increase the useful sky-coverage of an adaptive optics system. The atmospheric distortion of multiple point sources are estimated using measurements from wavefront sensors. Atmospheric tomography then uses the multiple point spread functions of these guide beacons to estimate and reproduce the spatially variant point spread function for a science target that is outside the isoplanatic patch of any individual guide beacon. As ground-based telescopes grow in size the dimensionality of the atmospheric tomography problem increases exponentially. Coupling this with increasingly demanding use-cases for atmospheric tomography, such as for space situational awareness, or for imaging dynamic off-axis targets; the increasing dimensionality of the atmospheric tomography problem poses a problem in terms of computational efficiency. New methods must be employed to either reduce the complexity or dimensionality of the problem without compromising performance. One method that has been explored is using different basis functions to reduce the dimensionality of the point spread function representations. The most commonly used basis functions for tomographic reproduction are Zernike polynomials. There are growing blocks of research that use wavelets, the related ridgelets, and novel machine learning processes to reduce the complexity of estimation for tomographic reproductions, when compared to Zernike polynomials. Other fields of tomography have used the discrete cosine transform as the basis functions. In this paper we explore and compare the effects of different basis functions on the performance of tomographic reproduction algorithms, using Shack-Hartmann and Geometric wavefront sensors. Tomographic reproduction performance is evaluated in terms of accuracy, computational/time complexity, noise rejection, and off-axis target performance.

Comparison of transmissive and reflective SLMs for the emulation of discontinuous wavefronts

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Abstract

It has been known for some time that the Low Wind Effect (LWE) has the potential to severely limit the quality of images obtained using adaptive optics on ELTs. This effect and ways to measure the resulting piston between 'petals' of the telescope pupil is an active area of research, relying mostly on numerical simulations, and also laboratory experiments using reflective spatial light modulators (SLMs). In the work presented here we investigate using a transmissive SLM to simulate the petaling effect. This type of SLM is very easy to incorporate into an experimental setup, and has a lower cost than reflective SLMs. The fact that transmissive SLMs are thicker (for the same simulated wavefront error) and therefore slower is not so important for this application. We describe a laboratory setup to demonstrate petaling, including a simple interferometric technique to measure the piston errors. The ability of transmissive and reflective SLMs to generate discontinuous wavefronts is examined and compared.

Coupling a pyramid-based AO system to a high contrast arm: dealing with NCPA

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Abstract

In 1995 the first exoplanet was discovered at Observatoire de Haute Provence (OHP) around a solar type star. 30 years later, more than 5000 exoplanets have been detected, mainly using indirect methods. The next step aims at using direct imaging techniques to characterize the chemical content of their atmosphere and better understand their formation process. The main difficulty relies on the scene observed: the tiny spark of the planet's light is overwhelmed in the huge flux coming from its close parent star. The angular separation is a fraction of arcsecond, and the flux ratio reaches 106 (jupiter planets) to 109 (rocky planet). Imaging the planet photons and extracting their spectra is therefore an instrumental challenge. The recipe to reach such a challenging objective consists of an extremely large telescope, an eXtreme performance Adaptive Optics (XAO) and a high-contrast instrument equipped with high resolution spectroscopic capabilities. This paper focuses on the coupling between an XAO system equipped with a pyramid Wave-Front Sensor (WFS) and a high-contrast arm. This setup requires a perfect compensation of the Non Common Path Aberrations (NCPA). These aberrations translate into residual light (speckle) in the focal plane, that can be easily mistaken with planets. They therefore need to be measured and corrected, which is achieved by sending offsets to the WFS.
As well, an absolute control of the Tip/Tilt is required to perform a precise injection in a fiber spectrograph. At last, to create dark hole areas at the location of the planet, static dark-hole maps must be applied to the deformable mirror. All of these elements contribute to operating the Pyramid far from a zero-aberration regime with its associated non-linearities. The scope of this work is to master the reconstruction with the pyramid WFS working around a non-zero aberrated wave-front. Being highly non-linear, this task is complex. Making use of a Gain Sensing Camera, we aim at identifying and compensating very accurately the optical gains variations, enabling the pyramid to work outside of a flat wave-front regime. As such, in this paper, we

report our latest experimental results of optical gains tracking using the GSC of the PAPYRUS instrument installed at the OHP and we compare it to a numerical twin model of the bench developed in Python. The goal of this activity is to prepare the commissioning of the VIPA spectrograph associated with a coronagraph, scheduled to be installed on PAPYRUS by the end of the year.

Deep learning for low-order phasing of segmented telescopes

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Abstract

Earth observation from space has greatly benefited from advancements in angular resolution, which are essential for obtaining valuable scientific insights. Achieving high angular resolution relies on large telescope apertures. Recently, space telescopes have been designed to exceed the size limitations of the platform and rocket fairing, necessitating segmented pupils. This approach has proven successful for space telescopes (e.g., JWST) but also for large ground-based telescopes (e.g., Keck, ELT). Interestingly, such segmented pupils can also be implemented in small-volume platforms, such as CubeSats, which offer the advantage of reduced payload weight and launch costs, enabling higher revisit rates with satellite constellations. In our work, we present a novel implementation of a segmented telescope within a CubeSat. While segmented pupils allow for a relatively large aperture, they present a significant challenge in terms of achieving perfect alignment between the independent mirror petals. This alignment is crucial for realising the full angular resolution potential promised by a large aperture. However, the limited computation power and impossibility of having additional optics or dedicated wavefront sensors forces us to perform the wavefront sensing solely on a single focal plane image, requiring the use of more complex methods than classic ones. One of the main challenges of focal plane wavefront sensing is the non-linear relationship between phase and image intensity. Therefore, we leverage deep learning algorithms to address this problem directly. By utilising the spatial information from each pixel, convolutional neural networks algorithms excel at solving non-linear problems. Moreover, the computational burden is alleviated through off-line training steps, enabling efficient on-board computations. In this work, we focus on the identification of segmented pupil piston and tip-tilt phase coefficients from a single focal plane image of a point source. Our deep learning-based method successfully extracts the first three Zernike coefficients for each of the four petals, even in the presence of noise, higher-order aberrations, and stronger aberrations arising from the initial deployment. We demonstrate diffraction limit results in visible wavelength (about 15nm at 800nm) for relatively small NN architectures compared to the state-of-the-art ones. We then propose the application of our method to explore the phasing of larger space telescopes with more degrees of freedom, such as JWST with 18 segments. Finally, we extrapolate the potential application of our method to ground-based telescopes.

Deep learning for phasing the ELT petal mode

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Abstract

Earth observation as well as astronomy are scientific domains where high angular resolution images are required to guarantee the scientific return. High angular resolution requires large telescope apertures, often necessitating segmented pupils as demonstrated by large ground-based telescopes (Keck,10-meter / 36 segments and ELT, 37-meter / 798 segments) and also for space observatories (JWST, 6-meter / 18 segments). A segmented pupil allows the telescope to deliver a bigger aperture but nonetheless comes with a significant challenge: each segment require a perfect alignment (at a fraction of the imaging wavelength, typically 50nm at visible wavelength) with respect to the others in order to reach the full angular resolution promised by the large aperture. To reach its theoretical resolution, (4mas in visible wavelength, 12 mas in K-band) the ELT will have to be equipped with powerful AO systems, able to correct wavefront aberrations up to few tens of nanometers. Due to the 6 large spiders, (50cm width) and to the segmented surface of one of the mirrors (M4), the ELT pupil will behave as a segmented pupil, potentially degrading strongly the performance. Measuring and correcting this phasing error is crucial. This phasing can potentially be solved by using a single focal plane image by using well-known algorithms such as asymmetric pupil phase diversity for instance. However some constraints will make this type of solution limited. First the AO residuals are slowly evolving and will not be averaged out enough in the image, challenging the phasing sensor to disentangle them from phasing speckles. Second, ELT will also produce non-Kolmogorov phase residuals (Low Wind Effect) difficult to modelize, and that can be misinterpreted with phasing errors. We therefore want to explore non-linear learning methods to address this task, at least with minimal contributors at first. In this work we propose a deep learning method using a single focal plane image,using a method the authors developed for a space-borne deployable telescope. Deep learning algorithms are well suited to this type of problem. They are well-known and widely used nonlinear problem solvers allowing a direct image parameter identification. This method is studied for a simple ELT imager without atmosphere, then with residual turbulence averaged over short and long periods, for different seeings and correction regimes. We study the impact of these residuals during the learning phase and on the final performance, and we look for neural network architectures that best fit the need. This method shows a phase identification allowing the telescope to reach the diffraction limit in K band. We quantify robustness when guiding on different star magnitudes and with varying amounts of high order residuals.

Deep neural networks for non-modulated Pyramid Wavefront Sensors

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Abstract

The pyramid wavefront sensor (PyWFS) [1] is one of the best contenders to use on adaptive optics (AO) for extremely large telescope thanks to its performance, resolution and high sensitivity compared with other wavefront sensors. However, the PyWFS a limited linearity. To overcome this problem, the PSF is modulated around the pyramid apex using a Tip-Tilt mirror (TTM), where the modulation radius is defined by the non-dimensional value

Deep Optics for Wavefront Sensing: Beyond the Pyramid Wavefront Sensor

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Abstract

Our group have recently updated the Pyramid Wavefront Sensor (PWFS) [1] with a diffractive optics layer that acts as an optical preconditioner to the PWFS measurements, under the assumption that the reconstruction is based on a modal/zonal linear least-squares reconstruction stage. The newly Deep Optics PWFS (DWPFS) [2] is designed by using a methodology derived from artificial intelligence techniques based on deep learning, and that have been recently adapted to treat the forward and inverse models of a physical system as being a neural network, where, in this case, the only trainable parameters (or weights) are at the added diffractive optics layer, that has been place at the Fourier plane. With the goal of improving the linearity of the PWFS, we designed a DPWFS using an End-2-End training scheme as seen in Fig.1, where we used a collection of known wavefront phase maps from a variety of turbulence strengths, particularly where the PWFS response becomes more non-linear. Extensive tests in simulations and in the PULPOS optical bench [3] show that the estimation performance of a modulated traditional PWFS can be achieved by a non-modulated version of the proposed DPWFS. Of course, there is a loss in sensitivity when gaining linearity, similar to what happens with modulation, though this time we can even avoid modulation at all. Somehow, the DPWFS serves to demonstrate that we can offload some of the hurdles of the used linear mathematical inversion process towards an optical preconditioner. Nonetheless, we know that we can achieve even better inversion if we train a deep neural net to solve for the inverse problem related to wavefront reconstruction, as previously reported in [4,5]. This is particularly true for a nonlinear system as the PWFS. Therefore, the questions that arises now is whether we can design a DPWFS with a deep optics preconditioner based on a deep neural network for the inversion process, replacing the traditional linear method. In this work we will discuss our current efforts in designing new optical preconditioners for the PWFS based on neural nets. One of the clear caveats of this new adventure is that as we have more free parameters, either in the optical layer or in the digital layers, we may require massive training sets and computational resources. We are currently facing challenges in finding a good balance between the optical and digital layers, though as much as we offload towards the optical side we may expect lightweight computational requirements in the inversion, and thus faster estimations as well. At some point it seems easier to fix as many parameters as possible, which in the DPWFS case is the fixed optical architecture based on the PWFS, though we may also conjecture of what could happen if we remove the pyramid and free the optical transformation of the WFS towards a generalized Deep Optics WFS architecture.

Defining the Information Limit for a Laser Beacon

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Abstract

To date, laser guide star (LGS) system performance has primarily been measured on the efficiency of exciting mesospheric sodium atoms and total return flux. While this focus has led to numerous advances, the ultimate utility of an LGS system is determined not by the efficiency and raw return flux, but the quality of the wavefront measurement attained from the laser beacon. Thus, a simple efficiency metric for LGS operation is inadequate for evaluating important system-level design decisions. A laser system that is less efficient at exciting sodium atoms may out-perform a more efficient laser format if the less efficient format leads to greater wavefront measurement sensitivity. This effect is most readily seen in LGS systems incorporating pre-compensation of the laser beacon to achieve a smaller beacon width in the mesosphere. A smaller dimmer beacon may yield less total measurement error than a larger brighter beacon, even if the efficiency of the laser excitation is reduced. This work examines the interaction between the spatial coherence of the beacon and the noise gain of a theoretical wavefront measurement to explore the fundamental information limit for a given beacon format. The analysis first examines the optimal beacon size with a Pyramid and modified Zernike wavefront sensors (WFS), and then extends the analysis to a theoretical wavefront sensor model to numerically approximate the fundamental limit for a general linear WFS for any beacon size or shape. Using this formulation, the suitability of various proposed LGS system designs (pre-compensation, beam shaping, pulse tracking, etc.) can be evaluated to determine the optimal design from the perspective of minimizing wavefront measurement error.

Defining the MOSAIC GLAO image quality budget

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Abstract

MOSAIC is the ELT wide-field spectrograph capable of observing over 200 targets simultaneously within an AO-corrected 7.4 arcminute diameter field of view (FoV) across a wavelength range of 400-1800nm. The instrument has a highly-modular design to accommodate the multiplex capability between the various observation modes, which is a significant difference from other ELT instruments. The accessible FoV spans a diameter of up to 10 arcminutes, and this large area is what enables the multiplexing capability. Accordingly, the requirements for the AO correction is specified in terms of enclosed energy (EE) appropriate for spectrometer inputs: spectrograph fibres which are illuminated via a relay at the focal plane, or the IFU input apertures which are also re-imaged from the focal plane via relay optics. To increase the EE into the apertures of either sub-system, GLAO is the only technology which can cover the FoV required for the focal-plane fibre-illumination. Although the IFUs could utilise MOAO--due to their limited number, this would be feasible--it has been found that GLAO delivers sufficient performance to meet the specifications. Therefore GLAO is the only AO mode designed for MOSAIC and the instrument controls M4/M5 to correct

the entire FoV over the ELT NoAO mode, which is the telescope-delivered PSF after the Pre-Focal Station. The baseline GLAO conceptual design is to use 4 LGS WFSs to derive the high-order wavefront measurements and three guiding sensors to correct for residual instrument--telescope distortions (internal and Nasmyth flexure) and focal plane image distortions directly from the telescope e.g. field rotation from M4 to M5 tip/tilt off-loads, to give one example. We assume that a conventional simulation (MC or Fourier) is sufficient to produce GLAO correction which is compatible with the design i.e. the correction over NoAO is equivalent to the conventional simulation correction over seeing-limited. This then implies all fast residual vibrations are eliminated, leaving the AO residual wavefront and any slow vibrations. These slow vibrations are corrected for by the guiding sensors, and so slow vibrations and focal plane distortion is modelled by additional convolutions or linear transforms of the PSF, depending on the longevity/time-scale of the effects. For modelling the image quality, the focal plane distortions are not relevant as we assume the instrument can measure and then offset apertures to account for these errors: over an hour, estimated to be 540mas. The errors that cannot be measured in the same situation are estimated to be 51mas. For context, the FWHM of the NoAO PSF is estimated to be 550mas at a wavelength of 1650nm, and for the seeing-limit the FWHM is 600mas. Our PSF model begins with a static, long-term GLAO-corrected PSF as the image delivered to the focal plane. The relay optics to the final spectrograph fibres and the IFU apertures can add additional aberrations, always reducing the EE. Therefore given a AO-simulation EE and PSF at the focal plane, the EE at the final apertures needs to be quantified. Unlike Strehl, the WFE is insufficient to define EE as the wavefront cross-correlation is relevant: differences in EE for equal WFE from adding various Zernikes relative to adding just tilt (Z2/3) often exceed 10% and even reach 50% for some modes. Therefore modelling the aperture's EE requires a more detailed set of parameters than just WFE. To formally define EE, given a statistically averaged PSF, we can use the OTF as part of the calculation: the EE is an integral of the pupil's OTF multiplied by both the Fourier transform of the EE aperture and by an exponential factor that represents residual, homogenous phase aberrations which need not be isotropic (there is field-dependency from M4's non-pupil conjugation.) To use this to calculate EE with additional aberrations implies calculating the exponential factor--from the simulation's residual power-spectra for example--and then modifying the pupil OTF to include the additional aberration and introducing the EE aperture term above before integration. The complexity of this OTF approach--which nonetheless allows a pre-defined AO PSF to be used in a calculation--has led us to consider alternatives by parameterising the EE calculation. First, a convolutional direction which models EE degradation by convolving the AO-corrected PSF with a kernel which is defined for various well-known aberrations. Second, simplifying the OTF-based EE calculation by conversion to a 1D equivalent by averaging azimuthally. Finally we examine approaches to even simpler parameterisation. Bringing the above together, we discuss the potential routes to calculating the image quality budgets for MOSAIC GLAO and difficulties we encounter in simplification to make the process usable within the consortium for the system engineering and design processes.

Deformable Mirror for large telescopes: ALPAO technology roadmap

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Abstract

Adaptive optics (AO) systems are now used in nearly all large telescopes. Over the past years the specialization of wavefront correctors has dramatically increased. General-purpose deformable mirrors (DM) are now replaced by a full range of devices. Some are optimized for single-stage correction where large amplitude of deformation is necessary (typically more than 15µm p2v). Extreme AO (XAO) will push the number of actuators (currently up to 128x128), the speed and the resolution (typically below 0.1nm). Multi conjugate AO systems (MCAO) also requires open-loop stability in various operating condition, including change of temperature and gravity vector. This paper presents the technology roadmap defined by ALPAO to

meet all these requirements, including embedded electronics, stroke optimization, new materials and improved step response.

Demonstration and comparison of new generation turbulence monitoring at ESO Paranal including the 24hSHIMM and FASS

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Abstract

Optical turbulence monitoring instrumentation is a key component in the operation of both astronomical and solar observatories around the world. Alongside turbulence forecasting tools, such instruments are vital in scheduling observations so that measurements demanding high sensitivity can be carried out in suitable turbulence conditions. Additionally, they are necessary in the development of ground based optical instrumentation such as adaptive optics systems, providing measurements of optical turbulence profiles and typical values of atmospheric parameters to include in simulations and design requirements. In this talk we will present the results of a turbulence monitoring campaign at ESO Paranal observatory in which we investigate measurements from two next-generation turbulence monitoring instruments: the 24-hour Shack Hartmann Image Motion Monitor (24hSHIMM) and Full Aperture Seeing Sensor (FASS). They will be compared both with one-another and with the observatory's permanently installed SCIDAR and MASS-DIMM instruments. The 24hSHIMM utilises slope and intensity measurements in an infrared Shack-Hartmann wavefront sensor to estimate a four-layer vertical optical turbulence profile at any time of the day or night. The FASS measures the power spectrum of intensity in concentric rings of a telescope pupil image to estimate a high-resolution turbulence profile at night. Both instruments are based around small commercial telescopes, off-the-shelf optics and seek to provide modern alternatives to the traditional MASS and DIMM instruments. We further explore how these next-generation turbulence profilers may be used for site monitoring to support the development of ground-based optical instrumentation and their integration with optical turbulence forecasting tools.

Demonstration of real-time linear closed-loop control with a photonic lantern focal-plane wavefront sensor

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Abstract

Current pupil-plane adaptive optics (AO) faces two major challenges. The first are non-common-path aberrations (NCPAs), quasistatic aberrations which appear along the optical path due to differences between the sensing and science arms of the instrument. The second challenge, especially relevant for telescopes with large apertures subdivided by spiders and/or mirror segmentation, is petaling: aberrations which, in the pupil, form phase discontinuities at subaperture boundaries. These aberrations drastically impact the capabilities of high-contrast instruments even when correction is good; to date, petaling modes remain difficult to correct with conventional pupil-plane AO. One solution is to add a dedicated wavefront sensor stage which senses aberrations in the final focal plane. In this work, we consider how the photonic lantern (PL), a waveguide that efficiently couples aberrated light into single-mode fibers, may be used in such a way to correct low-order NCPAs. Since we envision the PL operating downstream a conventional pupil-plane AO, our analysis is centered in the linear (i.e. small wavefront error) regime. We also consider sensitivity to petaling modes, and potentials for spectrally dispersed wavefront sensing. Finally, we present a first experimental verification of real-time closed-loop control with the photonic lantern wavefront sensor (PLWFS), using a linear phase-retrieval algorithm, as well as first demonstrations of on-sky performance. We find that our prototype PLWFS can effectively correct ~100nm RMS of low-order Zernike wavefront error, with potential to push further; and even more gains are possible with nonlinear neural-net phase retrieval (see abstract from Barnaby Norris). In the future, novel sensor architectures like the PLWFS may prove to be critical in resolving challenges in NCPA correction, petaling, and cophasing posed by upcoming ELTs.

Design and challenges for the HARMONI laser guide star sensors

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The project is preparing for Final Design Reviews. The laser Tomographic AO (LTAO) system provides AO correction with very high sky-coverage and it is supported by two systems: the Laser Guide Star Sensors (LGSS) and the Natural Guide Star Sensors (NGSS). The LGSS analyse the wavefront coming from 6 laser guide stars (LGS) created by the ELT; light that is picked up at the at the very entrance of the instrument with a dichroic mirror. LTAO is complemented with NGSS that probe the wavefront on natural guide star for tip, tilt, focus determination. The LGSS is made of 6 independent wavefront sensor (WFS) modules mounted on a rotator of 1100 mm diameter to stabilise the pupil onto the microlens array in front of the detector and with an accuracy of 90". Each LGS WFS is designed to compensate variations of the LGS mean layer centroid from 75 km to 92 km altitude at zenith angles from 0°

to 60° with a dedicated mechanism in each module. We present the optical and mechanical design of the LGSS proposed for FDR. The optical design is based on the use of freeform lenses to minimize the numbers of optical components, to accommodate for the diversity of sodium layer configurations and to ensure a small amount of aberrations in each LGS path. The WFS itself is based on a CMOS detector from SONY: it provides a large number of pixels to accept elongated spots up to 16 arcsec without truncation and to sample the pupil with 68 sub-apertures with a pixel size of 1.15". The trade-off of the mechanical design is also presented to illustrate how materials (carbon benches) have been carefully selected to ensure resistance to earthquake with a reduced mass to obtain a complete system smaller than 3 tons and with a first mode larger than 12Hz. The current challenge of the design relies on the choice of the microlens array technology to minimize the transmission loss.

Design and performance of MICADO high contrast mode

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Abstract

MICADO, the European Extremely Large Telescope first-light imager, will be equipped with a high contrast imaging mode dedicated to the observation and characterization of the exoplanets and planetary architectures. The increase in sensitivity and angular resolution between the current instruments like SPHERE or GPI and MICADO will allow a quantitative and qualitative jump on the study of these planetary systems. MICADO will be equipped with a set of three classical Lyot coronagraphs, one phase-apodized pupil coronagraph and two sparse apertures. These components are optimized for different observing conditions in narrow or large spectral band between 1150 nm and 2300 nm and will mostly rely on the well-corrected point spread function delivered by the Single Conjugate Adaptive Optics of MICADO. After describing the final design of the MICADO high contrast mode, we will present the high contrast numerical tool we developed to simulate the performance of MICADO coronagraphs. The final trade-offs and technical choices that derive from these numerical simulations will also be given along with the expected performance of the coronagraphs for different atmospheric conditions.

Design and prototyping of HARMONI's light-injection module for AO calibrations

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450 nm to 2450 nm and can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NoAO. The project is preparing for Final Design Reviews. The Adaptive Optics Calibration Unit (AOCU) of HARMONI is comprised of a set of on-axis sources (covering 0.5-2.4 µm) with a deformable mirror (CalDM) to control the wavefront. It will deploy into the instrument focal plane to inject calibration light into the rest of the system. The AOCU includes six diffraction-limited sources and a resolved source, emitted by seven LED sources hosted in the electronics cabinet. To deliver this light to the rest of the system (located tens of metres away), the LED sources are coupled into multimode (MM) optical fibres which are routed through the instrument. MM fibre optic couplers are used to split the light for monitoring and for combining several light sources together. Finally, MM fibres are butt-coupled into single-mode fibres. Because of the wide range of wavelengths that need to be coupled into a single SM fibre (effectively between 600-1800 nm), we use endlessly single-mode optical fibres. This arrangement leads to large attenuations but provides huge design flexibility. In this paper, we present the design of the AOCU, focusing on the light-injection module. We present theoretical photometric budget and evaluate experimental performance in the laboratory. We show that despite large attenuations ranging from 102-107, the scheme delivers the required beam quality (flux, geometry). Owing to the good performance and high level of flexibility of this scheme it will be used for the AOCU and is being replicated for several internal light-sources of HARMONI.

Design, Integration and Tests of SPIDERS: a Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra

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Abstract

SPIDERS is a Subaru Pathfinder Instrument for Detecting Exoplanets and Retrieving Spectra. This visitor instrument is currently integrated and tested at NRC-HAA before shipping to Subaru Telescope scheduled later this year. SPIDERS will be installed on the infrared Nasmyth platform of Subaru behind the newly upgraded AO3k system and the new Beam Switcher mechanism. The telescope beam can be either shared between SPIDERS and SCExAO for simultaneous observations during engineering runs, or sent entirely to only one instrument for doing science. SPIDERS is a pathfinder for GPI 2.0 CAL update and also for future Adaptive Optics (AO) instruments on Extremely Large Telescopes. The optical layout of SPIDERS is very compact and can be adapted to work behind virtually any future AO facilities, such as NFIRAOS on TMT, or MORFEO on E-ELT, either as a focal-plane wavefront sensor sending offset commands to the main AO loop, or as a stand-alone second-stage AO instrument. SPIDERS is based on the Fast Atmospheric Self-Coherent Camera (SCC) Technique (FAST) that can enhance the contrast up to 100 times. The key-components are an ALPAO DM468 used as a second-stage AO corrector, a pupil apodizer mask, a Tilt-Gaussian Focal Plane Mask (FPM), a reflective Lyot stop feeding two cameras. The transmitted light feeds a First Light Imaging C-RED2 camera imaging a 5" FoV in narrow bands and acting as a SCC focal plane wavefront sensor and as a science imager. The blocked light is reflected to a Low-Order Wavefront Sensor complementing the SCC wavefront sensing. In addition, a beam-splitter located on the SCC path feeds an imaging Fourier-Transform Spectrograph and a SAPHIRA camera for spectroscopy up to R~20,000 over a 3.3" FoV. This paper will present the overall opto-mechanical design, along with the integration steps and

preliminary lab test results.

Detecting Storms on Extrasolar Giant Planets with Extremely Large Telescopes

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Abstract

Extremely large telescope (ELT) instruments with adaptive optics, high-contrast imaging, and high-resolution spectroscopy will enable the exploration of directly-imaged exoplanet atmospheric dynamics and chemistry. The European Southern Observatory's Mid-infrared ELT Imager and Spectrograph (ELT/METIS) and the Thirty Meter Telescope's Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph (TMT/MODHIS) offer the spectral resolution and signal-to-noise (S/N) necessary to Doppler image planetary atmospheres based on temporal spectral variations due to surface inhomogeneities. Using our publicly-available code, Imber, developed and validated in Plummer & Wang (2022), we evaluate these instruments' abilities to identify and study dynamic and enduring atmospheric features on extrasolar giant planets in the Beta Pic and HR 8799 systems. We find both ELT/METIS and TMT/MODHIS are suitable for Doppler imaging Beta Pic b over a single rotation. The HR 8799 planets require multiple-integrated rotations to constrain spot parameters. We compare the spectroscopic technique against photometry-exclusive inference and find that combining spectroscopic and photometric observations leads to improved Bayesian inference of surface inhomogeneities and offers insight into whether planetary atmospheres are dominated by spotted or banded features.

Development of a non-linear curvature wavefront sensor for the Subaru Telescope's AO3k system

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Abstract

AO188 has been used as a facility adaptive optics (AO) system for the Subaru telescope since 2006. The current AO188 system mainly consists of a 188-actuator bimorph deformable mirror (DM) and a visible curvature wavefront sensor (CWFS) with 188 avalanche photodiodes (APDs). It allows Strehl ratios of about 20~40% in the H-band in median seeing. Also, AO188, in combination with infrared instruments at the Nasmyth platform, led to the publication of more than 100 papers with high impacts in the high-contrast

imaging/high-resolution community. To improve the AO system's performance, the Subaru telescope is developing both wide-field AO with ground-layer AO (GLAO) and narrow-field AO. Especially the AO188 upgrade will support narrow-field AO observations. A few years ago, we started upgrading AO188, including the real-time control system, laser guide star system, DM, and WFSs. We expect these upgrades to enhance the performance of all downstream instruments at the Nasmyth platform. There are many ongoing AO upgrades at the Subaru telescope. However, this presentation will focus on developing a non-linear curvature wavefront sensor (nlCWFS). We propose the nlCWFS as a new visible WFS for the upgraded AO system. One major AO upgrade is replacing the current DM with a new 3K DM. Consequently, a significant motivation for this work is that the current WFS has insufficient modes that can be measured compared to a new DM with ~3000 actuators. To overcome this limitation, we use an sCMOS camera instead of APDs. Thanks to the number of pixels of the camera, we can measure more than 16,000 modes as we design each pupil to have 128x128 pixels. Also, this nlCWFS uses four defocused pupil planes for the WFSing, allowing better sensitivity for low-order and high-order modes. This nlCWFS provides three different modes as follows. For the LGS mode, the nlCWFS will be operated as a linear curvature WFS with two near-pupil planes, similar to conventional CWFSs. In the NGS mode, all four planes will be used with a non-linear reconstructor to combine high sensitivity and dynamic range. In extreme-AO mode, the nlCWFS will be operated in its linear range on all four planes, providing high-speed (2kHz) high-accuracy wavefront reconstruction. We will introduce the optical and optomechanical design of the nlCWFS. We will present linear and non-linear wavefront reconstruction algorithms. We will also show closed-loop experiments in the lab with the SLM (Spatial Light Modulator). Finally, we will present the planned integration of the nlCWFS at the Subaru telescope.

Development of PSF reconstruction for first light instruments on the ELT

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Abstract

Even though Adaptive Optics (AO) correction is used in modern instru- ments of ground based telescopes, the quality of astronomical images still is degraded due to the time delay stemming from the wavefront sensor (WFS) integration time and adjustment of the deformable mirror(s) (DM). This re- sults in a blur which can be mathematically described by a convolution of the original image with the point spread function (PSF) of the instrument, telescope and residual atmospheric perturbations. The PSF of an astronom- ical image varies with the position in the observed field, which is a crucial aspect in observations on Extremely Large Telescopes (ELT). We present an algorithm to reconstruct the PSF in any position in the field of view using AO telemetry data and knowledge on the atmospheric profile. Our algorithm can easily be adapted to Single Conjugate AO (SCAO) and Multi Conjugate AO (MCAO) systems. In particular, we adapt an approach for atmospheric tomography to be used with a time series of AO telemetry data in SCAO mode. As input our algorithm requires knowledge of the strength of the different turbulent atmospheric layers, their wind speeds and directions in order to perform the tomography step. To obtain the respective contribution to the PSF, we project the reconstructed layers in the direction of interest. Our results are obtained for a simulated ELT setting in OCTOPUS, the ESO end-to-end simulation tool, and in Compass, the simulation tool de- veloped by LESIA, as well as for on-sky data from LBT. For a variety of atmosphere and system parameters, they suggest a good qualitative perfor- mance along with reasonable computational effort.

Development of test devices for the validation of MORFEO's reconstruction and control algorithms

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Abstract

The upcoming Multi-conjugate adaptive Optics Relay For ELT Observations (MORFEO) shows new and challenging issues, that need to be tested and prototyped before integration and troubleshooting on sky. One of the most critical aspects of this module is the reconstruction and control algorithm. To overcome the problem of unseen modes, MORFEO will implement a Minimum-Mean-Square-Estimator (MMSE) tomographic reconstructor, based on an a priori estimation of turbulence and noise statistics, that will be included in a Pseudo-Open Loop Control (POLC). In this work, we aim at analyzing and testing the reconstruction and control algorithms foreseen for MORFEO through a simplified single-conjugated adaptive optics system test-bed and a numerical simulator. The optical setup includes a Shack-Hartmann Wavefront Sensor (SH-WFS) to sense the wavefront aberrations, a Spatial Light Modulator (SLM) to inject and also compensate for the disturbances and a scientific camera to analyze the correction performance through the Point Spread Function. In order to simulate MORFEO's wide field, we compute the projection of the atmospheric turbulent volume along the line of sight of each of the nine WFSs of MORFEO, then we apply it on the SLM and measure it through the SH-WFS. The measurements from all the directions are used to compute the tomographic reconstructor and, consequently, to infer the commands to the SLM. The whole process is reiterated by shifting the phase maps previously simulated, in order to take into account the temporal evolution effects between successive iterations of the control loop. In this work, we show the current status of the test bench and the results of the first tests.

Developments towards an adaptive secondary mirror for KECK

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Abstract

TNO and partners at university of Hawaii and the Center for Adaptive Optics at UCSC are developing adaptive secondary mirror technology based on a unique electromagnetic actuator, which yields high efficiency in terms or force per unit volume and unit power. This actuator technology enables an overall compact and robust adaptive secondary mirror without the need for active cooling. Several design studies have been performed to investigate the potential of an ASM's based on this technology for telescopes such as TMT, KECK, Gemini, and the European Solar Telescope. Over the last three years several prototypes systems have been realized to verify the actuator technology and demonstrate its performance. Furthermore, a design upgrade of the actuators has been made that enable an even higher force density due to reduced size and easier manufacturing. The current focus of the team is the realization of the ASM designed for the NASA Infra-red Telescope Facility (IRTF) and the University of Hawaii 2.2-meter Telescope with 36 and 210

actuators respectively. These systems are aimed to demonstrate the potential of this technology within a representative environment and on operational astronomical facilities on Mauna Kea. In parallel, the team is developing the design of the Keck ASM which will have a diameter of Ø1.4 meters and between 2000 and 5000 actuators. The current focus is on the design of the lightweight and stiff support structure to support such large amount of actuators, and the packaging of the drive electronics. This paper will present the latest test results of TNO's novel actuator technology, the integration status of the UH2.2-ASM and IRTF-ASM, and the design status of the KECK-ASM.

Disentangled cascade adaptive optics for the SPHERE instrument forthcoming upgrade

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Abstract

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is a European Southern Observatory exo-planet imaging instrument installed on the 8m Very Large Telescope at Paranal (Chile). It has been operated for over 8 years since its commissioning in 2014 [1, 2]. Exo-planets observations rely on the quality of the adaptive optics correction which should provide the best possible imaging contrast. Considering the already achieved results, it has been decided to define new science objectives through an upgrade of this instrument within the SPHERE+ project [3]. In particular, the AO system main update will consist in the addition of a second stage (SAXO+) of correction that will take as input the residual phase of the current SPHERE AO system resulting in a Cascade AO (CAO) system. The second stage will use a pyramid wavefront sensor (WFS), taking advantage of the fact that the residual phase of the first stage will be already partially corrected allowing the use of a high sensitivity WFS. It should also run at a nominal frequency two to three times faster than the first stage. As a part of the design process for this new AO system, we propose to perform simulation regarding the specificities of CAO systems. We propose to explore especially the implementation of disantangled CAO (dCAO), see Figure 1. When the two AO stages operate

at different rates, the residual phase entering the 2nd stage includes an oversampled version of the slower 1st stage correction. This oversampling generates a non-stationary high-frequency see-saw signal which cannot be efficiently compensated by a linear time-invariant 2nd stage controller [4]. The proposed disentanglement procedure enables to compensate for this effect, with the control effort computed by the faster 2nd stage effectively split between the two DMs [5]. This procedure has been shown to improve significantly the image raw contrast with respect to two loops managed separately. This dCAO structure will be here designed and evaluated in the context of SAXO+ and compared with CAO using the COMPASS [6] end-to-end simulator. Controlling both loops with different RTCs or with a single one that drives all the components will be discussed in the light of the results obtained.

Durham Adaptive Optics (DAO) RTC solution

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Abstract

Durham Adaptive Optics (DAO) is a powerful and flexible software solution for adaptive optics systems developed at Durham University in the United Kingdom. DAO enables real-time correction of wavefront distortions caused by atmospheric turbulence and optical aberrations, improving the image quality of ground-based telescopes. DAO can be used with both GPU and CPU processing and is highly flexible, allowing it to be integrated with a range of hardware systems and configurations. DAO can work with several types of wavefront sensors, including Shack-Hartmann and pyramid sensors, and can support both deformable mirrors and tip-tilt mirrors. The team in Durham has extensive experience building adaptive optics systems, including the widely used Durham Adaptive Optics Real-Time Controller (DARC). The experience gained through the development and operation of DARC has informed the development of DAO. Systems at other observatories such as Subaru and Keck are also using similar solution. We will present the architecture of DAO and use cases for HARMONI and MOSAIC demonstrating its capabilities to solve ELT-scale AO system problems. The presentation will cover the software's flexible architecture, which enables it to be integrated with a variety of hardware systems and configurations. The use cases will demonstrate the real-time correction of wavefront distortions in an adaptive optics system, highlighting the software's efficient data handling, parallel processing techniques, small latency, and low jitter performances. DAO-like systems have been successfully implemented in several adaptive optics systems and have contributed to breakthrough discoveries in astrophysics, such as high-resolution imaging of planets, stars, and galaxies. With their efficient data handling and parallel processing techniques, DAO-like systems are valuable tools for researchers and astronomers looking to improve the resolution and quality of their ground-based telescope observations.

Dynamic and non linear phase reconstruction applied for Fourier Filtering Wave-Front Sensor

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Abstract

The next generation of Extremely Large Telescopes (ELT) will provide high angular resolution and broad sky coverage allowing astronomers to study very faint object such as exoplanets. To achieve the required resolution, Adaptive Optics (AO) corrects the perturbations induced by atmospheric turbulence. However, the fragmented pupil of the ELT introduces new aberrations such as differential piston or the Low-Wind Effect that need to be corrected to reach the full potential of these instruments. Standard AO systems are optimised to measure and correct for atmospheric perturbations, and may not be sensitive to these specific aberrations. It is therefore necessary to explore new wavefront sensors, which can cope with both the telescope and atmospheric perturbations. Toward this goal, the exploitation of the Fourier Filtering Wave-Front Sensors (FFWFS) appears to be a viable solution because of their high sensitivity compared to the Shack-Hartmann. However, high sensitivity often comes at the cost of non-linear behaviour. To overcome this difficulty, we explore a way to implement the non-linearities of these sensors in the classical matrix formalism. The mathematical formalism of this new way to implement the non-linearities of FFWFS is describe in Olivier Fauvarque's abstract "How to describe Fourier filtering wave front sensors non-linearity with interaction matrices". This new phase reconstructor complete the optical gain formalism by adding the modal confusion terms. We need the cross-terms that reflect the modal confusion that appears when working outside the linear regime of the FFWFS. Therefore, the construction of the whole gain matrix is an alternative approach to tackle non-linearities of FFWFS. To do so we will do an End-To-End simulation and explore a Deep-Learning approach to compute both the exact optical gain and the cross-terms. We present and compare the results of a new phase reconstructor obtained with both approaches. Experimental results obtained in a close-loop situation will also be presented.

Effect of deformable mirror sequence on performance of multiconjugate adaptive optics

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Abstract

Multi-conjugate adaptive optics (MCAO) uses two or more deformable mirrors (DMs) at conjugate altitudes approximately matched to the atmospheric turbulence layers to increase the corrected field of view. Previous numerical and theoretical studies suggest that ordering the DMs from lowest to highest altitude reduces the effects of scintillation, while recent on-sky experiments report that the best performance is attained with the lowest altitude DM placed last. In this paper, we demonstrate using analytical calculations and numerical experiments with Fresnel propagation of Kolmogorov turbulence that scintillation is not affected by the DM order because the spatial frequencies associated with scintillation are higher than what

astronomical adaptive optics systems are able to correct. In closed loop, the registration between the DMs and the wavefront sensors changes dynamically. We show using end-to-end numerical simulations with Fresnel propagation that the effect of dynamic misregistration is minimized by placing the ground-layer DM last, leading to increased loop stability and lower wavefront errors. Contrary to conventional wisdom, we recommend that the DMs be sequenced from highest to lowest altitude.

Effect of precipitate water vapor on high-contrast imaging in the thermal infrared

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1 - Universite de Liege(Belgium)

Abstract

The mid-infrared (IR) regime provides the optimal contrast for detecting rocky exoplanets. Currently, 8-10 m class ground-based telescopes are capable to image giant planets in the habitable zone of nearby stars. One such major demonstration of high-contrast imaging (HCI) capability in the mid-IR was the NEAR (New Earths in the Alpha Cen Region) experiment. NEAR demonstrated a detection sensitivity of a few Jupiter mass planets within a few hours of observing time in nearby systems. One of the biggest limitations to HCI in the mid-IR is the thermal sky background, which is directly correlated with the amount of precipitate water vapor (PWV) in the atmosphere. The effect becomes more important the bigger the telescope is, and it is one of the main risks for the ELT-METIS HCI performance at ten micron. In this work, we show that PWV is the principal contributor to thermal sky background and science PSF quality. In the presence of high PWV, the contrast in the background limited regime is significantly degraded.

ELT Telescope Wavefront Control

Bonnet henri [1], Spyromilio jason , Rubin adam , Esselborn michael

1 - European Southern Observatory(Germany)

Abstract

The ELT telescope control scenario shall be presented. The presentation shall focus on the various sensors available to the telescope and discuss their usage. The phasing station sensing shall be presented as a component of the telescope characterisation and calibration strategy. The telescope GPAO (Guide probe AO mode) shall be described and the process of reaching the conditions for handover discussed.

Enabling high resolution visible AO at the W.M. Keck Observatory

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1 - W.M. Keck Observatory(United States)
2 - Department of Physics [Santa Barbara](United States)
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Abstract

The W. M. Keck Observatory, in response to community workshops led by the Keck Adaptive Optics (AO) Future Study Group, has identified visible AO as an attractive science path for the observatory. Given the 10-meter aperture of the Keck telescopes, a visible AO system can achieve extremely high spatial resolutions. In collaboration with the National Aeronautics and Space Agency (NASA) the observatory recently installed a visible camera (ORKID) that works behind AO as part of the Orbiting Configurable Artificial Stars (ORCAS) mission. ORCAS is a first-of-its-kind hybrid space and ground observatory, using a satellite-based laser as the AO beacon for wavefront sensing. The ORKID camera is currently used in lucky imaging mode, while the AO system locks on a natural guide star. The intent is to use the camera for long integrations after upgrading the AO system with a higher order deformable mirror and to use the satellite-based laser as the AO beacon. With this camera we have imaged the close binary Theta Orionis C, in a Hydrogen-Alpha narrowband filter (650-660nm). The binary is detected with an intensity ratio of 6.3 to 1, and at a separation of 44.4 mas. This separation is roughly equivalent to the full-width at half-maximum (FWHM) of a K-band (~2.2um) point spread function (PSF), making it difficult to resolve the two components at longer wavelengths. With the FWHM of this image at 15.1 mas, this is the sharpest PSF ever measured at Keck demonstrating the potential offered by visible AO. We present results from ORKID and our development plans for visible AO moving forward

ERIS AO system and the interfaces with the telescope

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1 - European Southern Observatory(Germany)
2 - INAF - Osservatorio Astrofisico di Arcetri(Italy)

Abstract

The ERIS AO system is the first adaptive optics (AO) system designed to support an instrument delivered at Paranal (UT4) for the astronomical community, without any prior functional or performance tests with the deformable secondary mirror (DSM) or with the four Laser Guide Star (4LGS) system available in the Adaptive Optics Facility (AOF). Previous AO systems, like GALACSI and GRAAL, were tested at ESO Garching premises with the ASSIST telescope simulator, where the DSM was integrated and fully functional in the same configuration as on UT4, along with a LGS and NGS sources simulator and turbulence generator to reproduce the atmospheric conditions of Paranal. In contrast, the ERIS AO consortium faced all interfaces to the DSM and 4LGSF for the first time once installed on the UT4 telescope. This paper highlights the standard interfaces definition (a priori), issues faced (reality), and the lessons learned that can be applied

to the ESO-ELT related to interfaces between the instruments and systems such as M4 or the ESO-ELT lasers. Although the ERIS AO consortium has extensive experience with the LBT telescope, the VLT system was a new challenge that required significant coordination among the consortium's multiple institutes. As telescopes and instruments grow in size and complexity, developing prototypes and coordinating multiple systems is becoming increasingly challenging. Despite this, focusing on the smallest details is also critical to ensure the success of the project.

Error budget analysis for wavefront estimation using cGAN and UNet methods

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3 - Australian National University - Research School of Astronomy and Astrophysics - Advanced Instrumentation Technology Centre(Australia)

Abstract

Development of improved adaptive optics (AO) methods for large, ground based optical telescopes is required for future instrumentation design as we build ever larger telescopes, such as the ELT. Early results of new data driven machine learning (ML) methods for wavefront estimation have shown some potentially useful improvements in simulation, however rigorous analysis of these simulated results in the astronomical domain have been difficult to evaluate due to the data driven nature of the neural networks applied. Due to their opaque operational nature, these methods require robust performance analysis before they can be considered for practical use. In this paper, we present a careful error analysis from the projection of the wavefront estimateson a set of Karhunen-Loeve modes, and compare with similar statistics generated for simulated benchmarks We then use this technique to examine previously published estimation techniques that estimate wavefronts from Shack-Hartmann wavefront sensor images [1, 2], outlining their relative strengths and weaknesses for pseudo open-loop control and point spread function reconstruction (PSF-R). Finally, we conduct a thorough analysis of the effects of noise on conditional Generative Adversarial Network (cGAN) and UNet wavefront estimation methods and provide an assessment of suitability to control and PSF-R applications from simulated results. (1) Smith, J.; Cranney, J.; Gretton, C.; Gratadour, D. In Uncertainty in Artificial Intelligence, Proceedings of the Thirty-Eighth Conference on Uncertainty in Artificial Intelligence, UAI 2022,1-5 August 2022, Eindhoven, The Netherlands, ed. by Cussens, J.; 0001, K. Z., PMLR: 2022; Vol. 180, pp 1846–1856. (2) Smith, J.; Cranney, J.; Gretton, C.; Gratadour, D. Journal of Astronomical Telescopes, Instruments, and Systems 2023, 9, 019001.

Exoplanet detection and characterization with moderate resolution spectroscopy

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Abstract

Moderate to high-resolution spectroscopy can resolve molecular features in exoplanet atmospheres and therefore allows precise measurements of atmospheric composition. Identifying trends in the present day composition of exoplanets, such as metallicity or carbon to oxygen ratio, can then inform their formation pathways. Additionally, higher-resolution integral field spectroscopy is a powerful tool for planet detection. It is virtually insensitive to the speckle noise from the host star, which is the limiting factor for high-contrast instruments at small separations (

Exoplanet imaging with ExAO: exploring a second-stage AO approach with a Zernike wavefront sensor for high-contrast imaging with ELTs

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Abstract

We propose to explore a two-stage extreme Adaptive optics (ExAO) approach with a second stage based on a Zernike wavefront sensor (ZWFS) for exoplanet imaging and spectroscopy. Most exoplanet imagers currently use a single-stage ExAO to correct for the effects of atmospheric turbulence and produce high-Strehl images of observed stars in the near-infrared. While such systems enable the observation of warm gaseous companions around nearby stars, adding a second-stage AO enables to push the wavefront correction further and possibly observe colder or smaller planets. This approach is currently investigated in different exoplanet imagers (VLT/SPHERE, Mag-AOX, Subaru/SCExAO) by considering a PWFS in the second arm to measure the residual atmospheric turbulence left from the first stage. Since these aberrations are expected to be very small (a few tens of nm in the NIR), we propose to investigate an alternative approach based on the ZWFS. This sensor is a promising concept with a small capture range to measure residual wavefront errors thanks to its large sensitivity, simple phase reconstruction and easy implementation. In this contribution, we perform two-stage AO simulations to determine the best functioning points for the ZWFS-based second-stage AO in terms of image quality. Preliminary tests are then investigated on the GHOST testbed at ESO to validate this approach experimentally. Finally, we discuss a first comparison between PWFS-based and ZWFS-based second-stage AO to draw preliminary conclusions on the interests of both schemes for exoplanet imaging and spectroscopy with the upgrade of the current exoplanet imagers and the envisioned ExAO instruments for ELTs.

Experimental comparison of model-free and model-based dark hole algorithms

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Abstract

One of the major scientific endeavors of the astronomical community in the next ten years is to directly detect and spectroscopically characterize exoplanets in pursuit of finding a habitable world. Coronagraphic instruments provide the best chance of enabling high contrast spectroscopy and require high performing focal plane masks in combination with precise control of the wavefront phase and amplitude to achieve dark holes for planet detection. Several wavefront control algorithms have been developed in recent years that might vary in performance when paired with different coronagraphic masks. This study tests and compares model-free and model-based algorithms, primarily self-coherent camera (SCC) and Electric Field Conjugation (EFC), when paired with a vector vortex coronagraph (VVC) or a scalar vortex coronagraph (SVC) in the same laboratory conditions. We present experimental results from the In-Air Coronagraph Testbed (IACT) at JPL in monochromatic and polychromatic light comparing the pros and cons of each of these wavefront sensing and control algorithms.

Experimental results of an apodized vortex coronagraph for segmented apertures

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1 - Caltech Department of Astronomy [Pasadena](United States)

Abstract

Segmentation of the primary mirror enables larger apertures for both ground-based and space telescopes. However, the complex shape of the aperture geometry is detrimental to the back end coronagraphic instruments, especially to vortex coronagraphs (VC) known to suffer from a drastic loss in performance when the PSF deflects from the Airy pattern. Apodization of segmented aperture allows to reshape the pupil geometry and to overcome this effect. The High Contrast Spectroscopy Testbed (HCST) aims to develop and validate key technologies for future exoplanet imaging instruments. We ordered an apodizer based on a carbon nanotube coating. This technology presents a very low reflectance conducive to high performance apodization. Using a BMC kilo-DM for wavefront control, we test this apodization upstream of a vector VC and present our latest experimental results.

Experimental validation of Flip-flop modulation on the ESO GHOST

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Abstract

The adaptive optics systems of extremely large telescopes (ELTs), such as the European Southern Observatory's ELT, will have to cope with the pupil segmentation caused by the secondary mirror support structure (spider). The pyramid wavefront sensor, which is the baseline wavefront sensor for the single conjugate adaptive optics (SCAO) mode for many instruments, has a poor sensitivity to piston errors between the pupil segments. The pyramid wavefront sensor is typically operated in one of two modes: modulated, where the telescope's focal point is modulated about the tip of the pyramid in a circular pattern, and unmodulated, where the telescope's focal point is on the tip of the pyramid. By increasing the radius of the modulation, the linearity and dynamic range of the sensor are improved, whilst the sensitivity of the sensor is degraded. Previously in simulation, we have shown that an unmodulated pyramid wavefront sensor has a significantly greater sensitivity to segment piston modes when compared to a modulated pyramid. Based on this observation, Flip-flop modulation was presented, where the pyramid is operated in modulated (70% duty cycle), and unmodulated (10% duty cycle) modes and the remaining 20% is used to switch between the states. This paper details the experimental validation of Flip-flop modulation on the GPU-based High-order adaptive OpticS Testbench (GHOST) at ESO and the characterisation of the modulation mirror to fine-tune and verify the modulation path. Using the spatial light modulator of the GHOST, arbitrary pupil/spider geometries are emulated, with an adjustable segment piston, allowing the performance of Flip-flop modulation to be characterised under various conditions.

Experimental validation of large differential piston sensing with the double-wavelength LIFT

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Abstract

Adaptive optics systems for the future Extremely Large Telescopes will have to deal with large gaps in the pupil due to the spiders and/or the segmentation of one or several mirrors. These gaps are typically larger than the expected r0 at the sensing wavelength. They can thus create significant discontinuities in the wavefront, which lead to the so-called "island effect" or "petaling": the wavefront in each segment is well corrected, but differential pistons at a multiple of the sensing wavelength appear between the segments. During the design phase of the Natural Guide star Wavefront Sensor prototype for the Giant Magellan Telescope (GMT), we have studied the Linearized Focal-plane Technique (LIFT) as a potential solution to correct the differential pistons while the adaptive optics system is running. LIFT uses a single image with a known phase offset to estimate wavefront aberrations. The reconstruction of the differential pistons from a single image is limited to the range [-lambda/2, +lambda/2], with lambda the sensing wavelength, due to the 2-pi ambiguity. However, several micrometers of capture range are needed to finely co-phase the GMT. We partially removed the ambiguity and thus increased the capture range by using two LIFT estimations at different wavelengths. At Arcetri premises we set up a test bench in order to obtain a first proof of concept for the dual-wavelength LIFT. The experimental setup includes a diffraction limited near-infrared source and a custom-made mirror with two segments. The longitudinal position of one of the halves is controlled via a motor with a precision of about 5 nm on a 10-mm range. LIFT images were taken on a defocused camera placed downstream of the segmented mirror. The dual-wavelength was achieved by alternating between two

narrowband filters. In this presentation, we show that we were able to reconstruct the differential piston either with two J-band filters or two H-band filters in the whole theoretical capture range.

Exploring an event camera-based pyramid wavefront sensor

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1 - Pontificia Universidad Católica de Valparaíso(Chile)

Abstract

Adaptive optics (AO) is essential in the Extremely Large Telescopes (ELT) era to reach their scientific goals in terms of accuracy and sensitivity [1]. Similarly, AO is fundamental to boosting the performance of future ground-satellite optical communications [2] and improving space situational awareness [3]. Owing to these new challenges for AO systems, innovations can be carried out by taking advantage of cutting-edge sensor technologies based on non-traditional principles. That is the case of the event-based cameras, which use a dynamic vision sensor where every pixel works independently and asynchronously so that each one quantizes local relative intensity changes to generate spike events [4]. Due to its high acquisition speed and dynamic range, this sensor appears as a promising alternative to be incorporated in a pyramidal wavefront sensor (PWFS), leading to a potentially low-cost, though still sensitive enough, solution. However, a new challenge arises. How to correctly obtain the interaction matrix of and event-based system? In this work, we test a PWFS based on an event camera sensor at the PULPOS bench [5], an AO bench that have either a PWFS made with a 4-face pyramid prism of Zeonex or a digital PWFS, and that can be stimulated by high-order wavefront aberrations and pupil discontinuities (spiders or secondary obscuration) with a combination of spatial light modulators (LCOS or DMD) at the pupil plane. The event data is collected during a fixed emulated integration time to obtain an equivalent interaction matrix. Samples of the response to some known aberrations are shown in Fig.1. We are currently investigating its potential and limitations for wavefront estimations. References: [1] Hubin, N., Ellerbroek, B. L., Arsenault, R., Clare, R. M., Dekany, R., Gilles, L., Kasper, M., Herriot, G., Le Louarn, M., Marchetti, E., Oberti, S., Stoesz, J., Veran, J. P., & Vérinaud, C. (2005). Adaptive optics for extremely large telescopes. Proceedings of the International Astronomical Union, 1(S232), 60-85. [2] Chen, M., Liu, C., Rui, D., & Xian, H. (2018). Performance verification of adaptive optics for satellite-to-ground coherent optical communications at large zenith angle. Optics express, 26(4), 4230-4242. [3] Copeland, M., Bennet, F., Rigaut, F., Korkiakoski, V., d'Orgeville, C., & Smith, C. (2018, July). Adaptive optics corrected imaging for satellite and debris characterisation. In Adaptive Optics Systems VI (Vol. 10703, p. 1070333). International Society for Optics and Photonics. [4] Lichtsteiner, P., & Posch, C. (2008). C. and T. Delbruck,"An 128× 128 120 dB 15 μs latency temporal contrast vision sensor. IEEE Journal of Solid State Circuits, 43, 566-576. [5] Tapia, J., Bustos, F. P., Weinberger, C., Romero, B., & Vera, E. (2022, August). PULPOS: a multi-purpose adaptive optics test bench in Chile. In Adaptive Optics Systems VIII (Vol. 12185, pp. 2222-2231). SPIE.

Exploring the capabilities of the geometric WFS

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Abstract

With the imminent arrival of large telescopes, the development of incredibly sensitive and faster Adaptive Optics (AO) systems has meant new challenges in Wavefront Sensor (WFS) performance. The investigation of new algorithms, techniques and concepts is therefore a booming field. In general, an ideal WFS would have the following main characteristics: high dynamic range, sensitivity, linearity and efficiency. To date, no WFS has been found that exhibits all these properties at the same time. For the new era of telescopes, the Pyramidal Wavefront Sensor (PyWFS) has replaced the Shack-Hartmann (SH) WFS as the reference for high-performance AO. The characteristics that have led to its implementation are the increase in sensitivity through modulation control, improved SNR and adaptability to correct for wavelength, and a better adjustment to the source brightness thanks to the possibility of changing the spatial sampling and gain during operation and adjusting the modulation amplitude. However, the PyWFS is a nonlinear device. The most widespread way to deal with nonlinearity is to apply modulation at the cost of reducing sensitivity. Consequently, there are still some points against it. The need for dynamic modulation requires the incorporation of a high-frequency moving component inside the instrument and therefore the implementation of high-precision optics. This is why the study of new strategies for sensing and reconstruction continues to be an active field of researching. There are several studies comparing the response of SH and PyWFS but despite the great results obtained with the geometric WFS, named as Two Pupil Plane (TP3), this sensor remains unknown among the AO astronomical society. Here we want to present a complete study of the TP3 WFS to compare its capabilities versus the widespread WFS in Astronomy, the SH and the PyWFS. To carry out the comparison, a system was simulated in Python using the Hcipy library to generate the optical elements of the system. Linearity, dynamic range, sensitivity and efficiency tests have been achieved and the results are very promising.

Extreme Adaptive Optics from 8- to 40-m telescopes

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Abstract

Extreme Adaptive Optics (XAO) is widely used at current 8-m class telescopes to power high-contrast imaging instruments mostly dedicated to the observation of self-luminous Exoplanets and circumstellar disks. I will review the current systems and briefly introduce upgrades planned for the near future. The next generation of 30-40 meter class telescopes will literally open new worlds as direct imaging of Earth-like Exoplanets will come into reach. For this demanding science case, the XAO must push the residual halo at small angles down by orders of magnitudes below what is currently reached for the 8-m telescopes. New developments are needed in key AO technologies such as DMs with tens of thousands of actuators, fast RTCs supporting advanced control methods, and wavefront sensors with superior sensitivity and the capability to sense phase discontinuities in segmented apertures. I will review current activities in these areas and finish the talk with a first prediction of the Exo-Earth imaging capabilities of the XAO-powered Planetary Camera and Spectrograph (PCS) instrument for the ELT.

FASS: TOWARDS A FULLY AUTOMATED MONITOR

Guesalaga andrés [1]

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Abstract

The FASS monitor (Full Aperture Scintillation Sensor) provides estimates of profiles, together with seeing, and isoplanatic angle. The aim of the monitor is to support observations requiring the characterization of total atmospheric parameters as well as stratified information of turbulence strength in altitude. The technique uses the wavefront scintillation phenomena, and the processing is based on frequential image processing of these pattern. So far, the development of FASS has been aimed to validate the method rather than developing a fully autonomous monitor to support rutinary operations observatories. We first present the progress in aspects of servocontrol (mount), star/pupil centring and tracking, user interface, communications, and automatic scheduling of beacon stars. For star pointing, the Alt-Az mount ensures sideral tracking accuracies better than 0.3 as and pointing accuracy lower than 10 as. Rapid variations such windshake or vibrations can be effectively eliminated thanks to the short exposure times of the camera and a fast pupil centring, providing a correct sampling of the image rings used in the technique. Then we present a summary of the results obtained in a last campaign carried out at Paranal observatory between February 27th and March 4th, 2023. The main difference in FASS configuration with respect to previous campaigns [1] is that the sensor was run in the generalized mode (GM), something not tested before. The GM is, in optical terms, the extended wavefront propagation below the pupil to allow scintillation to build up when generated by layers near the ground, where the standard scintillation setup is blind. Several sensors concurred to this activity, namely: MASS/DIMM SCIDAR RINGSS SHIMM FASS FASS results are compared to the other sensors and the GM performance is analysed and discussed, suggesting that this configuration can be very sensitive to the optics modelling errors, star colour mismatch and noise retrieval. We believe that the impact of these factors is amplified in ill-posed problems such as the model-matching generally used in scintillation sensors. [1] Guesalaga A., et al, (2021), FASS: a turbulence profiler based on a fast, low-noise camera, MNRAS 501, 3030.

Final design and estimated performance of the ELT/METIS high-contrast imaging modes

Absil olivier [1]

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Abstract

The mid-infrared Extremely Large Telescope imager and spectrograph (METIS) went through its final design review (FDR) in late 2022, and is currently scheduled for installation at Cerro Armazones in late 2028. Since the start of Phase B in 2015, the design of METIS has been optimized to provide high-contrast imaging capabilities that can be coupled with both its imaging and high-resolution integral field spectroscopy cameras. Thanks to its high-contrast imaging modes, METIS is bound to provide an unprecedented vantage point on the inner parts of planetary systems around nearby stars, potentially down to the rocky planet regime. In this contribution, I will review the design of the METIS high-contrast imaging modes at FDR as well as the on-going procurement activities, and present the estimated coronagraphic performance based on end-to-end simulations. I will highlight the main contributors to the coronagraphic performance budget, with a particular emphasis on the main sources of non-common path aberrations that we have included in our simulations. I will also discuss to what extent the behavior of the single-conjugate adaptive optics (SCAO) system drives the high-contrast imaging performance, and describe the interplay between the focal-plane wavefront sensing strategy and SCAO operations within METIS. Finally, I will explain how water vapor seeing will drive the METIS coronagraphic performance in the 10-μm region, and present the on-going investigations using the Very Large Telescope Interferometer to improve our understanding of this phenomenon.

Finally, let's use all the modes!

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Abstract

Subtitle: A stable DM fitting avoiding modal truncation For the AO Control of the ELT instrument METIS a two-step method has been developed. First, we reconstruct the incoming wavefront from modulated Pyramid WFS measurements, second, we project this wavefront estimation on a set of modes defined on the M4 of the ELT. Here we focus on the second step, the stable fitting step of a wavefront on modes. In very bad seeing conditions or for faint guide stars previous methods have utilized modal truncation. In order to stay stable, the number of modes was reduced, i.e., less spatial frequencies were used. If simply truncating modes one is not able to explicitly control spatial frequencies, the effects of the truncation are visible in the modal representation of the wavefront, the overall quality of the AO system decays. To avoid these effects of truncation and to adapt the fitting step to the statistics of either full atmospherics screens or residual screens we introduce a regularized fitting step using all available modes based on the same statistical information as the wavefront reconstructor. We will present the properties of this fitting steps as well as improved closed loop simulation results for the instrument METIS. We will show that with very few reconstructor parameters, even with a constant set of parameters for the control, we obtain a stable and good performance of the AO system over all seeing and flux conditions studied.

First on-sky demonstration of a three-sided reflective pyramid wavefront sensor using the 3-meter Shane Telescope

Sanchez dominic [1], Hinz philip [1], Chun mark [2], Dillon daren [3], Ratliff christopher [3], Bond charlotte [4]

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2 - Institute for Astronomy(United States)
3 - UCO/Lick Observatory(United States)
4 - UK Astronomy Technology Centre(United Kingdom)

Abstract

The pyramid wavefront sensor (PWFS) is a prime candidate to be implemented into the next generation of extremely large telescopes for low order wavefront sensing. There are a few PWFS designs, however, they are all transmissive and must be optimized for their intended wavefront sensing wavelength. Furthermore, fabricating these four-sided glass prisms is difficult and more expensive, which has led to the development of the double-roof PWFS configuration. To mitigate these challenges, we propose a three-sided reflective pyramid wavefront sensor (3-RPWFS) as a possible alternative to existing PWFS designs. In this paper, we present the first on-sky demonstration of a 3-RPWFS using the Shane Telescope's adaptive optics system (ShaneAO) on Mount Hamilton, California. To implement the R-PWFS on ShaneAO we developed a hybrid transmissive/reflective design to fit in the available space. This includes a novel spinning glass wedge to implement the modulation. Both the reflective pyramid and the transmissive wedge are unique aspects of this implementation that may be useful for future pyramid designs. On-sky closed loop operation is performed using natural guide stars for a performance comparison with the current Shack-Hartmann wavefront sensor (SHWFS) in ShaneAO. The on-sky closed loop results demonstrate proof of concept and this sensor will be further optimized to effectively assess performance.

Focal Plane WFS with Machine Learning: an experimental proposal to estimate aberrations trough neural networks

Di Francesco benedetta [1]

1 - INAF- Osservatorio Astronomico d'Abruzzo(OAAb)(Italy)

Abstract

Nowadays, many Adaptive Optics solutions are able to get the expected correction from an aberrated incoming wavefront. However, the Focal Plane Wavefront Sensor (FPWFS) represents a desirable system, especially for new Extremely Large Telescope (ELT) generation, since it overcomes some still existing limits such as Non-Common Path Aberrations (NCPA) or Low Wind Effect (LWE), which are responsible for low-order aberrations and detrimental residuals unseen by classical AO configurations. This research proposes to set up an experimental test bench and carry out machine learning techniques to recognize the aberrations of an image directly taken from the focal plane and transported through optical fibers. This is an attempt to face the obstacles of wavefront sensing, in sight of new boundaries of Extreme AO applications.

Fourier-type wavefront sensing – a general and nonlinear approach

Hutterer victoria [1], Neubauer andreas [1], Obereder andreas [2], Shatokhina julia [3], Ramlau ronny [1 3]

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Johannes Kepler University Linz(Austria)
2 - MathConsult GmbH(Austria)
3 - Johann Radon Institute for Computational and Applied Mathematics Linz(Austria)

Abstract

Advanced Adaptive Optics (AO) instruments have applications in the future generation of Extremely Large Telescopes (ELTs). Many of these AO systems include Pyramid Wavefront Sensors (PWFSs) in their design. The classical PWFS is 4-sided and its competitors include the 3-sided PWFS and the iQuad. All of these Wavefront Sensors (WFSs) are considered Fourier-type because they use optical Fourier filtering with a suitable optical element in the focal plane. Conventionally, these sensors perform wavefront reconstruction using Matrix-Vector-Multiplication (MVM) approaches that need to be calibrated to the system. There also exist several model-based reconstructors which depend on the underlying mathematical model of the WFS. Additionally, methods like MVMs are linear techniques applied to the inversion of nonlinear Fourier-type WFS models. However, in nonlinear regimes, linear approaches critically degrade image quality due to approximation errors, sometimes compensated by the so-called optical gain. Here we present a novel type of nonlinear reconstructor that is a generalised wavefront reconstruction method for all Fourier-type sensors. A significant advantage to this approach is its direct applicability to any Fourier-type WFS without calibration. Moreover, the algorithm has been designed to be robust in nonlinear regimes. Several Fourier-type wavefront sensors will be considered for ELT-scale instruments and their performance evaluated for different atmospheric settings. We will investigate whether optical gain compensation is automatically included in the nonlinear wavefront reconstruction method. Comparisons will be made to linear reconstruction approaches (e.g., MVMs) operating in nonlinear regimes.

From AO Simulation to Real-Time Turbulence Correction using the same Software Interface

Schimpf armin [1], Martin bruno [1], Boudjema idir [1 2], Benammar bouchra [3], Charton julien [1]

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2 - Laboratoire d'Astrophysique de Marseille(France)
3 - Centre National d\'Études Spatiales [Toulouse](France)

Abstract

We present ALPAO's adaptive optics control and simulation software ACE. We show that thanks to a unified software interface between RTC and simulation environment, the design, integration, and validation process of an adaptive optics system could be much streamlined. First, we discuss recent developments in ACE's simulation layer which include realistic detector models, a diffractive Shack-Hartmann and Pyramid-WFS model and a perturbation data import feature for complex electrical fields produced by third party simulators. Debug tools, calibration and command matrix computation routines developed in the simulation environment can then be readily applied to the RTC in the lab experiment. Since the telemetry data format is identical, all scripts for performance analysis can be reused. The RTC also features open interfaces to read pre-computed perturbation data from disk in real-time that can be used to tamper with the wave-front corrector commands or the wave-front sensor measurements before processing begins. In this way, using a fully software-based approach, the effects of phase perturbation and non-homogeneous flux conditions can be emulated.

Gemini North Adaptive Optics System Performance Simulations

Jackson kate [1]

1 - NRC Herzberg Astronomy and Astrophysics(Canada)

Abstract

The Gemini North Adaptive Optics (GNAO) system is the planned upgrade the Gemini North telescope's AO system. GNAO will have a single ground-conjugated deformable mirror (DM) and use an asterism of 4 sodium Laser Guide Stars (LGSs) which can be configured in both narrow and wide field modes. As part of one of the Adaptive Optics Bench (AOB) Phase A design study teams, The Object Oriented Matlab Adaptive Optics (OOMAO) simulation tool has been used to model the performance of the GNAO system in both modes. A large parameter space has been explored, including the effects of wavefront sensor (WFS) and DM order, LGS asterism radius, tip/tilt (T/T) star number and location, and performance as a function of telescope zenith angle. A variety of error terms, including noise, NCPA, and secondary mirror print through have been incorporated. This work has been used to produce the expected error budget of the proposed AOB design.

Giant Magellan Telescope Adaptive Optics Overview

Bouchez antonin H. [1], Close laird M. , Conan rodolphe , Esposito simone , Demers richard , Groark frank , Males jared , Mcleod brian , Quiros-Pacheco fernando , Rob sharp , Sitarski breann , Peter thompson , Van Dam marcos

1 - Giant Magellan Telescope(United States)

Abstract

The 25.4 m diameter Giant Magellan Telescope will have four first-generation observing modes: Natural seeing, ground-layer AO, natural guide star AO, and laser tomography AO. These control modes are enabled by a suite of wavefront sensors and metrology systems that provide feedback to a segmented active primary mirror and a segmented adaptive secondary mirror. A telescope-wide laser metrology system enables rapid optical alignment. The telescope Acquisition, Guiding, and Wavefront Sensing Subsystem provides all necessary wavefront sensing for the natural seeing and GLAO observing modes, and controls field-dependent aberrations in the diffraction-limited modes. Natural and laser guide star wavefront sensors deployed with each diffraction-limited instrument sense atmospheric and telescope wavefront errors. Together with the 4725-actuator adaptive secondary mirror, these sensors will deliver high contrast in the visible and near-infrared when using bright natural guide stars, and diffraction-limited image quality in the near-infrared over 80% of the sky. There have been several changes made to the GMT AO design since the last conference. The Natural Guide Star Wavefront Sensor now incorporates both a pyramid wavefront sensor for high-order control and a Holographic Dispersed Fringe Sensor to increase the segment phasing dynamic range. The On-Instrument Wavefront Sensors of the GMTNIRS and GMTIFS instruments have been further developed and now include real-time phase retrieval to sense segment piston errors at high frame rate. The design of the GMagAO-X high-contrast instrument has advanced, and it will be deployed in the first generation of GMT instrumentation. We are developing laboratory optical testbeds and prototype wavefront sensors to validate active optics and AO algorithms. We are also fabricating the first off-axis adaptive secondary mirror segment to retire fabrication risk and verify its performance. We will report our progress and recent results in all these areas.

GMagAO-X: A First Light Coronagraphic Adaptive Optics System for the GMT

Kautz maggie [1], Males jared , Close laird , Haffert sebastiaan , Guyon olivier , Gasho victor , Coronado fernando , Durney olivier , Hedglen alexander , Noenickx jamison , Ford john , Connors tom , Kelly doug , Demers richard , Bouchez antonin

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Abstract

GMagAO-X is a visible to NIR extreme adaptive optics (ExAO) system that will be used at first light for the Giant Magellan Telescope (GMT). GMagAO-X is designed to deliver diffraction-limited performance at visible and NIR wavelengths (6 to 10 mas) and extreme contrasts on the order of 10-7. The primary science case of GMagAO-X will be the characterization of mature, and potentially habitable, exoplanets in reflected light. GMagAO-X employs a woofer-tweeter system and includes segment phasing control. The tweeter is a 21,000 actuator segmented deformable mirror (DM), composed of seven individual 3,000 actuator DMs. This new ExAO framework of seven DMs working in parallel to produce a 21,000 actuator DM significantly surpasses any current or near future actuator count for a monolithic DM architecture. Bootstrapping, phasing, and high order sensing are enabled by a multi-stage wavefront sensing system. GMT's unprecedented 25.4 m aperture composed of seven segments brings a new challenge of co-phasing massive mirrors to 1/100th of a

wavelength. The primary mirror segments of the GMT are separated by large >30 cm gaps so there will be fluctuations in optical path length (piston) across the pupil due to vibration of the segments, atmospheric conditions, etc. We have developed the High Contrast Adaptive-optics Testbed (HCAT) to test new wavefront sensing and control approaches for GMT and GMagAO-X, such as the holographic dispersed fringe sensor (HDFS), and the new ExAO parallel DM concept for correcting aberrations across a segmented pupil. The CoDR for GMagAO-X was held in September 2021 and a preliminary design review is planned for late 2023. In this talk we will discuss the science cases and requirements for the overall architecture of GMagAO-X, as well as the current efforts to prototype the novel hardware components and new wavefront sensing & control concepts for GMagAO-X on HCAT.

GMT NGAO Integrated Modeling

Rod conan [1], Dribusch christoph [1], Romano rodrigo [1], Fitzpatrick henry [1], Shabram megan [1], Sitarski breann [1], Walls brian [1]

1 - Giant Magellan Telescope Organisation(United States)

Abstract

The Giant Magellan Telescope Project relies on a comprehensive integrated modeling tool to evaluate Observatory Performance Modes, ranging from Seeing Limited to Adaptive Optics. This STOP (Structural-Thermal-Optical Performance) model includes the dynamics of each domain-specific model, accounting for time-varying disturbances such as wind jitter, vibrations, and temperature fluctuations. However, creating such a model presents challenges due to the wide range of scientific and engineering expertise required, as well as the large number of degrees of freedom to handle. Adaptive Optics presents additional challenges due to its high sampling rate of 1kHz or more, exacerbated by the need to simulate long science exposures under various operating conditions. This paper will introduce the main components of the integrated model, including finite element, optical, control, and computational fluid dynamics, as well as the stringent verification and experimental validation processes that the model undergoes. The choice of computing framework that integrates domain-specific models into a unified model is critical and will be described in detail. The development of the integrated model is driven by the need to accurately estimate errors that affect the science instrument data products and mitigate technological risks associated with the telescope. Examples will be given on how the error budgets and risk register are used to set priorities for the integrated modeling simulations queue. The GMTO project has identified a set of Key Performance Parameters (KPP) that summarize the expected performance for each Observatory Performance Mode. These KPPs are statistical quantities derived from Monte-Carlo simulations of the Observatory under various operating and environmental conditions. This paper will show how Monte-Carlo simulations have been performed at the Observatory level for the Natural Guide Star Adaptive Optics Observatory Performance Mode.

GNAO: the new AO facility for Gemini North, facility overview and project updates

Sivo gaetano [1], Scharwächter julia [2], Lamb masen [2], Lazo manuel [1], Blain celia [2], Goodsell stephen [2 3], Gaspar claudio [1], Van Dam marcos [4], Rambold william [2], D'amato joe [2], Tomasino-Reed kim [2], Tschimmel martin [1], Lotz jennifer [2], Cardenes ricardo [1], Gaggstatter tim [1], Gigoux pedro [1], Schneider thomas [2], Cavedoni charles [2], Kang stacy [2], Karewicz stanislas [2], Carr heather [2], Sato logan [2], Ball jesse [2], Hirst paul [2], White john [2], Magill lindsay [1], Grogan molly [2], Sivanandam suresh [5], Muzzin adam [6], Chapman scott [7], Dunn jennifer [8], Kerley dan [8], Veran jean-Pierre [8], Andersen morten [9], Marchis franck [10], Diaz ruben [1], Blakeslee john [2], Pierce michael [11], Carrasco rodrigo [1], Kim hwyhyun [2], Feldmeier-Krause anja [12 13], Mcconnachie alan [8], Jee james [14], Fraser wesley [8], Ammons mark [15], Packham christopher [16], Bally john [17], Dupuy trent [18], Huber daniel [19], Lemoine-Busserolle marie [2], Puzia thomas [20], Turri paolo [21], Trujillo chadwick [22], Lee janice [2]

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3 - Department of Physics [Durham University](United Kingdom)
4 - Flat Wavefront(New Zealand)
5 - UNIVERSITY OF TORONTO(Canada)
6 - York University(Canada)
7 - Dalhousie University(Canada)
8 - NRC Herzberg Astronomy and Astrophysics(Canada)
9 - European Southern Observatory(Germany)
10 - SETI Institute(United States)
11 - University of Wyoming(United States)
12 - Max Planck Institute for Extraterrestrial Physics(Germany)
13 - University of Chicago(United States)
14 - Yonsei University(South Korea)
15 - Lawrence Livermore National Laboratory(United States)
16 - The University of Texas at San Antonio(United States)
17 - University of Colorado(United States)
18 - University of Edinburgh(United Kingdom)
19 - University of Hawaii(United States)
20 - Pontifica Universidad de Chile(Chile)
21 - University of British Columbia(Canada)
22 - Northern Arizona University(United States)

Abstract

The Gemini North Adaptive Optics (GNAO) facility is the upcoming AO facility for Gemini North providing a state-of-the-art AO system for surveys and time domain science in the era of JWST and Rubin operations. GNAO will be optimized to feed the Gemini infrared Multi Object Spectrograph (GIRMOS). While GIRMOS is the primary science driver for defining the capabilities of GNAO, any instrument operating with an f/32 beam could be deployed using GNAO. The GNAO project includes the development of a new laser guide star facility which will consist of four side launched laser beams supporting the two primary AO modes of GNAO: a wide-field mode providing an improved image quality over natural seeing for a 2-arcminute circular field-of-view using GLAO and a narrow-field mode providing near diffraction-limited performance over a 20 × 20 arcsecond square field-of-view using LTAO. The GNAO wide field mode will enable GIRMOS's multi-IFU configuration in which the science beam to each individual IFU will be additionally corrected using multi-object AO within GIRMOS. The GNAO narrow field mode will feed the GIRMOS tiled IFU configuration in which all IFUs are combined into a "super"-IFU in the center of the field. GNAO will include a new Real Time Controller (RTC), Facility System Controller and new Adaptive Optics Bench, each at different stages of their development lifecycle. We present an overview of the GNAO facility, its science goals and provide a status update of the development of each facility product.

GPI 2.0: End-to-end simulations of the AO-coronagraph system

Nguyen jayke [1], Maire jerome , Perera saavidra , Do O clarissa , Konopacky quinn , Chilcote jeffrey , Fitzsimmons joeleff , Hamper randall , Kerley dan , Macintosh bruce , Marois christian , Rantakyro fredrik , Savransky dmitry , Veran jean-Pierre , Agapito guido , Ammons mark , Bonaglia marco , Boucher marc-Andre , Dunn jennifer , Esposito simone , Filion guillaume , Landry jean Thomas , Lardière olivier , Madurowicz alex , Nguyen meiji , Nickson bryony , Peng dillon , Por emiel , Poyneer lisa , Soummer remi , Li duan

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Abstract

The Gemini Planet Imager 2.0 (GPI 2.0) is an in-progress upgrade to the original GPI, an instrument for directly imaging exoplanet systems, which is being moved to the Gemini North telescope atop Mauna Kea, Hawaii. Major changes involve improved coronagraph designs and upgrading the adaptive optics (AO) system with a new pyramid wavefront sensor (PWFS). The addition of these new components require revised models for evaluating the performance and understanding the limitations of the system. This in turn helps us inform the broader GPI 2.0 science goals. We use PASSATA, an end-to-end AO simulation software, to assess the performance of GPI 2.0 AO under typical atmospheric conditions on Mauna Kea. We use these simulations to help us determine operating parameters such as the limiting stellar magnitude, maximum Strehl ratio, and the contrast achieved by the joint AO-coronagraph system before speckle-suppression. The point spread function of the system is also thoroughly characterized. This information will be used to predict the science performance on a range of targets and design observing strategies.

GPI 2.0: Performance Evaluation of the Wavefront Sensor's EMCCD

Do O clarissa [1], Perera saavidra [1], Maire jerome [1], Nguyen jayke [1], Levinstein daniel [1], Konopacky quinn [1], Chilcote jeffrey [2], Fitzsimmons joeleff [3], Hamper randall [2], Kerley dan [3], Macintosh bruce [4], Marois christian [3], Rantakyro fredrik [5], Savransky dmitry [6], Veran jean-Pierre [3], Agapito guido [7], Ammons s. Mark [8], Bonaglia marco [7], Boucher marc-Andre [9], Dunn jennifer [3], Esposito simone [7], Filion guillaume [9], Lardière olivier [3], Li duan [6], Madurowicz alex [10], Peng dillon [2], Poyneer lisa [8], Spalding eckhart [2]

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2 - University of Notre Dame [Indiana](United States)
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5 - Gemini Observatory [Southern Operations Center](Chile)
6 - Cornell University [New York](United States)
7 - INAF - Osservatorio Astrofisico di Arcetri(Italy)
8 - Lawrence Livermore National Laboratory(United States)
9 - Opto-Mecanique de Precision(Canada)
10 - Stanford University(United States)

Abstract

Electron multiplying CCDs (EMCCDs) are detectors capable of counting single photon events at high speed and high sensitivity. In this work, we characterize the performance of the HNü 240 EMCCD from Nüvü Cameras, which was custom-built to be used in the pyramid wavefront sensor (PWFS) upgrade of the Gemini Planet Imager 2.0 (GPI 2.0). Like GPI 1.0, GPI 2.0 aims to directly image and characterize extrasolar planets, with an upgraded ultra low-noise wavefront sensor that is expected to give the adaptive optics (AO) system the capability to achieve high Strehl ratios on stars two magnitudes fainter than the current limit. The HNü 240 EMCCD's characteristics make it well suited for extreme AO: it has low dark current (< 0.01

e-/pix/fr), low readout noise (0.1 e-/pix/fr at a gain of 5000), high quantum efficiency (>90% at wavelengths from 600-800 nm; >70% from 800-900 nm), and fast readout (up to 3000 fps full frame). We tested the EMCCD's noise contributors, such as the readout noise, dark current, pixel-to-pixel variability and CCD bias. We also tested the linearity and EM gain calibration of the detector. All camera tests were conducted before and after its integration into the GPI 2.0 PWFS system. After integration, the effects of temperature on the performance of the camera were explored. To test the pyramid wavefront sensor in the laboratory, we used a custom-built test source unit to simulate the light incident from the telescope to the sensor.

GPI2.0: Implementing a Zernike wavefront sensor for Non-Common Path Aberrations measurement.

Chambouleyron vincent [1], Salama maissa , Guthery charlotte , Dillon daren , Perera saavidra , Konopacky quinn , Wallace kent , Veran jean-Pierre , Savransky dmitry , Chilcote jeffrey , Jensen-Clem rebecca , Macintosh bruce

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Abstract

Gemini Planet Imager is a high-contrast "planet hunter" instrument installed on Gemini South telescope in 2014. After 6 years of operation, it is now going through a set of upgrades before being moved to Gemini North (commissioning expected in 2024). The upgrades will include: (i) an EMCCD pyramid wavefront sensor (WFS) to push performance limits of the extreme adaptive optics system (ii) new coronagraph designs (iii) new observing modes for the Integral-Field-Spectrograph. One large limitation of this kind of instrument is the quasi-static non-common path aberrations (NCPA) between the WFS and the science paths. To measure these NCPA, we propose to implement a Zernike wavefront sensor (ZWFS) in the system: a reflective Zernike phase mask will be placed in the focal plane masks wheel of the coronagraphic setup and the wavefront detection will be performed by a pupil imaging branch (FLI/Cred-2 camera) already installed on the previous version of GPI (see Figure below). Thanks to high-sensitivity of the ZWFS, this setup will allow us to measure the NCPA in a limited amount of time before each observation run. After presenting the overall strategy for NCPA measurements, we discuss the main motivations that drove the ZWFS parameters: dimple size, phase-shift, wavelength, and bandwidth. One peculiarity of the GPI2.0 setup is that the ZWFS will routinely work with upstream coronagraphic amplitude apodizers. We will present end-to-end simulations of expected performances comparing different reconstruction techniques and results of on-going tests on the SEAL adaptive optics testbed at UCSC.

Guiding on the ELT with HARMONI's LTAO system

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from

60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. Recently the LTAO system has been upgraded to be able to use a second natural guide star to guide the telescope and stabilise the field during observations. In this contribution, we present the requirements placed on the sensor observing this second guide star and how its design was chosen to comply with them. In particular, we detail the simulations made in order to assess guiding performances in new challenging conditions, i.e. with a partially AO-corrected PSF that can be both close to or far from the axis of correction.

HARMONI SCAOS sub-system prototyping

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from R ($\equiv\lambda/\Delta\lambda$) 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics [AO] modes - SCAO (Single Conjugate AO, including a High Contrast capability) and LTAO (Laser Tomography AO) - or with no AO. The project is preparing for Final Design Reviews. The SCAO Sensors subsystem (SCAOS) is located within the NGS Sensors System (NGSS) which includes several wavefront sensors (WFS) to cover the needs of the different HARMONI observing modes and operates at +2°C. To reach the required performance, the SCAOS will use different modules and mechanisms (Dichroic module, Object Selection Module, Low-Order Module, Pupil Rotator, Atmosphere Dispersion Compensator, Beam Correction Module and Pyramid Sensor Module) among which we have identified two particularly critical devices that we have prototyped: The Pyramid Modulator Unit (PMU) and the Object Selection Mirror Unit (OSM). The two modules have been already designed, manufactured and assembled in our laboratory. Recently, we have already presented the results of different tests of the two systems, both at room temperature and cold environment, in terms of resolution, linearity, repeatability or still of working frequency, ...). However, further tests have yet to be finalised to carry out this study and to conclude on the final performances. In the present work, we will then focus on these remaining tests: OSM: although component compliance has been demonstrated, we still need to optimize the calibration algorithm for reaching the full performance. Lifetime cycling measurement and PLC functional control validation will also be performed. PMU: PLC functional control validation and Lifetime cycling also planned. The results will be presented and discussed.

HARMONI's Adaptive Optics Control System: Design and Performance Update

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1 - Department of Physics [Durham University](United Kingdom)

Abstract

HARMONI is a first light instrument for the European Extremely Large Telescope (ELT) that uses near-infrared integral field spectroscopy to capture detailed spectral information across astronomical objects. The Adaptive Optics Control System (AOCS) for HARMONI is designed to correct for atmospheric turbulence and ensure high-quality imaging. The AOCS for HARMONI is a critical component that enables the instrument to achieve its scientific goals and will be essential for future astronomical observations. We present the design and performance of the AOCS for HARMONI. We provide a detailed status report of our development efforts, with a focus on the system design and the results of our recent prototyping efforts. Specifically, we present the prototype of the HARMONI hard real-time control system (HRTC) and its design, including timing results from a full-scale HRTC in the laboratory. We have recently updated our designs with the development of Durham's next-generation AO RTC called DAO, which has been shown to meet the requirements will help HARMONI achieve its scientific goals. We also present the design and status of the soft real-time control system (SRTC) for HARMONI, including algorithm performance results that drive computation and system dimensioning. Additionally, we discuss the integrating of the AOCS with ESO's Real-Time Control Toolkit (RTCtk).

Herzberg Extensible Adaptive Real-time Toolkit (HEART) for ELT

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Abstract

The Herzberg Extensible Adaptive Real-time Toolkit (HEART) is a collection of libraries and other software components developed at NRC-HAA that can be used to control different types of Adaptive Optics (AO) systems. HEART supports all flavours of AO, including Single Conjugate AO (SCAO). Multi-Conjugate AO (MCAO), Laser Tomography AO (LTAO), Ground Layer AO (GLAO) and Multi-Object AO (MOAO). The HEART RTC design has two main components: the Hard Real-Time RTC (HRT), which include all the time-critical high-speed processing tasks; and the Soft Real-Time RTC (SRT), which include the non-time critical tasks such as optimizations, AO parameter updates and diagnostics. The HRT and the SRT are connected via a private network. The design of HEART took into consideration the rapidly advancing technology and uses commercial-off the shelf (COTS) CPUs running standard Linux distributions to using Matrix Vector Multiplication (MVM) reconstruct wavefront error coefficients from WFS measurements. Through extensive benchmarking, we have demonstrated that this approach meets the stringent latency and jitter requirements of modern AO systems. HEART is written in standard C and Python languages and can be readily customized to adapt to the specificities of any AO system, including specific Input/Output interfaces, or specific data processing flows and algorithms. In all cases however, the HRT processing is heavily parallelized and pipelined so that most of the processing is done as the pixels are streamed during the WFS camera read-out, resulting in a minimal latency between when the last pixel arrives and when the wavefront correction commands are ready to be written out. HEART was originally designed for NFIRAOS, the first light AO System for the Thirty Meter Telescope (TMT). However, thanks to its modularity, it has been adapted to several new generation Gemini AO instruments, including the Gemini North AO (GNAO – LTAO/GLAO system) facility, the Gemini Planet Imager 2.0 (GPI 2.0 – high-order SCAO system) and the Gemini InfraRed Multi-Object Spectrograph (GIRMOS - MOAO system). HEART is also slated to be used for two major instruments for the European Extremely Large Telescope (ELT): MORFEO, formerly known as MAORY (MCAO system) and ANDES, formerly known as HIRES (SCAO system). This paper will delve into the unique design of the ANDES RTC and MORFEO RTC. In particular, we will discuss the specificities of these instruments requiring software customization, as well as the new challenges of operating in the ELT environment. Using HEART for two different ELT instruments will not only ensure excellent real-time performance for each of them, but will also guarantee higher robustness and easier maintenance for both of them.

High Contrast Imaging Tools at Keck Observatory

Guthery charlotte E. [1], Delorme jacques [1], Ragland sam [1], Bottom mike [2], Walker sam [2], Vincent maria [2], Jensen-Clem rebecca [3], Salama maissa [3], Chambouleyron vincent [3], Van Kooten maaike [4], Wallace kent [5], Bond charlotte [6], Cetre sylvain [7], Wizinowich peter [1]

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2 - Institute for Astronomy(United States)
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5 - Jet Propulsion Laboratory(United States)
6 - UK Astronomy Technology Centre(United Kingdom)
7 - Department of Physics [Durham](United States)

Abstract

High contrast imaging (HCI) is limited in practice by uncorrected wavefront errors within traditional adaptive optics (AO). Keck observatory experiences roughly 130nm of residual wavefront error even with well calibrated AO. Multiple HCI tools currently in development are presented, focused on minimizing these errors and improving contrast during typical observation nights: (1) Fast and Furious is a focal plane wavefront sensing algorithm shown to correct for large portions of non-common path aberrations between the NIRC2 science instrument and the primary Keck wavefront sensor (WFS). On sky demonstrations of an operational version of this algorithm show an increase in Strehl ratio up to 17% in a single run. (2) The Keck primary mirror phasing is known to degrade between routine segment exchanges. A Zernike WFS (ZWFS) is currently installed within the Keck Planet Imager and Characterizer (KPIC) to take passive measurements of the primary mirror to maintain the phasing. The detection of segment piston wavefront errors down to 50 nm with the ZWFS demonstrates the first step of maintaining phasing in parallel with science observations. (3) Operational speckle nulling algorithms are in test to minimize bright speckles during HCI. (4) As an addition to an upgraded real time controller, predictive wavefront control will be further developed to minimize errors due to large windspeeds and servo lag. These HCI demonstrations will be presented as reliable, robust, and simple to control operational tools which will become available to greatly benefit observers.

High-Spectral Resolution Dark Holes: Concept, Results, and Promise

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Abstract

Next generation high contrast imaging instruments face a challenging trade off: they will be required to deliver data with high spectral resolution at a fast cadence and across a wide field of view. For instruments that employ focal plane wavefront sensing and therefore require super-Nyquist sampling, these requirements cannot simultaneously be met with a traditional lenslet integral field spectrograph (IFU). For the SPIDERS pathfinder instrument, we are demonstrating an imaging Fourier transform spectrograph (IFTS) that offers a different set of tradeoffs than an IFU, delivering up to R20,000 spectral resolution across a dark hole. We will

present preliminary results from our instrument including the first high-resolution chromaticity analysis of a self-coherent-camera based dark hole. This concept and our results have the possibility to shape how future high contrast imaging spectrographs and focal plane wavefront sensors are designed and deployed to upcoming extremely large telescopes.

How to exactly describe WFS non-linearities with interaction matrices

Fauvarque olivier [1], Cisse mahawa [2 3], Chambouleyron vincent [4], Neichel benoit [3], Sauvage jean-François [2 3], Fusco thierry [2 3]

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Abstract

Angular resolution of the future ELTs imaging system will depend on the performance of their Adaptive Optics systems, i.e. on the quality of the phase aberrations estimation. This estimation can essentially be decomposed into two parts. The first one is related to noise propagation and is linked to the concept of sensitivity. Such a performance criteria is a matter of optical design optimization which should ensure a high photons efficiency by the Wave Front Sensor (WFS). The second aspect is related to how the phase is estimated from WFS measurements. To do so, a mathematical operator, called reconstructor, transforms WFS signal into Deformable Mirror (DM) commands. Such an operator may be seen as the inverse function of the 'DM towards WFS' system. To get the most efficient estimation, a description of the WFS/DM as close as possible of the WFS behavior while sensing the phase is needed. Moreover this model has to be easily invertible and also to provide a reconstructor fast enough to be operated in real time. That is why in AO context, methods based on calibration matrices are especially relevant. Unfortunately, such methods prove to be less efficient when working in the non-linear regime of the WFS. As a consequence, methods have been developed to tackle these effects that may occur during sensing. If analytic reconstructors may be used, such approaches are not always easy to implement. That is why a matricial method, called Optical Gains (OG,) has been developed to compensate the phase underestimation due to non-linearities. This method does improves the performance of AO loop but is still imperfect, especially when non-linearities imply cross-talks between phase modes. To further improve the reconstruction, the next step is therefore to compute the cross-terms of the gain matrix. However, there is no way, at the present time, to compute the full gain matrix. In this paper, we introduce a numerical tool to build such a matrix that describes precisely the link between WFS signal and the input phase, whether the sensor is working on its linear regime or not. We will show how to calculate it and how to improve phase estimation. We will also present some ways to get it in practice.

Impact of DM misregistration for NCPA compensation in HARMONI's SCAO system

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450 nm to 2450 nm with resolving powers from 3500 to 18000 and spatial sampling from 60 mas to 4 mas. It can operate in two Adaptive Optics modes – SCAO (including a High Contrast capability) and LTAO – or with NOAO. The project is preparing for Final Design Reviews. Wavefront sensing for the SCAO mode is provided by the SCAOS subsystem, mainly by a Pyramid WaveFront Sensor (PyWFS). The high sensitivity of the PyWFS comes at the expense of a small dynamic range, limiting its ability to compensate for Non-Common Path Aberrations (NCPAs) through offsets of the operating point (i.e. using reference slopes). As NCPA compensation is crucial for good image quality, especially for high contrast operations, a low-order loop upstream of the PyWFS will be implemented to correct for NCPAs. This loop consists of a Shack-Hartman WFS (BlueSH) controlling a Low-Order DM (LODM). The reference slopes of the BlueSH will be modified so that the LODM absorbs large low-order NCPAs and delivers a flat wavefront to the PyWFS. A Calibration DM (CalDM) will be used to calibrate NCPAs and determine the BlueSH's reference slopes. However, constraints in the optical design requires the LODM to be rotated with respect to the CalDM, and places them several metres apart, leading to misregistations. In this paper, we present the results of Monte Carlo simulations of the CalDM-LODM system to determine how residual WaveFront Errors (WFEs) between the DMs vary with these misregistrations. We find residual WFEs to be ≤ 3% for all rotation angles and pupil shifts ≤ 0.5 a DM pitch (5% of the pupil) when controlling the first 50 Zernike modes. Small magnification errors contribute little to overall error. This result confirms the LODM can deliver a flat wavefront to the PyWFS even with large misregistrations.

Implementing the crossed-sine wavefront sensor for astronomy application with a single natural guide star

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1 - IPAG(France)
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Abstract

Le capteur de front d'onde sinusoïdale croisé (WFS) est basé sur un filtre de transmission de gradient et un réseau de mini-lentilles 2 x 2, permettant une imagerie achromatique simultanée à une résolution spatiale élevée et une précision de mesure comparable à celles des interféromètres laser [1-2]. Le système d'imagerie est très compact et peut servir à une large gamme d'applications à haut débit en astronomie, biomédecine et métrologie. Les performances du système ont été démontrées récemment dans le laboratoire d'optique [3]. Cependant, le principe du WFS sinusoïdale croisé est basé sur l'acquisition simultanée de quatre sources lumineuses hors axe, ce qui peut être une limitation lorsqu'il s'agit de systèmes d'optique adaptative (AO) pour l'astronomie. Cette communication présente une conception alternative permettant au système de fonctionner avec une seule étoile guide naturelle sur l'axe. La nouvelle conception est décrite et les simulations numériques confirment que la performance obtenue est similaire à celle de la conception originale.

Implementing the LIFT algorithm on Keck I adaptive optic system

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Abstract

Current applications of adaptive optic systems for astronomy are heavily dependent on wavefront measurements gathered by observing Laser Guide Stars (LGSs). These artificial, relatively bright stars provide high signal-to-noise high-order wavefront information where no appropriate Natural Guide Star (NGS) exists in the vicinity of the science target. However, the significant caveat of LGS wavefront measurements is the lack of low-order information such as tilt, tip, and focus, particularly due to the sodium layer altitude fluctuation. To resolve this issue, simultaneous observation of at least one natural guide star (NGS) remains essential. Traditionally, a Low-order Shack-Hartman sensor is dedicated to this task, typically working in the visible spectrum. A major upgrade to this architecture, both in terms of sensitivity optimization and sky coverage, is the use of a focal plane wavefront sensor in infrared bands. LIFT is a noise-effective, low-order focal-plane sensor algorithm that is designed for this application. We used the Keck I adaptive optics facility to study the feasibility and efficiency of replacing the low-order Shack Hartman sensor with LIFT and the TRICK IR focal plane detector. The result of this study is a milestone in the Keck All-Sky Precision Adaptive Optic system (KAPA) project as well as paving the way for improving the design of future adaptive optic systems in terms of sky coverage, efficiency, and reducing overall physical bench size.

Improved Diagnostic Systems for the Laser Beam Transfer Optics at Gemini South Observatory

Oyarzún valentina [1 2 3]

1 - Cristian Moreno(Chile)
2 - Ryan Ketterer(Chile)
3 - Vincent Garrel(Chile)

Abstract

GeMS, the Gemini South telescope MCAO facility located on Cerro Pachon Chile, uses five Laser Guide Star (LGS) beams to correct the atmospheric turbulent wavefront. The Beam Transfer Optics (BTO) system relays the output of a Toptica SodiumStar 22 W laser along the telescope truss to a center launch telescope behind the secondary mirror. The system was designed to split the laser into five beams, equal in power and polarization state, before propagating them on-sky in an X-shaped constellation. The BTO system's strategies for polarization control, however, have not produced the intended results for the Toptica SodiumStar laser (in use since 2017). Measurements taken with the telescope at zenith and horizon show a power imbalance and varied polarization states among the five beams after the splitting optics of the BTO. The paper presents a

characterization of the BTO system, including the state of polarization and power distribution, obtained from improved and newly developed diagnostic systems that allow for measurements at different telescope elevations. It discusses system upgrades that optimize the polarization state and power output of the five beams, aiming to improve the photon flux return at the wavefront sensors of the AO system.

Including the pyramid WFS non-linearities into a fast PSD error breakdown tool

Fetick romain [1 2], Chambouleyron vincent [3], Heritier cedric Taissir [1 2]

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Abstract

Adaptive optics (AO) for astronomy requires to lock on fainter and fainter sources, and thus to increase the sensitivity of wavefront sensors. The pyramid sensor, and more generally the Fourier Filtering wavefront sensors (FFWFS), become the baseline for current or future AO systems since they achieve higher sensitivity than the legacy Shack-Hartmann one. The drawback of the sensitive FFWFS is to be highly non-linear, since the response drops dramatically as the incoming wavefront error increases. Designing from scratch a new AO system, foreseeing its performances and then comparing its on-sky performances with the expected ones requires analytical expressions (if available) and simulations. The end-to-end simulation tools are particularly suited to describe the full response of the AO system, including its non-linearities. Even though the end-to-end simulations are highly representative of the real response of the system, they are subject to drawbacks: - Long exposure PSF requires high computation time and CPU/GPU resources - Temporal sampling must be managed with care, since a poor interpolation of the random phase between pixels may induce high frequencies artifacts - AO effects are combined all together, making it difficult to disentangle for targeting one specific effect. Multiple simulations are then necessary to identify tendencies and response to different observing conditions. We thus propose a simulation of the pyramid based on the phase power-spectral-density (PSD), often called "Fourier plane" simulations. These simulations do not suffer the issues mentioned above, and have been used in tools such as TIPTOP. The novelty of our method is to take into account the non-linearities through the optical gains of the pyramid by a recursive computation of the PSF: 1- Compute the conventional error terms (fitting, aliasing, temporal, noise) 2- Compute the PSF and then the optical gains using the convolutive model 3- Include these optical gains in the error transfer function, and iterate to step 1 We show good agreement between our method and end-to-end simulations for estimating long-exposure PSF, with typical computation time of few minutes for large systems.

Increased sky coverage for the 23-meter LBT

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1 - USN NRL(United States)
2 - Steward Observatory(United States)
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Abstract

Twin adaptive secondaries at the Large Binocular Telescope enable powerful observing modes. Two of these, imaging (Fizeau) interferometry and nulling interferometry, make the LBT in many respects the first ELT (see Ertel, et al, at this same meeting). Science programs that have been conducted using LBT as a 23-meter telescope include measuring habitable-zone dust around nearby stars and imaging planets during early stages of formation. To allow LBT to function as a 23-meter telescope, the light from its two 8.4-meter segments must be combined coherently. To this end, the Large Binocular Telescope Interferometer (LBTI) co-phases the two incoming beams via a piezo-electric pathlength corrector. This device is controlled by a fringe-tracking system that measures optical path difference in real time. In this talk we describe an upgrade to this system: the Fizeau Fringe Tracking Camera (FFTCam). FFTCam will improve the limiting magnitude of LBT 23-meter science from magnitude 5 at K, to magnitude 11 at K; an improvement of 6 stellar magnitudes! In addition to presenting the technical details of the project (which include upgrading the existing Rockwell PICNIC detector to a Saphira electron avalanche array), we will provide examples of the new science that will be enabled, for example, increasing the number of stars in the Taurus star-forming region that can be imaged (with 2–5 AU resolution) by nearly two orders of magnitude.

Initial results from the new Robo-AO 2.0 adaptive optics system

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3 - Department of Physics and Astronomy [Chapel Hill](United States)

Abstract

The Robo-AO 2.0 automated AO system is in the early stages of deployment on the University of Hawaii 2.2m telescope on Maunakea. It is the new, improved version of Robo-AO, which was able to observe some of the largest high resolution surveys to date. The new instrument includes many improvements in the optical system to increase throughput and AO system performance, a new wavefront reconstructor software system based on an expandable threaded architecture, and a natural guidestar channel that will allow tests of hybrid AO operations. Robo-AO 2.0 will also operate robotically, with an eye towards rapid follow up of interesting time domain targets as well as large surveys of targets of interest from instruments such as TESS. This presentation will discuss the new instrument, improved AO control software, and early on sky performance and science results.

Integrated turbulence parameters estimation from NAOMI adaptive optics telemetry data

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4 - European Southern Observatory(Germany)

Abstract

Context: Estimating turbulence parameters is important to e.g. site characterisation, adaptive optics (AO) performance optimisation and fringe tracking. The large number of AO systems now deployed on modern observatories makes them potential candidates to provide turbulence information complementary to dedicated seeing monitors. Aims: We seek to estimate the atmospheric seeing from NAOMI wavefront sensor telemetry data installed on the four Auxiliary Telescopes of the VLT Interferometer. Since the system is replicated on all four telescopes, we achieve four times higher spatial resolution with simultaneous observations than an individual telescope analysis. Methods: We perform a $\chi 2$ (chi-squared) modal fitting to the von Kármán turbulence model, namely variances expressed on a Zernike basis. The algorithm is modified, curated and optimised to operate correctly in a low spatial resolution scenario (4x4 Shack-Hartmann wavefront sensor). It estimates and compensates for measurement and remaining error using analytical expressions. Since the latter depends on the estimated turbulence parameters, we chose an iterative approach to jointly estimate the turbulence parameters and correct the remaining error. We also propose a Monte Carlo method to calculate the uncertainty, providing confidence levels to our estimates. Results: We optimise, curate and validate the algorithm in simulation using typical atmospheric conditions for the Paranal Observatory. We achieved sub-per-cent accuracy in estimating the Fried parameter for a temporal horizon of (37±5) seconds. On the other hand, without the correction of measurement noise and remaining error, the accuracy in the estimation of the Fried parameter was 17%. Using non-overlapping samples for a 2% accuracy in the estimation of the seeing, we achieved a maximum time resolution of 20 seconds. Application to on-sky data (N=8170 samples) shows that the mean seeing between 2018 and 2020 at the Paranal Observatory was 0.69 arc seconds. The median uncertainty for an individual estimation of the seeing was 1.2%. We show that our estimates have a 0.70 Pearson correlation coefficient with DIMM estimates while estimating a 5% smaller seeing on average. By comparing simultaneous telemetry samples, we found that the spatial distribution of the ATs accounts for 1.6% of the median seeing. Considering the median estimation uncertainty, we find no statistically significant variation of the seeing across the Observatory.

Integration and first tests of the Natural Guide Star Wavefront Sensor Prototype for GMT

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1 - INAF - Osservatorio Astrofisico di Arcetri(Italy)
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Abstract

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). The NGAO features a single conjugate natural guide star to measure wavefront while using the seven deformable secondaries and a post focal wavefront sensor called the Natural Guide Star Wavefront Sensor NGWS. The NGWS sensor 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 dedicated to the correct phasing of the seven segments of the GMT telescope. The Arcetri AO group, in collaboration with the GMTO and the University of Arizona, is in charge of providing the design, fabrication and test of the pyramid wavefront sensor channel of the NGWS prototype that will replicate all aspects of optical sensitivity including optical design, camera selection and data reduction. The NGWS prototype passed its Design Review in May 2022 and is now being integrated in preparation for shipment to the University of Arizona where it will be integrated (pyramid and phasing channel) and validation-tested in the High Contrast Adaptive Optics Testbed (HCAT) in late summer

2023. The test bench at the Arcetri Observatory features a deformable mirror and thus offers the possibility to close an AO loop and measure the sensitivity of the pyramid sensor. This paper reports on the integration and alignment of the main channel of the prototype as well as the preliminary tests performed at Arcetri.

Inverse problem approach for SPHERE+ adaptive optics control

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10 - Observatoire de la Côte d'Azur(France)

Abstract

The SPHERE+ project consists of an upgrade of the high-contrast SPHERE instrument at the VLT and in particular of an upgrade of its extreme Adaptive Optics (AO) system SAXO as SAXO+. The main goals of SAXO+ compared to SAXO are to improve the contrast at low angular separation and to push further the limiting magnitude to work on fainter near-infrared targets. SAXO currently uses a Shack-hartmann wavefront sensor, a 41x 41 deformable mirror (DM) and a tip-tilt mirror. SAXO+ will add a second stage equipped with a pyramid wavefront sensor and a second DM. In that respect, SAXO+ will also allow to demonstrate and compare advanced control methods in the perspective of the future PCS on the ELT. We present here the control method studied at CRAL for SAXO+. The originality of this control relies on its inverse problem approach. It is an evolution of the AO control developed and installed by the CRAL on the THEMIS solar telescope, running at 1kHz in the visible, itself derived from the FrIM (Fractal Iterative Method) reconstructor and the FrIM-3D tomographic algorithms developed for the ELT. We describe how our inverse problem approach can provide improved wavefront reconstruction even at low flux, and the effect it has on contrast performance. For SAXO+, we also introduce a novel regularized approach to distribute the commands on the high-order DMs and on the tip-tilt mirror. We present the performance of the controller evaluated on SAXO end-to-end simulations using COMPASS. Comparison is made with performance of the existing SAXO system as a reference, using the same end-to-end COMPASS simulation framework.

Investigating ways to use a Non-modulated Pyramid Wavefront sensor with a Rayleigh Laser Guide Star

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Abstract

Astronomical adaptive optics (AO) is a critical approach to enable science requiring ground-based diffraction-limited imaging. Artificial laser guide stars (LGSs) for AO have thus far only been used with a Shack Hartman Wavefront Sensor (SHWFS), but not yet with a Pyramid Wavefront Sensor (PyWFS). One of the technical challenges with PyWFS that a SHWFS does not face is using a pupil plane tip/tilt modulator to steer the PSF around the tip of the focal plane pyramidal phase mask per PyWFS frame, typically at a modulation radius of a few resolution elements. Such modulation is, however, generally necessary to provide sufficient dynamic range to close the AO loop on atmospheric turbulence. However, in this work we explore options to remove the need for a LGS PyWFS tip/tilt modulator, instead leveraging the inherent incoherent atmospheric scattering process between at uplink and downlink for LGS light. We show simulations that a custom static pupil plane phase mask for a LGS uplink can enable reaching close to the classical tip/tilt modulated PyWFS dynamic range, with more phase mask design parameter space to be explored for further dynamic range optimization. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This document number is LLNL-ABS- 849572.

Keck Planet Imager and Characterizer: status updates

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Abstract

The Keck Planet Imager and Characterizer (KPIC), deployed at Keck observatory since the end of 2018, connects the Keck-II adaptive optics system and the high-resolution spectrograph NIRSPEC through single-mode optical fibers to provide high-contrast, high resolution (R ~ 35000) K-band spectra of directly imaged exoplanets. Initially built as a pathfinder for future instruments such as HISPEC and MODHIS, KPIC successfully demonstrated its ability to detect and measure critical physical properties of directly imaged exoplanets. After a few years of exploitation and more than twenty substellar companions observed, KPIC was upgraded at the beginning of 2022 to improve its overall performance, simplify its operation, and test new modules and techniques. In addition to being 60% more sensitive, the second version of KPIC is easier to calibrate and operate during the night. It will also see its standard observing mode facilitized by the end of 2023. The other modules deployed during the KPIC upgrade such as the vortex fiber nuller (VFN), the Zernike wavefront sensor (ZWFS), the high order deformable mirror (HODM) and the Phase Induced Amplitude Apodization (PIAA) will be progressively tested and used to improve KPIC performances. We will present the current version of KPIC, discuss its performance and the mode expected to be offered to the community. We will also describe some of the ongoing developments and plans for the coming years.

Keck's Current and Future Roles as an ELT AO Pathfinder

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Abstract

The segmented nature of the 10-m Keck telescopes combined with facility-class AO systems and science instruments, and a history of science-driven upgrades to these systems, offers a uniquely powerful pathfinder for future AO science facilities on the segmented ELTs. Keck's pathfinder strength is not just demonstrating new techniques or technologies but developing them into operational science capabilities. For example, since first Keck AO science in 1999, Keck has successfully implemented three generations of sodium-wavelength lasers and is currently implementing its third generation of real-time controller (this time GPU-based). Current pathfinder-related developments include laser tomography, near-infrared low order wavefront sensing and PSF-reconstruction for high Strehl ratios and high sky coverage on the Keck I AO system. Current AO-based primary mirror phasing techniques under development include the use of Zernike, pyramid and phase diversity techniques. High-contrast AO developments include near-infrared pyramid wavefront sensing, on-sky phase diversity, speckle nulling and predictive wavefront control. New instrument capabilities include the Keck Planet Imager and Characterizer (KPIC). Another pathfinder development is the NASA Goddard-led ORCAS satellite to provide a bright artificial point source for AO-correction. A fast, visible science camera has been implemented in support of ORCAS, demonstrating 15 mas FWHM, and in a further move toward the visible ALPAO is developing a 2.5 mm spacing, 60x60 actuator deformable mirror for Keck. In addition, three new AO science instruments are planned: Liger as a prototype of TMT's IRIS, HISPEC which is the same as TMT's MODHIS (based on KPIC's science success), and SCALES. Finally, Keck's 2035 Strategic Vision includes visible, extreme and ground layer AO facilities all of which could support ELT AO pathfinding. We will discuss the current and future Keck AO developments and their potential roles in ELT AO pathfinding.

Lab demonstration of wavefront reconstruction for the fragmented aperture of the ELT

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Abstract

The fragmentation of the ELT pupil in six petals by the spider which supports its secondary mirror comes with a new challenge in the implementation of the instruments AO systems. With tens of centimeters thickness, i.e. several times the turbulence coherence length, the spider arms break the continuity of the incoming wavefront. In visible light, the pyramid wavefront sensor (WFS) was shown to be a poor candidate to reconstruct these differential pistons but their values can be inferred from Kolmogorov 's theory based algorithms. The SESAME testbed at LESIA enables to reproduce the relevant characteristics of the ELT (pupil fragmentation, high order DM, pyramid WFS prototype) and to carry experiments to validate these reconstruction methods. We demonstrate, in-the-lab, that the proposed algorithmic solutions effectively reduce the differential pistons errors and enable to recover the imaging capability of the ELT, provided that the wavefront to be reconstructed is continuous.

Laboratory Acceptance and Telescope Integration of the Gran Telescopio Canarias Adaptive Optics System

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Abstract

The Adaptive Optics (AO) system of the 10-m class Gran Telescopio Canarias (GTC) has completed the acceptance tests in the laboratory of the Instituto de Astrofísica de Canarias (IAC), and has verified the procedures for the integration in GTC at Roque de Los Muchachos Observatory (ORM), together with critical optics maintenance previous to the shipment. The GTCAO system is based on a single deformable mirror (DM) with 373 actuators, conjugated to the telescope pupil, and a Shack-Hartmann wavefront sensor (WFS) with 312 subapertures, using an OCAM2 camera. The performance required is 65% Strehl Ratio in K-band under average atmospheric conditions and bright NGS. The instrument will be shipped to the ORM in June, to be installed on the Nasmyth platform B of GTC, to be aligned with the telescope, to be integrated with the telescope control system and to start the technical commissioning. When in operation, the AO system will work as a focal station of the telescope, in charge of providing the commands to M2 for fast guiding and tip tilt correction, and offloading global low order modes to M1 and its segments using the WFS telemetry. Testing these functionalities is part of the initial technical commissioning on telescope. In this paper we focus in the final results of the laboratory acceptance, the integration in telescope and the commissioning plans to get the system ready for science.

LAser guide Star Sensor Integrated Extreme adaptive optics (LASSIE)

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Abstract

Extreme adaptive optics (ExAO) systems are optimized for high-contrast imaging and coronagraphy. ExAO systems are currently limited to wavefront sensing using a bright natural guide star (NGS) due to the performance requirements for high precision wavefront control. Laser guide stars (LGS) are artificial beacons widely used to increase sky-coverage of conventional AO systems, but have not yet been applied to ExAO systems due to the limitations inherent to a laser beacon such as extent, elongation, and focal anisoplanatic error. Recent advances in LGS technology such as AO correction of the laser uplink produce bright beacons that offer higher wavefront sensitivity than uncompensated beacons. Pairing this LGS technology with ExAO could enable better high-contrast imaging of dim targets. The LAser guide Star Sensor Integrated Extreme adaptive optics (LASSIE) project at the Starfire Optical Range will explore the trade space in beacon size, brightness, coherence, and wavefront sensor design to preform path-finding research on the potential performance of an uplink corrected LGS-ExAO system. We investigate a new type of hybrid wavefront

sensor that combines a Shack-Hartmann with a pyramid wavefront sensor to maximize the sensitivity of the wavefront measurement from a partially coherent extended beacon. The project will also explore incorporating a low-order NGS wavefront sensor to mitigate residual errors from spatial frequencies not well sensed by the LGS wavefront measurement. LASSIE is a newly funded project and we will present an overview of the project and our current progress. Approved for public release; distribution is unlimited. Public Affairs release approval #AFRL-2022-4238

Linearizing the unmodulated pyramid wavefront sensor

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Abstract

The Pyramid Wavefront Sensor (PyWFS) has gained considerable attention in the field of adaptive optics due to its high sensitivity and low wavefront noise. However, the PyWFS exhibits some non-linearities. To address this issue and increase the linearity range of the PyWFS, a modulation is typically applied, but this comes at the cost of decreased sensor sensitivity. In context of the VLT/RISTRETTO instrument, a high-resolution spectrograph that will be fed by an extreme adaptive system, a high sensitivity to low order wavefront aberrations will be particularly required to achieve its driving science goal of characterising the atmosphere of the rocky exoplanet Proxima b. Therefore using an unmodulated PyWFS would have significant performance gain. Hence, we are conducting a study to investigate the behaviour of the unmodulated PyWFS, with the goal to linearise the response of the sensor, with a particular focus on finding a phase basis that increases the linearity range of the sensor. The results of this study would also provide insights for the future ELT instruments, where an unmdolutated PyWFS could be used to detect small phase discontinuities across the ELT's spiders and segmented primary mirror.

Linking the high-contrast performance with AO internal data and environmental parameters. Lessons learnt from the High Contrast Data Center and perspectives for the ELT.

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Abstract

Adaptive Optics internal data include some information about environmental turbulence conditions and the actual wavefront incoming into the science detector. The High Contrast Data Center (HC-DC, previously named SPHERE Data Center) collects all SPHERE data (science detector images and time-stamped AO RTC data statistics) and provides science-ready data products to the community. This is an opportunity to address the question of the relationship between AO internal data and the final high contrast performance. A first application is the interest of a refined prediction of the final high contrast performance as a function of turbulence conditions and AO quality, in order to better prepare the scientific programs, to improve a

high-contrast ETC and to optimize observation scheduling. A second application is the use of AO data statistics in order to support and to guide the a posteriori data processing, in particular in the context of large data libraries, as used for reference star differential imaging. A third question is the potential use of extensive AO data telemetry in order to enhance a detailed characterization of the speckle field. This latter goal would also impact the AO archival approach and would raise some additional questions about the optimal data compression. After the current work on the SPHERE data, the center intends to include in the future additional high-contrast data, and in particular from ELT high-contrast (spectro-)imaging modes.

Long-term performance monitoring of the Adaptive Optics Facility

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Abstract

The Adaptive Optics Facility (AOF) started regular operations at the Very Large Telescope (VLT/ESO) in 2016 on the Unit Telescope 4 (UT4). We have now gathered several years of AO telemetry data for the following modules: GALACSI, GRAAL, the 4LGSF and the DSM. I will present here the tool and strategy implemented for monitoring these modules, their performance over several years, and how this regular monitoring is helping with operations and maintenance activities.

LTAO Mode of HARMONI : Status and update

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Abstract

Among the four ESO-ELT first light instruments, HARMONI will provide a large range of spectroscopic capabilities thanks to its integral field spectrograph optimized for near-infrared observations. It will offer a spatial sampling covering from R = 3000 to R = 17000 and a spatial sampling from 60 mas down to 4 mas. To reach the diffraction limit of the telescope, the instrument will be equipped with Adaptive Optics (AO) systems to compensate for the atmospheric turbulence. The design of the instrument includes two AO modes that are complementary. The first one consists of a Single Conjugate AO system to provide a very high correction with a low sky coverage and the second one consists of a Laser Tomography AO system to provide a very high sky coverage with slightly lower AO performance. This paper focuses on the LTAO mode only to present the consolidated design of the LTAO mode in preparation of the Final Design Review, scheduled for 2024. A general description of the AO concepts selected will be presented with its two channels for the Laser Guide Star path and Natural Guide Star path as well as for the truth sensor capabilities. In addition, a particular attention will be given to several key-points that have emerged since the Prelminary Design Review of 2017. The paper will provide (i) a description of the reconstruction strategy using the concept of super resolution with its associated performance, (ii) a sensitivity analysis of the global performance using end-to-end simulations, (iii) the calibration and control strategy and (iv) the Assembly Integration and Test preparation plan.

Machine learning driven adaptive optics photometry and astrometry

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Abstract

Context: Photometry and astrometry of stellar clusters is a key methodology in contemporary astronomy. Adaptive optics images exhibit a significant degree of spatial and temporal variability in the point spread function, which is challenging for classical approaches. These rely on point spread function fitting to detect and compute photometric and astrometric quantities. Machine learning techniques are extremely popular due to their precision, reliability, and computational cost, and outperform their counterparts, especially on datasets with significant noise and variance. This is the particular context of adaptive optics. Aims: Our goal is to develop an automatic point source detector that provides reliable and complete photometry and astrometry of stellar cluster fields. Methods: We will use simulated adaptive optics images of clusters with the ground truth to train the network and to quantify: a) the source detection efficiency; b) the accuracy of the photometry and astrometry of machine learning driven algorithms compared to classical DAOPHOT-like approaches. We will then apply the algorithm to real data. Results: We show that the algorithm has a significantly higher source detection efficiency than classical approaches. It also shows better performance in photometry. We discuss the details required for accurate astrometry."

Machine learning for a non modulated pyramid wavefront sensor

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Abstract

Most of the future single conjugate adaptive optics systems for the extremely large telescopes will use pyramid wavefront sensors and will face the challenge of measuring and controlling the turbulence and the differential piston. We know that this kind of sensor has a non linear response that cannot be fully exploited by linear reconstruction. In particular this is valid for a non-modulate pyramid wavefront sensor that has some advantage in terms of sensibility, but it is strongly affected by non-linearities. For this reason we explore the possibility of using a reconstruction method based on neural networks. Our goal is to replace the usual linear reconstructor which is normally obtained as the pseudo-inverse of the interaction matrix, with a non-linear one which has the form of a deep neural network. The network architecture and its training strategy are tailored for our problem, while the data used for the network training and its performance evaluation were produced in end-to-end simulation. We will show the promising results obtained for the open loop

reconstruction and the preliminary analisys performed in the perspective to apply this method in closed loop operations.

MagAO-X: a pathfinder for GMT extreme-AO and the search for life with the ELTs

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Abstract

Searching the atmospheres of nearby terrestrial planets for spectroscopic signs of life is one of the key science goals of astronomy for the next few decades. High-contrast direct-imaging with ground-based telescopes may play a large role in this, however the required significant improvements in wavefront sensing (WFS) and control (WFS&C;) performance have yet to be proven on-sky. One system designed specifically to test WFS&C; advances is the Magellan Adaptive Optics eXtreme (MagAO-X) instrument. MagAO-X is a 2040 actuator, 3.6 kHz extreme adaptive optics (ExAO) instrument on the 6.5 m Magellan Clay telescope. It is optimized for visible and near-IR high contrast imaging (currently working from 500 nm (g band) to 1350 nm (J band)). MagAO-X employs a modulated pyramid WFS, which controls 1600 linearly independent modes. The instrument includes classical Lyot, Phase Apodized Pupil Lyot, and Phase Induced Amplitude Apodization (PIAA) Lyot Coronagraphs. A separate non-common path deformable mirror (DM) in the coronagraph provides dedicated low-order WFS&C; and higher-order focal plane WFS (including coronagraphic dark holes with 1e-8 achieved in the lab). Science focal planes include dual-EMCCD spectral differential imaging, the VIS-X IFU, and an MKIDS IFU (XKID). MagAO-X has now detected several planets at H-alpha (656 nm) with new candidates undergoing follow-up, is conducting small inner working angle observations of circumstellar disks in scattered light, and serves as a laboratory demonstrator for new technologies (including GMT phasing). Additionally, the GMT GCLEF spectrograph will be deployed early to Magellan, and will be fiber-coupled as an IFU to MagAO-X offering up to R~400,000 visible spectroscopy with 20 mas spatial resolution. We will present the current status of MagAO-X, review science results to-date, and describe our ongoing Phase II upgrade program. Phase II consists of major upgrades to the coronagraph and its WFS&C; system, and is focused on perfecting the ability to image nearby planets in reflected light – with an ultimate goal of directly detecting Proxima b.

MagCcado: Development of magnification control technology for the ELT / MICADO camera

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Abstract

The Multi-AO Imaging Camera for Deep Observations (MICADO) of ELT is designed to work both with single- and multi-conjugate adaptive optics systems (SCAO and MCAO, respectively). During its initial phase of operation, the instrument will primarily utilize the opto-mechanically less complex SCAO mode. As correction for atmospheric turbulence and structural vibrations is limited to a single guide star in the center, the image magnification remains variable, resulting in lower Strehl ratios for stars near the edge of the field.
In our work, strategies to measure and control the fast image magnification (also known as plate scale) variations are developed, enlarging SCAO's usable field of view. This is of particular interest in the area of extremely large telescopes, since the ELT has an aperture similar to the outer scale of atmospheric phase disturbance, giving the corrected point spread functions (PSFs) a diffraction-limited core even outside the isoplanatic angle (Clenet et al. 2014). A recent study shows that wind-driven piston movement of ELT mirror 2 (M2) is one of the worst offenders for plate scale variations (Rodeghiero et al. 2018), we hence study the impact of different wind load frequencies and piston amplitudes at M2. Our work shows that the expected ELT M2 vibrations significantly reduce off-axis Strehl ratio if not compensated for under strong winds. The derived plate scale distortions are also put in context of the magnitude of atmospheric tip-tilt jitter in SCAO operation. Sensing concepts such as accelerometer based sensing and fast readout of the science detector are suggested to measure plate scale changes which are not visible to a SCAO wave front sensor. Finally, we systematically explore to which extend the current adaptive ELT mirrors could successfully compensate for the expected plate scale effect during closed loop SCAO operation.

Manufacturing status of the ELT Laser Projection System

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Abstract

Since early 2021, independent research organization TNO and its industrial partner Demcon have been working for ESO on the development of the Laser Projection System for ESO's ELT. Identical systems will also be used for the ESO VLT Gravity+ instrument. The design is an evolution of the highly successful 4LGSF of VLT UT4. The Critical Design and Manufacturing Readiness project milestones were passed in July and September of 2022, respectively. The project is now well into the manufacturing and integration phase. Integration of the first complete Laser Projection Subunit is scheduled to be completed by September 2023, with rigorous verification testing planned for December 2023. We present an overview of the design, the main performance predictions and in particular the design for ease of maintenance of each Laser Projection Subunit. We present the manufacturing and integration status of the various subsystems, as well as an outlook for the delivery of the first several units.

Marginalized semi-blind restoration of Adaptive-Optics-corrected images using stochastic sampling

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Abstract

Adaptive optics (AO) corrected image restoration is particularly difficult, as it suffers from the lack of knowledge on the point spread function (PSF) in addition to usual difficulties. An efficient approach is to marginalize the object out of the problem and to estimate the PSF and (object and noise) hyperparameters only, before deconvolving the object using these estimates. Recent works have applied this marginal blind deconvolution method, based on the Maximum A Posterior (MAP) estimator, combined to a parametric model of the PSF, to a series of AO corrected astronomical and satellite images. However, this method does not enable one to infer global uncertainties on the estimated parameters. In this communication, we propose a new restoration method, which consists in choosing the Minimum Mean Square Error (MMSE) estimator and computing the latter as well as the associated uncertainties thanks to a Markov chain Monte Carlo (MCMC) algorithm. We validate our method by means of realistic simulations, in two different contexts: an astronomical observation on VLT/SPHERE and a ground-based LEO satellite observation on ONERA's ODISSEE AO system at the 1.52 m telescope of the Observatoire de la Côte d'Azur. We discuss the uncertainties on the estimated parameters as well as on the sought quantities such as the OTF. Additionally, we study and interpret the correlations between the parameters. Finally, we present results on experimental images for both applications. Additionally, taking into account constraints on the object (such as support constraint) should help distinguishing what comes from the object or the PSF, therefore improve the PSF estimation and image restoration, but is more difficult in the marginalized MAP case and calls for complex computations. We discuss the impact of adding a support constraint on the object in a preliminary study.

Matrix-based vs. matrix-free real-time reconstruction with FEWHA for a MORFEO like setting

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Abstract

The Multiconjugate adaptive Optics Relay For ELT Observations (MORFEO) is one of the key Adaptive Optics systems on the ELT. It aims to achieve a good wavefront correction over a large field of view, hence, involves a tomographic estimation of the 3D wavefront disturbance. The reconstruction of the turbulent layers in the atmosphere has to be done in real-time and is ill-posed, which makes it a challenging task for reconstruction algorithms. We focus on the Finite Element Wavelet Hybrid Algorithm (FEWHA), which uses a wavelet basis to represent the turbulence layers in the atmosphere. Originally this algorithm is formulated in a matrix-free and iterative way, however, FEWHA can be represented as a matrix-vector-multiplication (MVM) as well. The iterative approach has several advantages, e.g., no precomputation of the inverse and on the fly parameter updates, but also some drawbacks. Here we study the performance of the matrix-based vs. the matrix-free FEWHA for a MORFEO like test setting using ESO's end-to-end simulation tool OCTOPUS. We will deal with questions like: Does the iterative approach affect the reconstruction quality in comparison to a direct solver? What is the computational performance of the matrix-free FEWHA on a CPU vs. the matrix-based FEWHA on a GPU? How much does pipelining influence the overall run-time?

MAVIS Project Update

Rigaut francois [1], Mcdermid richard , Cresci giovanni , Brodrick david , Viotto valentina , Neichel benoit , Mendel trevor , Gausachs gaston , Pinna enrico , Ellis simon , Agapito guido , Bergomi maria , Cranney jesse , Gratadour damien , Greggio davide , Gullieuszik marco , Pierre haguenauer , Haynes dionne , Plantet cedric , Salasnich bernardo , Sordo rosanna , Stroebele stefan , Zhang hao , Seemann ulf , Kuntschner harald , Madec pierre-Yves , Horton antony

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Abstract

MAVIS is a MCAO system for MCAO compensation in the visible for the VLT. It will feed a 30x30" imager and an IFU. MAVIS just passed its Preliminary Design Review. We present a project update, including a science update, progress in system design, RTC and control, simulation results, updated performance including the exposure time calculator and image generator.

MAVIS: Astrometric and NCPA Calibration Strategies and Prototyping

Cranney jesse [1], Chung jim [1], Liu xiaotian [1], Rigaut francois [1], Haynes dionne [1], Mcginness grace [1], Gausachs gaston [1], Vaughn israel [1], Brodrick david [1]

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Abstract

The adaptive optics module of MAVIS will feed an imager and spectrograph with an MCAO corrected wavefront, producing near-diffraction-limited science in the visible spectrum over a wide field of view. To capitalise on this, non-common path aberrations between the wavefront sensors and science instruments must be measured and corrected over the field. Additionally, there will always be a small amount of undesirable distortions over the field of view, which must be characterised to deliver the required astrometric performance. Both the NCPA and astrometric calibration methods depend on novel techniques, which we have simulated in software and are prototyping on the bench to verify these calibration strategies. We will introduce these techniques, and report on the status of these prototypes.

MAVIS: predictive Learn and Apply as a supervisory solution

Zhang hao [1], Cranney jesse , Gratadour damien , Doucet nicolas , Rigaut francois

1 - Australian National University(Australia)

Abstract

Learn and Apply is a 2-step reconstruction scheme for Adaptive Optics (AO) instruments, and has recently been extended to include a predictive step, i.e., predictive Learn and Apply (pL&A;). It estimates the pseudo-real-time atmospheric turbulence profile directly from the AO telemetry buffer (the so-called Learn step), and then performs tomographic reconstruction based on the outputs (the so-called Apply step). We implement the entire pL&A; pipeline in end-to-end simulations, where both the Learn and the Apply steps are performed in turns. We present the results of these simulations, as well as the challenges that were encountered and overcome -- in particular, the challenges which have had an impact on the design of the MAVIS AO module.

MCAO testbed for European Solar Telescope (EST): first laboratory results for SCAO and GLAO configurations.

Feijóo noelia [1], Rodríguez nicolás [1], Montoya luzma [1], González-Cava josé M [2], Martin Hernando yolanda [1], Chulani haresh [1], Nunez Cagigal miguel [1], González francisco [1], Quintero Nehrkorn jorge [1], Hernández-Delgado Ángela [1]

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Abstract

A Multi-Conjugate Adaptive Optics (MCAO) testbed has been developed at the Instituto de Astrofísica de Canarias (IAC) as a prototype of the AO for European Solar Telescope (EST). EST is a 4.2-m telescope that will provide high resolution in a 60" circular Field of View (FoV). For this purpose, EST will be equipped with an MCAO system that will be integrated into the telescope's optical path. The aim of the testbed is to analyse different sensing and wavefront correction strategies in order to check their suitability for EST. The testbed is a downscaled version of the telescope that has been designed to replicate its main features, including the telescope aperture, the FoV and the atmospheric conditions representatives of the telescope site. It allows to set up of Single Conjugate Adaptive Optics (SCAO), Ground Layer Adaptive Optics (GLAO) and MCAO configurations, both for point-like and extended sources. For this purpose, three Shack-Hartmann Wavefront Sensors (WFSs) have been developed and installed in the testbed. A High-Order Wavefront Sensor (HO-WFS) with 33x33 sub-apertures senses on-axis 10" FoV. Additionally, a Multi-Directional WFS (MD-WFS) estimate the turbulence over the entire atmospheric volume. It allows up to two possible configurations: one high-order spatial resolution (HO-MD-WFS); and another low-order spatial resolution (LO-MD-WFS). A pupil-conjugated Deformable Mirror (DM) with 820 actuators is currently available for SCAO and GLAO configurations. The introduction of two DMs conjugated to different altitudes will allow the correction of the wide field with high resolution in the presence of upper atmospheric layers. The main aim of this contribution is to present the results obtained for SCAO and GLAO configurations in the EST testbed under different turbulence conditions. A Centre of Gravity (CoG) algorithm was used to compute the sensor slopes when a point-like source was analysed. Different correlation algorithms were also evaluated when extended sources were studied. An image of solar granulation was used to that end.

Measurement of isoplanatic patch size using H-alpha images of the Sun

Subramanian saraswathi Kalyani [1], Rengaswamy sridharan [1]

1 - Indian Institute of Astrophysics(India)

Abstract

The isoplanatic patch is the region within which the PSF of the system is constant. We propose a new method to determine this size using long exposure H- images of the Sun. Due to its extended nature, the different regions of the Sun can be considered analogous to a distribution of point sources convolved with the object. So, the turbulence undergone by them would be different. The Parametric Search Method (PSM, Rengaswamy, Ravindra, and Prabhu (Solar Phys. 294, 5, 2019)) is used to find the Fried's parameter (r) from long exposure H- images. In PSM, the angular size used for deconvolution is limited to ensure that the field-of-view is lesser than the isoplanatic patch size. By varying the angular size starting from a minimum value of about 10 arc-seconds, r can be measured as a function of angle. The isoplanatic patch is defined as the point at which the plot (r versus angle statistically averaged over few regions of the same image) reaches a plateau (see figure). It should be emphasised that this isoplanatic patch size is determined from long exposure day-time images.

Measurement of the turbulence profile at 40-km by the HiCIBaS II balloon mission

Brousseau denis [1], Légaré ophélie [1], Watanabe-Brouillette koichi [1], Truchon philippe [1], Tremblay-Antoine Émile [1], Poulin-Girard anne-Sophie [1], Thibault simon [1]

1 - Laval University(Canada)

Abstract

With the arrival of the next generation of extremely large telescopes, increasingly complex and demanding adaptive optics systems are needed. This is to compensate for image distortion caused by atmospheric turbulence and fully take benefit of mirrors having diameters of 30 to 40 m. This requires a more precise characterization of atmospheric turbulence. Also, as few data exist for turbulence contribution of the stratospheric phase structure function and, since it has been shown that stratospheric turbulence does not significantly degrades short-exposure images of stars but does degrade long-exposure ones, gathering statistics about the stratosphere dynamics is certainly valuable. Building on gained experience and knowledge of the HiCIBaS (High-Contrast Imaging Balloon System) mission, a balloon borne telescope to demonstrate the usability of high contrast imaging equipment on board of a stratospheric balloon flight, HiCIBaS II proposes, as one of its several scientific goals, to use a wavefront sensor at 36-40 km to measure and gather data of the atmospheric dynamics of the atmosphere et those altitudes. The acquired data can help to validate existing models for the power spectrum of the refractive-index fluctuations in the stratosphere.

MEMS Deformable Mirrors for High Contrast Imaging

Bierden paul [1]

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Abstract

Deformable mirrors are critical components in high-contrast imaging systems for ground based and space based telescopes. Boston Micromachines Corporation's deformable mirrors use a unique microelectromechanical systems (MEMS) technology, which allows for the high spatial resolution and precise control over the shape of the mirror surface needed for this application. In recent years, BMC has made significant advances in their deformable mirror technology, including improved surface finish, higher speed, and increased actuator count. These improvements will enable new applications in high-contrast imaging. BMC deformable mirrors have already been used in a variety of telescopes around the world where groundbreaking discoveries in astronomy have been achieved, including the direct imaging of exoplanets and the characterization of their atmospheres. This talk will provide updates on the latest developments in BMC's deformable mirror technology and highlight the latest applications in high-contrast imaging. The talk will also discuss ongoing efforts to improve the performance of deformable mirrors for future telescopes.

METIS SCAO - implementing AO for ELT

Bertram thomas [1], Bizenberger peter [1], Van Boekel roy [1], Brandner wolfgang [1], Briegel florian [1], Cárdenas Vázquez maría Concepción [1], Coppejans hugo [1], Feldt markus [1], Henning thomas [1], Huber armin [1], Kulas martin [1], Laun werner [1], Mohr lars [1], Naranjo vianak [1], Rohloff ralf-Rainer [1], Scheithauer silvia [1], Steuer horst [1], Correia carlos M. [2], Neureuther philip [3], Absil olivier , Orban De Xivry gilles , Brandl bernhard [4], Obereder andreas , Glauser adrian M.

1 - Max Planck Institute for Astronomy(Germany)
2 - SpaceODT(Portugal)
3 - Institute for System Dynamics
Univerity of Stuttgart(Germany)
4 - Sterrewacht Leiden
Leiden University(Netherlands)

Abstract

METIS, the Mid-infrared ELT Imager and Spectrograph is among the first-generation instruments for ESO's 39m Extremely Large Telescope (ELT). It will provide diffraction-limited spectroscopy and imaging, including coronagraphic capabilities, in the thermal/mid-infrared wavelength domain (3 µm – 13.3 µm). Its Single Conjugate Adaptive Optics (SCAO) system will be used for all observing modes, with High Contrast Imaging imposing the most demanding requirements on its performance. The final design review of METIS took place in fall of 2022; the development of the instrument, including its SCAO system, has since entered the Manufacturing, Assembly, Integration and Testing (MAIT) phase. Numerous challenging aspects of an ELT AO system are addressed in the mature designs for the SCAO Control System and the SCAO Hardware Module: the complex interaction with the telescope entities that participate in the AO control, wavefront reconstruction with a fragmented and moving pupil, secondary control tasks to deal with differential image motion, non-common path aberrations and mis-registration. A K-band pyramid wavefront sensor and a GPU based real-time computer, tailored to needs of METIS at the ELT, are core components. The implementation of the METIS SCAO system includes thorough testing at several levels before the installation at the telescope. These tests require elaborate setups to mimic the conditions at the telescope. This presentation provides an overview of the design of METIS SCAO as it will be implemented, the main results of the extensive analyses performed to support the final design, and the next steps on the path towards commissioning.

MICADO SCAO: first study of the impact on AO performance of the ELT/M4-M5 dynamics and of the tip-tilt command split between M4 and M5, using a data-based LQG controller

Zidi amal [1 2], Raynaud henri Francois [2], Clenet yann [1], Gendron eric [1], Kulcsar caroline [2], Vidal fabrice [1]

1 - Laboratoire d'études spatiales et d'instrumentation en astrophysique(France)
2 - Laboratoire Charles Fabry(France)

Abstract

MICADO, the ELT first light near infrared imager, will enable to work close to the telescope diffraction limit. One of the challenges of the AO on ELT is to cope with windshake and vibrations affecting its huge structure. These disturbances have such an impact on tip and tilt modes that the standard integrator control fails to reach MICADO SCAO performance specifications. We present the design of a predictive controller taking into account: the temporal dynamics of the deformable mirror M4 and of the tip/tilt mirror M5 the control split of tip/tilt commands between M4 and M5. The proposed fully data-driven predictive tip-tilt controller is a linear quadratic gaussian (LQG) regulator built around a Kalman filter based on a stochastic disturbance model. This model is identified for tip-tilt modes (or for any number of low-order modes) from AO loop telemetry data. Higher optical modes are controlled using a standard integrator with optimized gain. Using end-to-end simulations performed with COMPASS for different disturbance scenarios, we studied the impact of M4 and M5 dynamics together with the tip-tilt command split on final performance, for both regulators: LQG controller and integrator. The impact of M4 and M5 temporal dynamics can be simulated without increasing the simulation sampling period. We give performance in presence of these dynamics for both regulators For the tip-tilt command split study, we chose to compare different split schemes in addition to the one designed by ESO. We showed that some split schemes proposed in the literature may lead to unwanted behaviors in closed-loop. As for the ESO M4/M5 split scheme, we show that combined with the data-driven LQG controller, it leads to the desired performance. We then conclude that combining the M4/M5 dynamics and the ESO M4/M5 split, the LQG tip-tilt control enables to obtain the desired SCAO performance.

MICADO SCAO: to be or not to be... in MAIT

Clenet yann [1], Gendron eric [1], Buey tristan [1], Vidal fabrice [1], Cohen mathieu [2], Chapron frédéric [1], Sevin arnaud [1], Taburet sylvestre [2], Guieu sylvain [3], Gennet camille [1], Borgo bruno [1], Huet jean-Michel [2], Blin alexandre [4], Dupuis olivier [1], Gaudemard julien [2], Ferreira florian , Raffard jordan [1], Fasola gilles [2], Chemla fanny [2], Lapeyrere vincent [1], Meyer eric [5], Gautherot nicolas [5], Tisserand emmanuel [5], Locatelli hervé [5], Meyer françois [5], Zidi amal [1 6], Kulcsar caroline [6], Raynaud henri Francois [6], Sassolas benoit [7], Pinard laurent [7], Michel christophe [7], Gratadour damien [1], Dembet roderick [1], Collin claude [1], Ghouchou lahoucine [1], Baudoz pierre [1], Huby elsa [1], Rabien sebastian [8], Sturm eckhard [8], Davies richard [8]

1 - LESIA(France)
2 - GEPI(France)
3 - IPAG(France)
4 - DT INSU(France)
5 - UTINAM(France)
6 - Laboratoire Charles Fabry(France)
7 - LMA(France)
8 - Max Planck Institute for Extraterrestrial Physics(Germany)

Abstract

MICADO is the ELT first light instrument, an imager working at the diffraction limit of the telescope thanks to two adaptive optics (AO) modes: a single conjugate one (SCAO), available at the instrument first light and developed by the MICADO consortium, and a multi conjugate one (MCAO), developed by the MORFEO consortium. The MICADO project started the final design review process two years ago, in Feb. 2021, and has been through four successive review sessions since then, covering the different MICADO subsystems, including the SCAO module. This final design review process should come to an end this year in 2023, allowing to enter into the manufacturing, assembly, integration and tests phase. Though, without waiting for the issue of the full review, manufacturing, integration and related tests have actually already started for several SCAO subsystems, first in order to validate the design of several parts by prototyping at "full scale", and second to avoid a loss of motivation of people being involved for a long time only on paper studies. This strategy hence allows to optimize the project resources and to save time on the planning. It concerns its K-mirror (allowing to compensate for the pupil derotation), its "WFS core" (i.e. the pyramid optical component, the WFS camera and the pupil imaging lenses that compensate for the axial pupil movements), its field selector, its modulation system, its real-time computer, its instrument control software, but also more basically its various motors. This contribution will present the requirements of these subsystems and their on-going prototyping, focusing on the encountered difficulties but also on the test results, very encouraging for the MAIT of the full SCAO. We also received from ESO the authorization to order in advance the project long-lead items, i.e. for the SCAO its optics. Hence the SCAO dichroic blank (a 300 mm CaF2 plate) is already ordered and all the SCAO optics (14 optical subsystems) are about to be. Details will be given about these optics, the strategy followed for their supply and the lessons learnt from their ordering. This contribution will finish by presenting the next steps in the SCAO MAIT plan, i.e. the MAIT phase while being still in France at Observatoire de Paris before shipping SCAO to Germany for MICADO system integration.

Model Based Systems Engineering for the Gemini North Adaptive Optics Bench Phase A

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Abstract

The use of model-based systems engineering (henceforth MBSE) can help offset some of the technical challenges associated with the realisation of adaptive optics systems for future extremely large aperture telescopes (ELTs). The establishment and maintenance of the single version of the truth (i.e. the model) for a large and complex project, increases the likelihood of project success. To this extent, the AAO-Macquarie and collaborators (ONERA/LAM/ALPAO) have adopted an MBSE approach for the proposed Gemini North Adaptive Optics Bench Phase A (AURA project). We use architecture representations and system decompositions using the SysML elements, both functional and structural, with diagrams, allowing each project stakeholder to focus on aspects of the problem. The SysML elements can be traced to requirements

and other elements, making it easier to assess risk and prevent costly mistakes discovered during development and operational phases. Therefore, the knowledge gained being beneficial to the system modelling of future adaptive optics systems.

MODHIS: the first-light single-mode fiber fed high resolution exoplanet characterization spectrograph for the TMT, project overview and status

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1 - University of California
Los Angeles(United States)

Abstract

MODHIS is a first light instrument that will enable high resolution spectroscopy from y-K band on the TMT. It is a single-mode fiber fed spectrograph that relies on the adaptive optics correction provided by NFIRAOS. By operating at the diffraction-limit the MODHIS spectrographs, split into two near identical units with a yJ and HK channel, are extremely compact and can be in the wedge room at the bottom of the building. Injecting light from a 30-m aperture into a single-mode fiber with a core size of the order of 5 microns requires a high-performance adaptive optics correction, schemes to eliminate non-common path errors, a high-quality correction to the differential atmospheric refraction, and precise pointing and tip/tilt control. These issues are currently under investigation with the pathfinder injection unit commissioned at Keck known as the Keck Planet Imager and Characterizer. MODHIS also leverages significant developments from a near identical precursor instrument aimed to be deployed to Keck in 2026: HISPEC. In this paper we will review the status of MODHIS, outline the science case for the instrument and the adaptive optics observing modes it supports. We will review the spectrometer backend capabilities and design heritage with HISPEC and other ongoing developments.

MODHIS: the first-light single-mode fiber fed high resolution exoplanet characterization spectrograph for the TMT, technical review of the AO fiber feed

Jovanovic nemanja [1], Ruane garreth , Baker ashley , Mawet dimitri , Fitzgerald michael , Konopacky quinn , Fucik jason , Pahuja rishi , Brown aaron , Wang eric , Dekany richard

1 - California Institute of Technology(United States)

Abstract

MODHIS is a first light instrument that will enable high resolution spectroscopy from y-K band on the TMT. It is a single-mode fiber fed spectrograph that relies on the adaptive optics correction provided by NFIRAOS. By operating at the diffraction-limit the MODHIS spectrographs, split into two near identical units with a yJ and HK channel, are extremely compact and can be in the wedge room at the bottom of the

building. Injecting light from a 30-m aperture into a single-mode fiber with a core size of the order of 5 microns requires a high-performance adaptive optics correction, schemes to eliminate non-common path errors, a high-quality correction to the differential atmospheric refraction, and precise pointing and tip/tilt control. These issues are currently under investigation with the pathfinder injection unit commissioned at Keck known as the Keck Planet Imager and Characterizer. MODHIS also leverages significant developments from a near identical precursor instrument aimed to be deployed to Keck in 2026: HISPEC. In this paper we will present a technical overview of the instrument and discuss the subtleties of the single-mode-fiber feed on an ELT. These topics encompass adaptive optics acquisition and correction, tracking, and non-common path error correction.

MOEMS-based future systems for ELTs

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Abstract

Studying all types of star clusters at different spatial scales, from Galactic globular clusters, the oldest known objects in the Universe, to young, star-forming, clusters in the Milky Way or in metal-poor galaxies of the local Universe; studying XUV galaxies in spectroscopy and photometry; studying mass distribution of Giant Low Surface Brightness Galaxies; studying kinematics in small galaxies for understanding if the compact ionised gas emission is associated to AGNs, or to individual clumps rather than tracing the global kinematics of these systems; all these Science Cases rely on a high spatial and high spectral resolution instrument in the visible and infrared. New concepts using breakthrough technologies must be proposed for the next generation of AO systems and instruments in ELTs. MOEMS devices, as large micromirror arrays (MMA), will lead to a new class of compact and efficient systems. MOEMS Deformable Mirrors (DM) are key components for next generation optical instruments implementing innovative adaptive optics systems, in existing telescopes as well as in the future ELTs. Due to the wide variety of applications, these DMs must perform at room temperature as well as in cryogenic and vacuum environment. We tested the PTT 111 DM from Iris AO: the device could be operated successfully from ambient to 160 K; using our calibration procedure and a specific driving scheme, we obtained a quasi-identical best flat as low as 10nm rms at room temperature and 12nm rms at 160K. We tested also Boston Micromachines continuous DMs at room temperature: due to the accuracy and the repeatability of the electrostatic actuators, we were able to generate a synthetic influence function with a residual as low as 0.4% with respect to the actual influence functions measured for the whole actuation range. MOEMS programmable slit mask for astronomical object selection are foreseen in multi-object spectrographs (MOS). We present in this paper the ability of a silicon-based micromirror array to fulfill the performances requested for future MOS instruments in UV-visible-infrared. We are engaged in a European development of tiltable micro-mirror arrays exhibiting remarkable performances in terms of surface quality as well as ability to work at cryogenic temperatures. MMA with 100 x 200 µm2 single-crystal silicon micromirrors were successfully designed, fabricated and tested down to 162 K. In order to fill large focal planes (mosaicing of several chips), we are currently developing large micromirror arrays to be integrated with their electronics. In future instrumentation, MOEMS DMs (wavefront correction) and tiltable MMAs (for object/field selection) are the key components for correcting/shaping the wavefront/field-of-view at the entrance or within the instruments. We propose new MOEMS-based instrument concepts in order to increase their efficiency and create new observational modes impossible to be implemented with current technologies. BATMAN family of spectro-imagers for current and future telescopes includes the MOEMS disruptive technology. As a pathfinder, we propose a spectro-imager able to deliver full coverage of a large AO-corrected FOV at high spatial and spectral resolution over a large wavelength band. This spectro-imager design must exploit the exquisite image quality delivered by a Multi Conjugate Adaptive Optics (MCAO) over a large field of view in the visible, i.e. MAVIS on the VLT, delivering a 30"x30" field corrected at 7.5mas/pixel, on a wavelength range from 370 nm to 950 nm. The design of BATMAN@MAVIS, an additional instrument covering science cases and instrument capabilities not covered by the baseline instrument is presented. BATMAN@MAVIS will then allow any part of the FOV to be oriented either towards an imager with the optimum spatial resolution delivered by MAVIS AOM, or towards a spectrograph with high spectral resolution (15 000) divided into 4 sub-bands; the wavelength range could be covered sequentially by changing the grating in the spectrograph. Instrument abilities are wide, including variable spatial bin and variable spectral resolution, as well as any combination of the above modes over the whole FOV. MOS and IFU (scanning slit) are available. Any slit mask configuration could be produced, i.e. any shape, including long slit, and a real time reconfiguration ability. These new features allow new observation strategies for optimizing the recorded scientific data over the FOV, following an optimized strategy on each object. For example, MOS and IFU combination any time and anywhere in the FOV are possible.

Monostatic LGS-AO with uplink beam precompensation and spot tracking on ELT: some analysis and considerations

Bonaccini Calia domenico [1], Agapito guido , Martinez Rey noelia , Stadler bernadette

1 - European Southern Observatory(Germany)

Abstract

Following the analysis and the work done for the construction of CaNaPy, a monostatic LGS-AO system with uplink pre-compensation and pyramid WFS which will be briefly illustrated,we review design and system analysis considerations on possibly extending the monostatic LGS-AO system concept to a 40m ELT, including spot tracking

MORFEO : the adaptive optics module for ELT

Ciliegi paolo [1]

1 - INAF - OAS(Italy)

Abstract

MORFEO (Multi conjugate adaptive Optics Relay For ELT Observation) is the adaptive optics module for the ESO ELT Telescope. The Project is in the Final Design Phase. In this presentation, I will review the status of the project with particular emphasis on the technical and managerial aspects (including the status of the procurements), the instrument performance and the scientific impact. Finally, the schedule foreseen up to the delivery of the instrument will be presented.

MORFEO enters final design phase

Busoni lorenzo [1]

1 - INAF - Osservatorio Astrofisico di Arcetri(Italy)

Abstract

MORFEO (Multi-conjugate adaptive Optics Relay For ELT Observation, formerly MAORY), the MCAO system for the ELT, will provide diffraction limited optical quality to the large field camera MICADO. MORFEO has officially passed the Preliminary Design Review and it is entering the final design phase. We present the current status of the project, with a focus on the adaptive optics system aspects and expected milestones during the next project phase.

Multi-(sub)Aperture Fiber Nulling for Exoplanet Sciences

Wang ji [1]

1 - The Ohio State University(United States)

Abstract

We will present simulation and laboratory demonstration for a novel technique, multi-aperture fiber nulling (MAFN). The technique conbimnes nulling interferometry and high-resolution spectroscopy, taking advantage of the high spatial resolution brought by the nulling interometry and the high contrast brought by the high-resolution spectroscopy. We show that with current facilities such as the Large Binocular Telescope Interferometer (LBTI) and future extremely large telescopes (ELTs), direct spectroscpy of radial velocity detected planets can be studied in unpresedented details to understand their orgin of formation and search for biosignatures in their atmospheres.

Multi-Object Adaptive Optics Performance for the Gemini InfraRed Multi-Object Spectrograph Instrument

Conod uriel [1 2], Jackson kate [2], Turri paolo [2 3], Chapman scott [2 3 4], Lardière olivier [2], Lamb masen [5 6], Correia carlos [7], Sivo gaetano [5], Sivanandam suresh [6], Veran jean-Pierre [2]

1 - University of British Columbia(Canada)
2 - NRC Herzberg Astronomy and Astrophysics(Canada)
3 - University of British Columbia(Canada)
4 - Dalhousie University(Canada)
5 - Gemini Observatory(Chile)
6 - Dunlap Institute for Astronomy and Astrophysics [Toronto](Canada)
7 - SpaceODT(Portugal)

Abstract

Developing and exercising Multi-Object Adaptive Optics (MOAO) technique on 8-meter class telescope is crucial and required to pave the road for the next generation of MOAO-assisted instruments to be installed on future 30-meter class Telescopes (ELT). The Gemini InfraRed Multi-Object Spectrograph (GIRMOS) is a new facility instrument for Gemini North Telescope using state-of-the-art Adaptive Optics (AO) correction in order to fully take advantage of the telescope's diffraction capability for imaging and spectroscopy. In this work, I will present (1) the GIRMOS MOAO system design, (2) the AO performance modelling, and (3) the risk mitigations activities related to MOAO. (1) The Adaptive Optics (AO) system of GIRMOS is designed around a two-stage framework. First, a Ground Layer AO (GLAO) correction over a 2 arcminutes field-of-regard is carried out by the Gemini North AO facility (GNAO). Second, an additional MOAO correction is performed by GIRMOS for each of its four Integral Field Unit (IFU) spectrographs. The choice of this specific two-stage architecture will be discussed in detail. An additional goal of the combined instrument is to demonstrate the key capability of AO and MOAO technique on 8m telescopes. Thus, providing the critical experience and technology necessary to develop a future 2nd generation MOAO instrument on ELTs. (2) Using numerical simulations, we developed a framework to model the full chain of GNAO-GIRMOS AO performance under different atmospheric conditions and configurations at Mauna Kea. We demonstrated the performance on real distant galaxies data. This AO performance modelling was integral to the design of the GIRMOS instrument. (3) For risks mitigation, we developed a prototype in the laboratory to characterize and exercise calibrations and open-loop AO, as required by the MOAO technique. In addition, we are performing on-sky open-loop experiment using the REVOLT platform on the Dominion Astronomical Observatory 1.2m telescope.

NGSs acquisition in MORFEO

Agapito guido [1], Busoni lorenzo , Plantet cedric , Carlà giulia , Bonaglia marco

1 - INAF(Italy)

Abstract

MORFEO (Multi-conjugate adaptive Optics Relay For ELT Observation) is the future multi-conjugate adaptive optics system for the ESO ELT that will feed the instrument MICADO (Multi-AO Imaging Camera for Deep Observations). It will use the 6 laser guide stars to give a uniform correction on a field-of-view of approximately 60arcsec of diameter. Tip, tilt and slow focus measurement will be done on up to three natural guide stars that could be really faint to maximize sky coverage. The current baseline is to use the reference wavefront sensor in the visible to acquire the star and center it on the low order wavefront sensor that has a much smaller field-of-view. In this work we study this problem focusing on the estimation error of the tilt from the reference wavefront sensor as a function of star magnitude and atmospheric conditions.

NIRVANA-VIS, an AO-assisted speckle holography add-on for visible wavelengths

Bergomi maria [1], Radhakrishnan kalyan [1], Arcidiacono carmelo [1], Di Rosa silvio [1 2], Dima marco [1], Greggio davide [1], Marafatto luca [1], Farinato jacopo [1], Viotto valentina [1], Briegel florian [3], Bertram thomas [3], Bizenberger peter [4], Ragazzoni roberto [1], Herbst tom [3]

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3 - Max-Planck-Institut für Astronomie(Germany)
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Abstract

Nirvana-Vis project proposes a visible-wavelength imaging channel upgrade for LINC-NIRVANA (LN), the Italian-German high angular resolution imager installed on the Large Binocular Telescope (LBT). LN is a near-infrared imager operating in the JHK photometric bands, equipped with a multiple-FoV MCAO system to deliver a near diffraction-limited two arcminutes FoV. The instrument has demonstrated on-sky consistent and stable Ground Layer Adaptive Optics (GLAO) correction, improving the FWHM of the PSF up to a factor 3. We plan to exploit in such a wide corrected field, the technique of AO-assisted speckle holography, in which images are reconstructed from a long series of short exposure frames whose image quality has been sharpened by adaptive optics for the visible regime. We will present the opto-mechanical upgrade allowing this additional mode (under italian PNRR STILES project financement) while keeping all functionalities of the NIRVANA instrument.

Non-Common Path Aberrations Strategy for the METIS High Contrast Imaging Modes

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Abstract

Non-common path aberrations (NCPAs) are widely recognized as one of the main limitations of current and future high-contrast imaging instruments. The slow variation of NCPAs generates quasi-static speckles (QSS) that are coherently modulated by the AO speckles. This increases speckle noise and reduces the achievable contrast, thus leading to a significant hit in HCI performance. In METIS, NCPAs – due to optical imperfections – are minimized by design, and the gravity-invariant design should keep their time variation to a low level. Yet the short- and long-term variations of the NCPA, driven e.g. by chromatic beam wander, can lead to a significant hit in HCI performance and need to be measured and corrected. But the METIS high contrast imaging modes face another challenge, especially at longer wavelengths, posed by water vapor turbulence. Because it is highly chromatic and changes dynamically, it sets new requirements on our NCPA algorithms: the ability to infer the phase aberration quickly at a 100% duty cycle. In this contribution, we present our latest developments and discuss how our strategy has been adapted to better tackle this challenge. In particular, we will detail the various algorithms we have been investigating : QACITS for tip-tilt sensing in the case of the vortex coronagraph, Phase Sorting Interferometry (PSI) for higher-order (quasi-)static aberrations, and finally focal plane wavefront sensing with an asymmetric Lyot mask to measure dynamically changing higher-order aberrations.

Non-modulated pyramid wavefront sensor for ELT SCAO systems

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Abstract

In the context of the single conjugate adaptive optics (SCAO) systems for the next generation of telescopes the pyramid wavefront sensor (PWFS) is the preferred solution. This kind of sensor will measure the continuous turbulence and the differential piston with the goal of compensating both and producing a well-corrected wavefront to the scientific instruments. In this work we study the possibility of disabling the pyramid modulation to maximize the sensitivity of the sensor. This configuration is particularly appealing for differential piston sensing, but it was historically discarded due to the reduced robustness in presence of residual turbulence. So we increased the loop stability in this configuration by setting a more accurate calibration of the non-modulated PWFS response in partial correction. We describe this new calibration approach and we show by the means of numerical simulations the sensitivity and performance of a SCAO system for the extremely large telescope with disabled modulation and we compare it with a case configured with a PWFS with a typical modulation radius of a few lambda/D.

Numerical Simulation of Astrometry Field with MORFEO on the ELT

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Abstract

We present the results of our numerical simulations on astrometry measurements using the Multi-conjugate adaptive Optics Relay For ELT Observations (MORFEO) instrument on the Extremely Large Telescope (ELT). Our simulation considers the spatially variable point spread function (PSF) of MORFEO, as well as the geometric distortion of MORFEO and its variation with rotation angle. We used the SIMCADO and/or SCOPESIM simulation packages to generate images of the astrometry field and test various data analysis software for achievable performance. Our study investigates the feasibility and accuracy of astrometry measurements with MORFEO in moderately crowded fields, demonstrating its potential for ELT astrometry. Our findings provide valuable insights into the use of MORFEO for the ELT and will provide information on future observational campaigns, contributing to the development of astrometry applications. We will begin by considering moderately crowded fields and later increase the crowding level to assess the potential of these instruments for high-precision astrometry measurements of dense stellar systems, including globular cluster targets in our simulations. Ultimately, our results will contribute to the development of astrometry science cases for the ELT and inform future observational campaigns.

Observing Debris disks with the ELT-HARMONI instrument

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The SCAO system will feed a High-Contrast Module that will allow the direct spectroscopy from 1.25 to 2.45microns of sources at high contrast ratio with their host star. Its prime science case focuses on young giant exoplanets at contrasts up to 16mag with their host star down to separations of 75mas. One of the other possible science cases for the High-Contrast Module is the direct spectroscopy of bright debris disks, for which HARMONI could measure scattered-light reflectance spectra, a key information to constrain the grain size distribution and composition in those systems. With its greater angular resolution and smaller inner working angles compares to VLT instruments, ELT-HARMONI has the capability to explore the inner parts of debris disks across the ice line for systems within 25pc, a region where giant planets are expected to form. High angular resolution and spectrally dispersed measurements of extended, resolved objects put however strong contraints on the brightness of the disk. Here we present a preliminary sensitivity analysis of HARMONI for the disk science case.

On-Sky Adaptive Secondary Interaction Matrix Calibration on the MMT

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Abstract

With the commissioning of the refurbished adaptive secondary mirror (ASM) for the 6.5-meter MMT Observatory under way, special consideration had to be made to properly calibrate the mirror response functions to generate an interaction matrix (IM). Like many upcoming extremely large aperture telescopes (ELTs), the MMT lacks a point in the optical path to place a calibration source to accurately sample the ASM's actuator response functions. Furthermore, to create an interaction matrix (IM) to operate a closed-loop adaptive optics (AO) system we must use on-sky or simulated methods. In this paper, we show how the DO-CRIME on-sky calibration method was successfully implemented at the MMT to extract the IM. We also present improvements to its base algorithm, which greatly improves its robustness to noise as well as errant actuators. We present both optical bench AO system validation as well as preliminary on-sky results from the MAPS (MMTO Adaptive optics exoPlanet characterization System) project on the MMT.

On-sky results with a real-time model-free reinforcement learning method

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Abstract

This paper introduces a novel real-time non-linear predictive control approach based on a model-free reinforcement learning (RL) method, with a non-linear reconstruction relying on supervised learning (SL) using a U-net architecture. We present our on-sky and bench results obtained on the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO instrument and show that our approach outperforms the standard modal integrator controllers. To develop our two-component model, we quantify the possible improvement of a non-linear reconstruction for the pyramid wavefront sensor (PyWFS) and a wavefront prediction depending on the intrinsic delay of the system. This analysis provides the basis for building our two-component model of non-linear prediction with RL and reconstruction with SL. The RL component is trained online with telemetry data and the SL model is trained offline with a previously built dataset of WFS images and phases.
The proposed model involves training (RL) and inferring (RL and SL) at high framerates (2kHz PyWFS images). To run at such speed, we propose a scheme that we integrate into the Compute and Control for Adaptive Optics real-time control package (CACAO), leveraging this framework to process the data and both infer and train at speeds that allow for increased performance. The main ideas of the scheme are TensorRT for inference, multiple GPU training for the RL model and a high degree of parallelization. Finally, we present our results demonstrating that our model can run at the required speeds and outperform a default modal integrator controller both on-sky and on the bench.

On-sky speckle nulling through a single-mode fiber with the Keck Planet Imager and Characterizer

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Abstract

The Keck Planet Imager and Characterizer (KPIC) is a series of upgrades for the Keck II Adaptive Optics system and the NIRSPEC spectrograph to enable diffraction-limited, high-resolution (R>30,000) spectroscopy in the K and L bands. KPIC uses single-mode fibers to couple the adaptive optics system to NIRSPEC, and its sensitivity at small separations is limited by the leakage of stellar light into the fiber. Speckle nulling is a technique that uses a deformable mirror to destructively interfere starlight with itself. We present the first on-sky demonstration of speckle nulling through an optical fiber with KPIC, using NIRSPEC to collect exposures that measure speckle phase for quasi-real-time wavefront control while also serving as science data. We show a decrease in the on-sky stellar coupling by a factor of 2.6 to 2.8 in the targeted spectral order, at a spatial separation of 2 λ/D. This corresponds to an estimated factor of 2.6 to 2.8 decrease in the required exposure time to reach a given SNR, relative to conventional KPIC observations. The performance of speckle nulling is limited by instability in the speckle phase: when the loop is opened, the null-depth degrades by a factor of 2 on the timescale of a single phase measurement. Future work includes exploring gradient-descent methods, which may be faster and thereby able to achieve deeper nulls. In the meantime, the speckle nulling algorithm demonstrated in this work can be used to decrease stellar leakage and improve the signal-to-noise of science observations.

One turbulent night: a thorough look at temporal tomography

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Abstract

The `imaka instrument is a ground layer adaptive optics (GLAO) system on the UH88" telescope on Maunakea, Hawaii. With five natural guide star wavefront sensors and an observing strategy that includes recording of open loop wavefront sensor slopes, it provides a wealth of information about the turbulence conditions during operation. We have been using `imaka to develop a new technique that we call "temporal tomography" which extends Fourier Wind Identification to also provide altitudes for the turbulent layers. We present a case study of the effectiveness of temporal tomography on a particular night by comparing the results to a variety of alternative approaches and external sources of data. For this we include the MASS/DIMM profile, the GFS and WRF weather forecasting models, wind ground speed and direction measurements from the Canada France Hawaii Telescope weather tower, and two alternate approaches to turbulence profiling with `imaka wavefront sensor data: SLODAR and temporal cross-correlations.

OOPAO: the Python legacy of OOMAO

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Abstract

The list of Adaptive Optics (AO) simulators in the community has constantly been growing, guided by different needs and purposes (Compass, HCIPY, OOMAO, SOAPY, YAO...). In this paper, we present OOPAO (Object Oriented Python Adaptive Optics), a simulation tool based on the Matlab distribution OOMAO to adapt its philosphy to the Python language. This code was initially intended for internal use but the choice was made to make it public as it can benefit the community since it is fully develloped in Python. The OOPAO repository is available in free access on GitHub (https://github.com/cheritier/OOPAO) with several tutorials. The tool consists of a full end-to-end simulator designed for AO analysis purposes. The principle is that the light from a given light source can be propagated through multiple objects (Atmosphere, Telescope, Deformable Mirror, Wave-Front Sensors...) among which experimental features can be input, in the spirit of OOMAO. This code was designed to model an AO system as close as possible from reality to generate pseudo-synthetic interaction matrices for AO instruments and includes the SPRINT algorithm to calibrate the DM/WFS registration. The primary goal of this tool is then to offer modularity to the end user and has been parallelized to perform multi-threaded operations. The goal of this communication is to introduce the code to the AO comunity, presenting its main functionalities and comparing its outputs with the theory. As well, an illustration of its application on the GHOST test-bench and on the Papyrus instrument will be presented.

Opening up a new dimension with time-resolved wavefront sensing

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Abstract

A time-resolved wavefront sensor (WFS) is a classical WFS for which the integration time is divided into N sub-steps, and an image is acquired at each sub-step. Therefore, each WFS measurement consists of a cube of N images (slices) instead of a single image. This recent concept [1] critically relies on the development of high-speed photon counting detectors, such as Photon-to-Digital Converter (PDC), based on an array of Single Photon Avalanche Diodes (SPADs), currently developed by University of Sherbrooke for quantum sensing, in the context of quantum communication. These detectors are supported by a CMOS integrated circuit that is able to measure the time of arrival of each photon with a few tens of picoseconds accuracy, and process this information in real-time, e.g. to produce images made from photons arriving within specific time frames, or implement even more sophisticated on-the-fly processing [2] For adaptive optics, time-resolved WFSing appears to be particularly useful for modulated WFSs, such as the Pyramid WFS, because it allows breaking up the modulation cycle into several time slices, so that information collected in different slices can be processed differently. In the pyramid WFS measurement process, the image of the NGS is stirred in a circle around the tip of the pyramid. For some wavefront modes, it can be shown that some time slices do not provide any information on that mode. It is therefore better to exclude photons collected during these time slices from the wavefront reconstruction process, because they only contribute noise. We have simulated the time-resolved pyramid WFS in OOMAO/OOPAO for a single-conjugate AO system similar to GPI 2.0. For such a system, modulation is needed in order to achieve sufficient dynamic range. However, it is well known that modulation reduces sensitivity to low order modes. Our results show that by excluding specific time slices from the reconstruction process for low order modes, this loss in sensitivity can be reversed, at least partially, leading to better delivered Strehl ratios and higher limiting magnitude for the system. We are also in the process of collecting telemetry data from a laboratory pyramid WFS. The modulation rate is slowed down by a factor 20 to 40 compared to the camera frame rate, allowing to collect 20 to 40 time slices for each modulation period. In this experimental setup, a deformable mirror (DM) is placed in front of the WFS, and we are able to record the response to various DM modes. By building interaction matrices with various combinations of time slices and evaluating the noise propagation from the wavefront reconstructor derived from them, we are hoping to confirm experimentally the gain in sensitivity afforded by rejecting time slices from the reconstruction process for some of the modes. We will also explore whether this time slice selection process results in loss of linearity. As mentioned above, the Pyramid WFS is only one example of a WFS that could potentially benefit from time-resolved measurements. Another example could be the curvature WFS, where the modulation represents a change in optical conjugation. Each photon could then be associated with the exact conjugation it was recorded at, potentially providing richer information than in a traditional set up where all the photons are bundled into only 2-4 images. [1] Véran, J.-P. et al., "Time-Resolved Pyramid Wavefront Sensing using Photon-to-Digital Converters", AO WFS Workshop, Porto, 2022, https://wfs2022.sciencesconf.org/426423 [2] Carrier, S. et al., "Photon-to-Digital Converters for Wavefront Sensing", this conference

Optically driven photothermal wavefront corrector

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Abstract

We present photothermal Spatial light modulators (PT-SLMs) allowing for polarization-independent active wavefront modulation of the transmitted beam with a broad wavelength range. The operation principle is based on the thermo-optics effect of plasmonic gold nanoparticles embedded in a polymeric matrix. A spatially patterned control beam is used to modulate the refractive index of the active PT-SLM layer. In our previous work, digital mirror devices (DMDs) were used to precisely address the PT-SLM profile allowing for rapid and efficient control of the optical wavefront.[1] However, the confined field of view and high demand for the power of the control beam limits the number of applications to specialized optical laboratories. Here, we enhance the concept of controlling the PT-SLMs using a set of acousto-optic deflectors (AOD) for high-speed applications and better energy efficiency. A response time as short as 2 μs and 16-bit grey scale amplitude modulations and position modulation of dAOD allow for dosing the distribution of the refractive index with great precision and a large field of view. The tunable feature size with almost continuous position resolution and no polarization sensitivity in the broad wavelength range opens new opportunities for the most demanding imaging applications. [1] Robert, H. M. L., ■i■ala, M., Piliarik, M., Shaping of Optical Wavefronts Using Light-Patterned Photothermal Metamaterial. Adv. Optical Mater. 2022, 2200960.

Optimal modal basis for ELT M4 mirror Force/Position control

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Abstract

Context. The deployment of large scale adaptive deformable mirrors on 10m-class telescopes is now well established. Furthermore, such mirrors have been adopted by two out of the three Giant Segmented Mirror Telescopes now under design. In all these cases, the proprietary technology is based on voice-coils and is limited in force, stroke and velocity. Aims. Our goal is to generate Karhunen-Loève (KL) bases for optimal wavefront control. Our basis integrate force limitations in their definitions whilst maintaining standard orthonormality, statistical independence and are expressed fully within the deformable mirror spanned space. Methods. We use the so-called double diagonalisation method whereby the principal components of a stochastic process (the turbulence) are expressed as linear combinations of the principal components of the deformable mirror (mechanical modes). The basis so obtained is ranked by the force applied on the actuators. Results. The analysis of this new KL basis for von Kármán turbulence statistics is made and the Fitting error, Positions and Forces distribution are presented. We further illustrate their use in the case of the early adopter instrument METIS – the Mid-Infrared ELT Imager and Spectrograph – to be installed on the Extremely Large Telescope (ELT), using transient analysis (time-domain) covering the handover period, from telescope to the instruments. Other non-stationary events, such as the recurrent optimisation of the mirror units is also covered.

Optimal nonlinear wavefront sensing and control with machine learning

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Abstract

Many wavefront sensors, including the Pyramid, Zernike and focal plane, have a nonlinear response for large phase aberrations. In this talk I will demonstrate techniques to mitigate these nonlinearities using machine learning. First, I will show how Neural Networks can be used as nonlinear mappings between wavefront sensor measurement and wavefront, and can lead to significantly increased dynamic range. Next, I will demonstrate how Reinforcement Learning can help us find predictive controllers that can deal with nonlinear dynamics/wavefront sensors. Finally, I will show that gradient-based optimization, which is commonly used in machine learning, can also be used to optimize the free design parameters of a wavefront sensor, leading to designs with sensitivity close to the theoretical limit.

Optimization of the performance of the MORFEO CU

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Abstract

After the Preliminary Design Review, the Calibration Unit (CU) of MORFEO, the Multiconjugate adaptive Optics Relay for ELT Observations, underwent a complete design overhaul. This process was aimed at trying to mitigate some critical aspects of the manufacturing, both in terms of optics and mechanics. While its optical configuration proved to be the best choice to meet the system requirements, especially on external interfaces, a slighly different layout has been investigated. By changing the displacement of the large beam splitters and applying small changes to a few optical elements, it would be possible to obtain a significant increase in the overall optical quality, for both the NGS and LGS arms. Moreover, some important modification to the mechanics could actually decrease the complexity of the assemblies and adjustments, also allowing a better accessibility to the CU from all sides, thus facilitating the MAIT operations. We present an overview of this new possible layout of the MORFEO CU.

PAPYRUS : Overview of the AO On-sky performance

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Abstract

PAPYRUS is a pyramid-based adaptive optics system installed at Observatoire de Haute Provence (OHP), on the T152 (1m52 diameter telescope). Its main purpose is the development and the experimentation of innovating ideas gravitating around AO and imaging for astronomy. The ongoing evolution of the bench is to promote it at the rank of scientific instrument. Combining PAPYRUS with the IR fiber spectrograph VIPA (developed by IPAG) will allow for instance the observation of binary stars and brown dwarfs, with contrast ratios similar to that between a star and a planet. The installation of an IR camera and coronagraph will allow the observation of protoplanetary disks and some exoplanets (e.g. HR8799, already observed at PALOMAR reduced at 1.5 m diameter). Before the installation of such a device it is important to well characterize the performances of the system. This preliminary work is necessary to develop the instrumental part. Thus we present in this work the nominal performance of the system as measured on-sky. Firstly, the bench is used in its simplest configuration: a visible pyramid-WFS controlling a 17x17 deformable mirror in closed loop running at 1500 Hz. The performance is estimated in terms of Strehl Ratio at visible and Infrared wavelength. In a second step, we explore the performances of the AO system optimized with an optical gains tracking method. The measurement of the optical gains in real-time is made possible with the integration of a gain sensing camera (GSC) and a convolutional-based analytical model. The GSC is localized in a focal plane conjugated with the tip of the Pyramid to capture a snapshot of the PSF shape that can be directly linked to the effective optical gains. Compensating the optical gains allows to enhance the performance of the system. Moreover, it will be a precious help in the future to increase the contrast ratio of the high-contrast arm by using dark-hole technique and NCPA compensation.

PAPYRUS : Shack-Hartmann Path

Leroux françois [1], Boudjema idir [2], Martin bruno [2], Schimpf armin [2], Bruni-Favier anne-Marie [2], Jouve pierre [3], Eric Stadler [6], Mojtaba Taheri [1], Rouquette paul [1], Camilo Weinberger [1], Neichel benoit [1], J. Schmitt [7], E. Muslimov [5], R. Fétick [1],

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Abstract

PAPYRUS (Provence Adaptive optics Pyramid Run System) is a pyramid-based adaptive optics system installed at Observatoire de Haute Provence (OHP), on the T152 (1m52 diameter telescope). It aims to deepen our knowledge on the Pyramid Wavefront Sensor (PYWFS) and to perform on-sky tests. The PYWFS is more sensible to small phases perturbations than previous WFS concepts but also suffers from a smaller dynamic range : when the phases perturbations reach a certain level, the PYWFS is not able to measure them accurately due to non linearity and modal confusion effects intrinsic to the physics of the system. Therefore, we compare the PYWFS with the widely used Shack-Hartmann Wavefront Sensor (SHWFS). A SHWFS path has then been installed on PAPYRUS, parallel to the PYWFS path. The technical solution chosen for the SHWFS detector part presents the originality of being a CMOS with low readout noise (2.5e-) sensor : the Cblue One built by the First Light Imaging company. Both PYWFS and SHWFS control a 17x17 actuators deformable mirror (DM) and are controlled with a Real Time Computer both (RTC) built by the ALPAO company. The design of the microlenses and their integration on the Cblue Camera, as well as the control Algorithm of the SHWFS have also been done by ALPAO. In this paper, the conception and integration of PAPYRUS SHWFS path is described, focusing on the error budget, sizing, and alignment of the system. The performances of the two systems are presented and compared for stars of different magnitude and elevation, these two parameters allowing us to test respectively noise sensibility and response to different turbulence strenght. The extended object case is also discussed, as well as other ideas involving the SHWFS path that we plan to set up in the future.

PAPYRUS : The new ALPAO RTC features

Boudjema idir [1 2], Martin bruno [1], Schimpf armin [1], Charton julien [1], Fetick romain [3], Chambouleyron vincent [4], Sauvage jean-François [2 5], Leroux françois [2], Jouve pierre [2 3], Neichel benoit [2], Fusco thierry [2 5]

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Abstract

PAPYRUS is a pyramid-based adaptive optics system installed on the 1.52m telescope of Observatoire de Haute Provence (OHP, France). Adaptive optics real time applications (Astronomy and FSO) require RTCs with increasing performance on ever larger problem sizes. This performance is often achieved at the cost of increasingly complex, more expensive, and less flexible clusters. ALPAO has developed its own RTC solution that runs on standard servers with a MATLAB layer (Alpao Core Engine software) as user interface. This solution allows greater ease of use and flexibility. Indeed, all the calculations that do not need to be done in real time are done in the MATLAB layer, such as calibrations and parameterization of the AO loop. ALPAO RTC can be easily adapted to various AO configurations. In addition to standard SISO (Single Input Single Output) configurations, the MIMO (Multiple Input Multiple Output) configuration is now supported. Various interfaces are available, such as camera link connections for wavefront sensors (WFS), 16-bit parallel connections for ALPAO DMs and 10 GigE Vision connections for DMs and WFSs. Thanks to the collaboration between ALPAO and LAM in the framework of the ALAMO project, the ALPAO RTC is now capable of closing the loop on-sky with the Pyramid wavefront sensor (PyWFS), in both slopes map and intensity map modes. Measurements with the PAPYRUS bench at OHP with a loop rate of 1.5kfps, a detector size of 240x240, a calculation area of 160x160 and an ALPAO DM241, yields an RTC latency of 130µs. A new ALPAO Shack Hartman WFS has been integrated into the PAPYRUS bench, with the same RTC as for the PyWFS at a loop speed of 900Hz, a 10 GigE Vision detector with a size of 512x512 and 32x32 micro lens array, yields an RTC latency of 29µs.

PAPYRUS at Observatoire de Haute Provence : Second stage Adaptive Optics

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Abstract

The Provence Adaptive optics Pyramid Run System (PAPYRUS) is a pyramid-based Adaptive Optics (AO) system installed at the Coude focus of the 1.52m telescope (T152) at the Observatoire de Haute Provence (OHP). PAPYRUS is a young researcher project that aims to strengthen our knowledge in AO. This bench is use as an education tool and technological platform to test and better understand Fourier Filtering Wave-Front sensors operating on sky. First images and characterisations of the pyramid-based AO bench were obtained last year. The next steps are implementing an optical gain compensation and implementing a second stage AO. The aim of this second stage is to significantly improve the AO correction of the first stage by reducing the temporal error which is the main limit of the PAPYRUS bench. To do so, the second stage will work in the NIR and with a low-order Deformable Miror with and fast control frequency. Furthermore, the wave-front sensor of this second stage will be a Fourier Filtering wave-front sensor (FFWFS). The main idea with this second is to test different FFWFS starting with the Zernike mask. With its two-stage AO system, PAPYRUS will provide high spatial resolution for a high spectral resolution instrument using an echelle spectrometer based on the used of VIPA (Virtually Images Phased Array). We present the optical setup of this second stage based on a Zernike mask. We also present first experimental result regarding the

second stage obtained on the LOOPS bench.

PAPYRUS: Advanced reinforcement learning control for improved performance

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Abstract

In this paper, we apply a model-based reinforcement learning (MBRL) method for predictive Adaptive Optics control. Our goal is to demonstrate how reinforcement learning algorithms can reduce the AO temporal error, and improve the overall performance. Our experiments are based on the use of the Object-Oriented Python Adaptive Optics (OOPAO) to simulate The Provence Adaptive Optics Pyramid Run System (PAPYRUS) optical bench and provide a real-time model of the optical system. This is of particular importance for PAPYRUS, where the temporal error is the main contributor in the total error budget. We first present a detailed description of the reinforcement learning framework, including the definition of the state space, the action space, and the reward function. The state space is represented by the wavefront measurements obtained from the OOPAO simulation, while the action space corresponds to the DM commands that can be applied to the system. The reward function is defined based on the wavefront error. The experiment section shows the results obtained by simulating the bench with a classical integrator in comparison to the same system run with the MBRL approach. We also provide results of the actual bench under a calibration source for a better contrast with the simulated bench. In conclusion, we present how running machine learning methods on a simulated bench can be beneficial to study and understand its implementation before applying it to the RTC of a real bench. Reinforcement learning methods have the potential to optimize the performance of adaptive optics systems by predicting the evolution of turbulence and learning better DM commands, and eventually improve the accuracy and efficiency of adaptive optics control.

PAPYRUS: current status and updates

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Abstract

The Provence Adaptive optics Pyramid Run System (PAPYRUS) is a pyramid-based Adaptive Optics (AO) system installed at the Coude focus of the 1.52m telescope (T152) at the Observatoire de Haute Provence (OHP). PAPYRUS was original developed as young researcher project and is now becoming a fully operational on-sky multi-purpose research platform. With an almost permanent access to the sky, Papyrus can be used as 1) an educational tool for various summer schools; 2) a technological platforme to test and better understand innovative AO concepts (new WFS, control laws, on-sky calibration and optimisation strategies) and components (new highly sensitive and fast detector and deformable mirror for instance); 3) a first AO stage to feed new multistage AO concepts for future eXtreme AO instruments to be installed on VLT or ELT 4) a fully optimized and well characterized AO system to feed new post focal instrumentation such as fiber spectrograph, optimized coronagrphic masks, new imager concepts (new science detectors, Mkids...) We present the current status of the bench, its current performance and its future developments. In particular in the following months, it is schedule to measure and compensate the optical gains thanks to the so-called gain sensing camera. Effects of pupil fragmentation will be investigated by extra widening of the spiders of the T152 telescope at OHP to match conditions of the ELT. Finally a second stage of extreme AO is planned to be added to the instrument in order to test innovative wavefront sensors and optimized control laws.

PAPYRUS : A pathfinder for ELT-PCS on GTC

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Abstract

The Provence Adaptive optics Pyramid Run System (PAPYRUS) is a pyramid-based Adaptive Optics (AO) system installed at the Coude focus of the 1.52m telescope (T152) at the Observatoire de Haute Provence (OHP). Imaging exoplanets and exoEarth with the ELT is a scientific grail, but also an instrumental challenge. Detecting the dimm light reflected by the planet among the huge flux coming from its host star, scrambled by the residual aberrations from the atmospheric turbulence, is the main challenge for the ELT second generation. It will require instrumental ingredients optimized toward this specific task, among which an high-contrast arm able to cancel the star light, a science instrument able to characterize spectrally the planet light, and an extreme AO system able to feed both previous systems with a well corrected wavefront. These ingredients must be facing the challenge of the ELT itself : a promising extreme angular resolution hidden in a complex environment (segmentation, non-kolmogorov aberrations and discontinuities, vibrations and windshake...). We propose in this paper to explore the interest of building a prototype of PCS on the large segmented Gran Telescopio Canarias (GTC) based on the PAPYRUS system recently installed at OHP. We explore the XAO scheme able to provide the best performance : optimised pyramid WFS, second stage AO, optimized control laws, and analyse its capabilities wrt the telescope environment. We base our analysis on the PAPYRUS performance measured on-sky. We analyse the science potential of such a system on a 10m telescope, in term of exoplanet spetral characterization and disk imaging.

Performance analysis of HARMONI SCAO system in the ELT telescope environment

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Abstract

The Extremely Large Telescope (ELT) is an astronomical observatory currently under construction. When completed, it is planned to be the world's largest optical/near-infrared extremely large telescope. Part of the European Southern Observatory (ESO) agency, it will provide unprecedented high angular resolution images (from 4milliarcsecond in visible to 12 milliarcsec in K band) and allow a harvest of science results one coupled to the instruments. Among the four ESO-ELT first light instruments, HARMONI will provide a large range of spectroscopic capabilities thanks to its integral field spectrograph with a spectral resolution covering from R = 3000 to R = 17000 and an angular resolution from 60 mas down to 4 mas. The ELT will only reach this diffraction limit when coupled to adaptive optics system. HARMONI provides two flavours of AO system : a Laser Tomographic AO and Single Conjugate AO systems, covering both large field and high performance. We present here the full end-to-end performance of the HARMONI SCAO system, coupled to the ELT. ESO provided a model of the telescope and its impact on the optical aberrations. This model includes contributors as low & high orders aberrations, main structure deformation, M1 segment phasing, vibrations, windshake due to wind load, but also non-kolmogorov terms (Low Wind Effect). We will study in this paper the behaviour and performance of the HARMONI SCAO system facing these contributors, and propose some workaround to improve the robustness and performance.

Performance analysis on wavefront prediction based on artificial neural networks.

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Abstract

The use of Adaptive Optics in large ground-based telescopes is necessary to improve the quality of the received images. Being able to correct the atmospheric disturbances in real time will allow us to reduce the uncertainties in the observations. In this work, we continue the studies in the application of Artificial Neural Networks to the prediction of atmospheric turbulences. Through the use of past information obtained by a Shack-Hartmann wavefront sensor, it is possible to predict the next frame captured by such sensor so the deformable mirrors in telescopes can be prepared beforehand to receive and correct the wavefront of the light coming from celestial sources. Nevertheless, in order to be ready to apply this technique in real telescopes, wavefront correction must work in small time intervals. Using the SOAPY simulation tool, we aim to improve the inference time of ANNs from previous studies over realistic simulations, reducing the possible quality loss. To achieve that goal, we will study the effects of different changes in the structure of the ANN, along with the performance of different machine learning libraries to help us to get the prediction as fast as possible.

Performance Evaluation of the Pyramid Wavefront Sensor for GPI 2.0

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Abstract

The Gemini Planet Imager (GPI) is a high-contrast imaging instrument designed to directly detect and characterize young, Jupiter-mass exoplanets. After six years of operation at Gemini South in Chile, the instrument is being upgraded and moved to Gemini North in Hawaii as GPI 2.0. As part of this upgrade, several improvements will be made to the adaptive optics (AO) system. This includes replacing the current Shack-Hartmann wavefront sensor (WFS) with a pyramid wavefront sensor (PWFS) and a custom EMCCD. These changes are expected to increase GPI's sky coverage by accessing fainter targets, improving corrections on fainter stars and allowing faster and ultra-low latency operations on brighter targets. The PWFS subsystem was independently built and tested in order to verify its performance before its integration into the GPI 2.0 instrument. Here, we will present the results from these pre-integration tests, which will include assessing the throughput, pupil image quality and linearity with and without modulation of the PWFS.

Performance of large-format deformable mirrors constructed with hybrid variable reluctance actuators III: laboratory measurements of dynamic behavior

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Abstract

Advancements in high-efficiency hybrid-variable reluctance actuators are an enabling technology for building the next generation of large-format deformable mirrors, including adaptive secondary mirrors. We present our performance results from laboratory bench testing of prototype large-format deformable mirror technology constructed by The Netherlands Organization for Applied Scientific Research (TNO). We overview how we achieved high-speed spatial measurements using the Quadrature Polarization Interferometer testbench located at the UC Santa Cruz Laboratory for Adaptive Optics combined with capacitive sensors internal to the deformable mirror. We report the dynamic performance of the TNO deformable mirror technology in the context of future use in high-contrast imaging systems.

Performance of the Fresnel Wavefront Sensor as a Function of Scintillation Strength

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Abstract

Local amplitude aberrations caused by scintillation can impact the reconstruction process of a wavefront sensor (WFS) by causing a spatially non-uniform signal at the pupil plane. The nonlinear curvature wavefront sensor (nlCWFS), also referred to as the Fresnel wavefront sensor (FWFS), has demonstrated the ability to precisely reconstruct wavefronts in the presence of scintillation, using amplitude aberrations to help inform the reconstruction process. The FWFS has been shown in previous work to also achieve better sensitivity compared to the Shack-Hartmann WFS (SHWFS) under low light levels. Building upon previous laboratory experiments and simulations, we present the results of laboratory testing to quantify the wavefront reconstruction performance of the FWFS compared to an equivalent SHWFS as a function of scintillation strength and relative input flux. Preliminary results and implications of the experiment are described.

Phasing the GMT in the Natural Guide star Adaptive Optics mode: from simulations to testbeds

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Abstract

One of the major challenges facing the Giant Magellan Telescope (GMT), which has a doubly-segmented primary mirror with a diameter of 25.4 meters, is achieving accurate and stable control of segment piston in the diffraction-limited adaptive optics (AO) observing modes, such as Natural Guide Star AO (NGAO) and Laser Tomography AO (LTAO). In the first part of this paper, we present NGAO bootstrapping simulations that start from a realistic initial state of GMT M1 and M2 segment misalignments and M1 figure errors, which have a wavefront RMS of approximately 100 microns. We demonstrate how multiple wavefront control loops, including Active Optics, Coarse Phasing, Adaptive Optics, and Fine Phasing, work together to reduce the wavefront error to the phased condition with an RMS of approximately 100 nm. To validate our wavefront sensing and control strategies, GMTO is collaborating with partner institutions to develop two laboratory optical testbeds. The Wide Field Phasing Testbed (WFPT), developed in collaboration with the Smithsonian Astrophysical Observatory, is currently being used to validate the Active Optics and Coarse Phasing aspects of wavefront sensing and control using a full-scale prototype of the GMT's Acquisition Guiding and Wavefront Sensor (AGWS) unit. Secondly, the High Contrast AO testbed (HCAT), developed in collaboration with the University of Arizona and INAF-Arcetri, will validate the Adaptive Optics and Fine Phasing aspects of NGAO control using a full-scale prototype of the pyramid wavefront sensor and the Holographic Dispersed Fringe Sensor (HDFS). In the second part of this paper, we describe the testbed models that we have developed to support the experiments, design tests and procedures, and predict testbed performances. We also discuss efforts to improve the models of the wavefront sensors to better match the characteristics of the prototypes, such as wavelength-dependent responses and optical fabrication errors.

Photon-to-Digital Converters for Wavefront Sensing

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Abstract

We are developing a new single photon counting detector technology based on the 3D assembly of Single Photon Avalanche Diodes (SPAD) onto CMOS electronics which renders a digital readout of the photon counts. In particular, we have developed a fast-timing Time-to-Digital Converter (TDC) readout in array with embedded advanced signal processing. We call this combination of SPAD, TDC and embedded processing a Photon-to-Digital Converter (PDC). A SPAD is an reverse biased photodiode set above its breakdown voltage. The arrival of a photon triggers an avalanche of current which is controlled by the quenching circuit next to the photodiode. In the case of a PDC, each SPAD has its own CMOS quenching circuit. The output of the quenching circuit provides a digital signal which is used to timestamp and process the photon. While SPADs benefit from cooling, they do not require it for operation. Each SPAD has a Time-to-Digital Converter (TDC) to precisely timestamp each photon with a resolution of 17.5 ps FWHM. Finally, the timestamps can be processed on-chip to reduce the large quantity of data to output. The processing can consist of timestamp sorting, skew correction, and others. PDCs offer a new dimension for wavefront sensing by measuring the timestamps of the incoming photons. Filtering and processing of incoming photons based on their timestamp, position, and correlation with external signals can increase wavefront sensing accuracy, therefore, leading to improved AO control and better delivered image quality. For example, in the case of the pyramid wavefront sensors, the timestamp can be correlated to the position in the modulation cycle, and using this information in the wavefront reconstruction process can lead to increased sensitivity. The paper will explain the functionality of PDCs and their possible operation as wavefront sensor.

Photonic phase correctors based on grating coupler arrays

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Abstract

Integrated optical devices are replacing bulk optics in IR astronomical instrumentation thanks to the growing field of astrophotonics, where miniaturization simplifies cryogenic control and enables multiplexability. Photonic spectrographs, beam combiners, and OH suppression filters have been reported in the literature with many undergoing on-sky testing and becoming facility instruments. Turbulence-induced distortions in light waves propagating through Earth's atmosphere limit the ability to couple them into single-mode fibers (SMFs) which is necessary for most photonic devices. These temporal and spatial distortions can be corrected by an adaptive optics (AO) system where deformable mirrors (DMs) and Shack-Hartmann wavefront sensors (WFSs) have been the preferred options to measure and apply the correction. However, photonic WFSs have recently been suggested to detect blind modes and non-common path aberrations (NCPAs), a limitation of pupil plane WFSs. Photonic wavefront correctors have also been used in experiments for satellite-to-ground free-space optical (FSO) communication. We propose a photonic integrated circuit (PIC) capable of coherently coupling the beamlets from the sub- apertures of a telescope pupil into an SMF. The PIC consists of a square array of grating couplers used to inject the light from free space into the plane of a single-mode waveguide in a chip. Resistive elements are used to alter the refractive index of a coiled section of the waveguides and shift the phase of the propagating modes. Consequently, the channels can be coherently combined, and the collected light can be delivered to an output SMF. In an AO system, the phase corrector would act as a DM commanded by a controller that takes phase measurements from a WFS. Simulations and proof-of-concept lab results are presented for a device capable of correcting 2×2 subapertures. Photonic phase correctors have smaller footprints and require less power than classical correctors. Depending on the design, they usually have larger strokes and can be driven faster than deformable mirrors. In very large telescopes (VLTs), and extremely large telescopes (ELTs), the multiplexability and flexibility of photonic phase correctors may be used in multi-object AO (MOAO) systems that feed multi-object spectrographs (MOSs).

PLICO: a framework for Adaptive Optics laboratory experiments

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Abstract

PLICO (Python Laboratory Instrumentation COntrol) is a framework for developing instrument control applications, such as the devices usually available in a scientific laboratory. Typical small laboratory experiments have 2-5 different devices that have to be controlled in a synchronized mode. To do this we decided to create a distributed framework that interfaces with the drivers provided by the device vendors and provides a user-friendly and standardized code at user level. The framework is entirely written in Python and based on a client-server model, using zeromq for message dispatching and pickle for data serialization and deserialization. The software architecture is designed to allow simple expansion of the server libraries with the introduction of new devices. The creation of the framework was a response to the need to use the instrumentation available in the Arcetri laboratories in a quickly and easily accessible format. It is available on Github where for each repository runs testing, pip upload, docs and codecov actions.

Poke: An open-source tool for modeling polarization aberrations in next-generation ground and space telescopes

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Abstract

Next-generation ground and space-based observatories aim to directly image and characterize Earthlike exoplanets in reflected light. This task requires tight constraints on the optical performance to maintain contrasts below 1e-7 in the infrared for the Extremely Large Telescopes (ELTs) and 1e-10 in the visible for a Habitable Worlds Observatory (HWO). A significant source of error for high-contrast imaging instruments on these telescopes are the aberrations induced by polarization. Polarization aberrations are a burgeoning issue for the astronomical community. However, we lack an open-source platform with which to study the polarization aberrations of next-generation observatories. Poke is an open-source polarization ray tracing (PRT) Python package that utilizes the Zemax OpticStudio API (ZOS-API) to compute polarization aberrations from ray traces of optical systems. We present a brief overview of Poke's simulation capabilities, including: Jones pupil computation from PRT data, multilayer thin film stacks, and interfacing with existing physical optics packages (POPPY, HCIPy). Poke has most recently been used in a study to analyze the polarization aberrations of the ELTs, where we quantified the degradation of coronagraphic performance due to polarization.

Polarization aberrations in next-generation Giant Segmented Mirror Telescopes (GSMTs)

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Abstract

Next-generation large segmented mirror telescopes are expected to perform direct imaging and characterization of Earth-like rocky planets, which requires contrast limits of 10^-7-10^-8 at wavelengths from I to J-band. One critical aspect affecting the raw on-sky contrast is the polarization aberrations (i.e., polarization-dependent phase and amplitude patterns in the pupil) arising from the reflection from the telescope's mirror surfaces and instrument optics. These polarization aberrations induce false signals for polarimetry that can be calibrated to a certain degree, but they can also fundamentally limit the achievable contrast of coronagraphic systems. As these aberrations affect the orthogonal polarization components in the

unpolarized light differently, these cannot be corrected by an adaptive optics system. Here, we simulate the polarization aberrations and estimate their effect on the achievable contrast for the three next-generation ground-based large-segmented mirror telescopes. We perform ray-tracing in Zemax to generate Jones pupils and analyze the impact of these aberrations on the contrast by propagating the Jones pupil maps through a set of idealized coronagraphs using hcipy. The optical modeling of the GSMTs shows that polarization aberrations create significant leakage through a coronagraphic system. The dominant aberration is retardance defocus, which originates from the steep angles on the primary and secondary mirrors and limits the contrast in the optical and near IR wavelength regions. The simulations also show that the coating plays a significant role in determining the strength of the aberrations. Polarization aberrations simulations will be beneficial while designing high-contrast imaging instruments for the next generation of extremely large telescopes.

Polychromatic optical gain tracking model with MKID-based pyramid wavefront sensor

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Abstract

The Pyramid Wavefront Sensor (PWFS) (Ragazzoni, 1996) is widely recognised as providing the best closed-loop performance for high contrast single conjugate adaptive optics (AO) systems, with many current and future AO systems selecting the PWFS as their primary natural guide star wavefront sensor. However, it is limited by its non-linear behaviour. Existing CCD/CMOS detector technology is well suited to PWFS operation, providing near-zero read noise detectors with frame rates of 1 - 3 kHz at either visible or near-infrared wavelengths. However, there is little scope for significant improvement in these detector technologies to further enhance PWFS AO performance and address non-linearities. Here we propose the use of a microwave kinetic inductance detector (MKID) (Day et al., 2003) array as an alternative PWFS detector technology and describe the benefits this can bring to future AO system performance. An MKID array is a superconducting detector with unique properties compared to CCD/CMOS detectors that provide a measure of the position, arrival time and energy of each photon incident on the array. Sorting the photons into wavebands allows us to measure the wavefront at multiple wavelengths simultaneously, providing additional information to overcome the limitations of the PWFS. In addition, photon counting becomes possible and new methods of reconstruction using temporal information can be explored. The manufacturing of MKID is flexible, allowing the user to enforce some of its different properties such as speed, energy measurement accuracy or the shape of the array according to the requirements. One of the current topics regarding PWFS limits is optical gain. Accurate tracking of these would improve PWFS performance and increase the contrast. In this presentation, we will demonstrate the advantage of using the wavelength sensitivity of the detector in optical gain (OG) tracking. Using an MKID-based PWFS simulation developed at Durham, we investigate the influence of wavelength, photon noise, modulation radius and Fried parameter (r0) on these gains. We show how wavelength information can be used to track the optical gain in real time and derive preferred device characteristics.

Prediction of AO corrected PSF for AOF NFM/SPHERE

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Abstract

Nowadays, the interest of the astronomical community in Point-Spread Function (PSF) reconstruction and prediction is growing exponentially since more and more instruments and scientific analysis routines require precise knowledge of PSF. Reconstruction is mandatory for scientific data analysis (image deconvolution, model fitting, etc.). At the same time, predicting PSF morphology is also instrumental for observational planning and exposure time estimation. Additionally, PSFs produced with the current- and future-generation Adaptive Optics (AO) facilities can serve as a valuable source of information that can be used for calibration, anomaly detection, petalling and low-wind effect measurements, etc. However, such AO-corrected PSFs have very complex PSF morphology, which recently became possible to realistically model using the progress made in the field (e.g., TIPTOP, PSFAO). In this study, we examine the TipTop and PSFAO models and apply them for PSF reconstruction and prediction within the scope of SPHERE and MUSE Narrow-Field Mode (NFM). We provide a comprehensive analysis of the accuracy of these techniques with both simulated and on-sky data and discuss the related limitations and challenges of these methods as well as address the ways to improve them. We propose machine learning-based approaches combined with mentioned analytical methods to provide a higher-quality PSF prediction framework. We also address the practical aspects of telemetry data extraction, reduction, and analysis, which are crucial for enabling robust PSF reconstruction and prediction.

Preliminary results of Pyramide Piston Sensor calibration

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Abstract

Measurement of a phase difference between the mirror segments is a crucial task that we face nowadays when it comes to telescopes with segmented mirrors. From different perspectives, we need to be able to obtain the phase difference in a precise way. We don't need the phase measurement only for the adaptive optics, but the measurement can be used for the initial co-alignment of the mirror after the maintenance, for example. At ESO, we built a Pyramid Piston Sensor test bench for testing methods of discontinuous phase measurements. The original research based on the experience with the GHOST bench was applied to the Pyramid Piston Sensor. The bench is equipped with a pyramid wavefront sensor with four facet pyramid and two different telescope simulators. The first telescope simulator emulates a segmented mirror using a Spatial Light Modulator. This telescope simulator is used for the calibration of the system. The other telescope simulator can host physical phase plates with known phase steps and is used for an actual measurement with the calibrated pyramid wavefront sensor. In this paper, we present the test bench and results of the calibration campaign along with the description of findings noted during the calibration of the pyramid wavefront sensor.

Progress on adaptive optics for astronomy in Key Laboratory of Adaptive Optics, Chinese Academy of Sciences

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Abstract

The Key Laboratory of Adaptive Optics, Chinese Academy of Sciences specializes in research of adaptive optics, including the theories study, devices manufacture, and system development. The recent progress on adaptive optics (AO) for astronomy are reported in this presentation. For astronomical observations, the recent AO systems developments for 4-meter night-time optical telescope, 1.8-meter solar telescope and the 1-m New Vacuum Solar Telescope (NVST) at Fuxian Lake Solar Observatory are presented respectively. The technological advancement, such as Laser Guide Star, Pyramid Sensor and Deformable Secondary Mirror, are also introduced.

Progress on deep-phase-retrieval Shack-Hartmann wavefront sensors for astronomical telescopes

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Abstract

Traditional wavefront reconstruction methods based on slope measurements limit the capability of Shack-Hartmann wavefront sensors to detect high-order aberrations. To ensure high signal-to-noise ratio sub-aperture spot images, the number of microlenses used to segment the wavefront in the Shack-Hartmann wavefront sensor is limited. For conventional wavefront reconstruction methods based on singular value decomposition or least-squares methods, it means that the number of reconstructed aberration modes is limited when the condition number of the reconstruction matrix is held in a relatively small range. We propose the Deep-Phase-Retrieval Wavefront Reconstruction (DPRWR) method to extend the Shack-Hartmann sensor's detection range of aberration modes under finite sub-apertures, at the same time improving the aberration detection accuracy. This method builds a nonlinear fitting model between Shack-Hartmann images and aberration mode coefficients by utilizing neural networks to mine more feature information in spot images. In this paper, the application limits, performance bounds, and robustness of this method were investigated in point source experiments. It was found that the aberration modes of about 3 to 6

times the number of sub-apertures can be measured by DPRWR with high accuracy when the full width of the spot at half height is higher than about 1 pixel and the bit depth is higher than 2-bit. Moreover, as regard to measuring the wavefront of extended scenes, an extended scenes-independent feature image extraction method is proposed to reduce the effects of object shape information on wavefront measurement. In combination with the DPRWR network, this method enables Shack-Hartmann sensors to obtain higher accuracy measurements of higher-order aberrations in extended scenes compared to the slope-based method.

Prototype Development of Scalable Adaptive Optics Real-Time Controller on Processor-based Platform

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Abstract

Adaptive optics (AO) is a technology to correct for the effects of atmospheric turbulence or optical aberrations. AO systems are typically composed of a wavefront sensor (WFS), a deformable mirror (DM), and a real-time controller (RTC). The RTC is responsible for measuring the distortions in the incoming wavefront from WFS and sending signals to the DM to correct for these distortions. We developed and demonstrated an AO RTC prototype on processor-based platform. Although Digital Signal Processor (DSP) and Field-Programmable Gate Array (FPGA) have been traditionally used as an RTC platform, processor-based platforms are being used as computer architecture supports high-performance computing technology and fast interfaces with low latency. Adaptive Optics RTC developed on the processor-based platform can easily not only connect various WFSs and DMs, and but also improve performance by increasing the number of processors or applying higher performance processors. We developed a prototype of the Scalable Adaptive Optics (AO) Real-Time Controller (RTC). It is based on the Shack-Hartmann Wave-Front Sensor (SHWFS) and supports adaptive optics system for both point source and extended source. Performance in terms of the speed of AO system depends on WFS and DM, but it supports the entire process with thousands of Hz performance, from receiving WFS image to controlling DM actuators. And AO RTC is designed to provide a web -based GUI to minimize the effects of analysis and control performance, and to control RTC and display information through HTTP.

PSF reconstruction from hyper-spectral AO science images - from VLT to ELT

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Abstract

Point-Spread Function (PSF) retrieval remains a key challenge in Adaptive Optics (AO) observations, and inadequate knowledge of the PSF sets a hard limit to deliver precise photometric and astrometric data, or to provide any information with a higher spatial resolution. The latter refers to deconvolution, where accurate PSF models are required to enhance low contrast features in the images. Deconvolution is highly sensitive to the input PSF and without an accurate PSF model, it is nearly impossible to perform this operation. Reference PSFs are not always available in the images, especially for observation of very crowded regions and extended sources. Our work aims to offer an operative solution to those who may not have access to a reference PSF and wish to obtain precise photometric, astrometric and enhanced spatial resolution for science observations. We recently introduced a significant improvement to such a PSF estimation process, by making use of the whole hyperspectral data cubes like one provided by MUSE. Our approach is based on blind-deconvolution (e.g. AMIRAL algorithm), which allows to estimate the PSF directly from the science observations. By first making use of an analytical PSF model that simplifies the PSF estimation process down to a few parameters, and then taking into account the known PSF variation across wavelengths, we significantly improve the statistical contrast (ratio between the number of available data (images) and the number of unknown to estimate), and eventually demonstrate accurate and robust PSF estimation directly from the science data. The PSF information can then be used for deconvolution, enhancing low contrast features in the observations. We illustrate our method with recent images of Ganymede and Callisto obtained with MUSE-NFM. We also show how this tool will be key for extended object observations from ELT-HARMONI.

PSI-Red v1.0 (SCALES)

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Abstract

The Planetary Systems Instrument (PSI) for the Thirty Meter Telescope (TMT) is comprised of 3 key modules: 1) an Adaptive Optics (AO) bench consisting of a large stroke, high actuator count 'woofer' Deformable Mirror (DM) and Wavefront Sensor (WFS) that is common to both the Red and Blue arms; 2) PSI-Red, covering 2-5 microns with a sophisticated suite of modular components based around a lenslet IFS coronagraph; and 3) PSI-Blue, covering 0.6 to 1.8 microns with its own suite of modular components including a 'tweeter' DM with its own WFS. An additional module is PSI-10, an 8-13 micron suite of modular components based around a lenslet IFS. The precursor to PSI-Red is currently being developed by UC Observatories, the Indian Institute for Astrophysics, and Durham University as SCALES (Slicer Combined with an Array of Lenslets for Exoplanet Spectroscopy). SCALES will operate in the mid-IR from 2 to 5 microns at the WM Keck Observatory where it will share a pyramid wavefront sensor with the HiSPEC instrument before being integrated with the remainder of PSI at TMT. Its fully cryogenic optical train uses a custom silicon lenslet array, selectable coronographs, and dispersive prisms and gratings to carry out integral field spectroscopy over a 2 arcsec field of view with low spectral resolution (50 to 200). A slicer module with a smaller field of view sits behind the lenslet array, allowing for medium spectral resolution (5000 to 10,000), which has not been available at the diffraction limit with a coronagraphic instrument in the mid-IR before. The opto-mechanical design takes advantage of modern diamond-turning materials and machining techniques with minimal risk and cost while delivering diffraction-limited performance both at Keck and TMT. Unlike previous IFS-based exoplanet instruments, SCALES is capable of characterizing cold exoplanet and brown dwarf atmospheres (

Pushing ELTs' sensitivity through PCA background subtraction

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Abstract

The thermal infrared is an important wavelength range for a wide variety of astronomical observations. At those wavelengths, the large ground-based telescopes, and in particular the ELTs reach higher angular resolution than space-based telescopes. However, their sensitivity is limited by the high thermal background due to both photon noise and imperfect removal of background structures from the sky and warm telescope optics. Developing more effective methods for the removal of spatially and temporally variable background structure is paramount for unlocking the full potential of existing and future large and extremely large ground-based telescopes operating at thermal-infrared wavelength. As recent studies have shown, the Principal-Component-Analysis (PCA) method can significantly improve the background subtraction compared to the more common method of subtracting the mean image from dedicated background exposure. We developed and optimized a background subtraction routine based on PCA. We used nulling-interferometric data from the Large Binocular Telescope Interferometer (LBTI) in the N band (11 μm). The LBTI connect the two aperture of the LBT to form the largest single-mount telescope in the word. This make the LBTI the best place to pioneer data reduction methods and procedures for future ELTs. We will present a comparison of classical (mean) and PCA background subtraction for both aperture photometry (mean retrieval and RMS) and high contrast imaging (contrast curves). The PCA background subtraction allows for improvement factors of two to three for both observing techniques. This will allow for improving the sensitivity of suitable, existing data by the same factors. More importantly, it will reduce by a factor five to ten the extremely valuable integration time required to detect a faint source with future ELTs!

Pyramid wavefront sensing developments at NRC-HAA

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Abstract

Many next generation adaptive optics (AO) systems, on both 10-m class telescopes and future giant segmented telescopes, plan to incorporate a pyramid wavefront sensor (PWFS) to achieve their performance requirements. As a non-linear wavefront sensor (WFS), different strategies have been proposed to ensure the optimal operation of the PWFS on-sky including various non-linear reconstructors and optical gain calibration/tracking algorithms. Since many of the instruments being developed at NRC-Herzberg contain a PWFS, we are re-establishing a PWFS testbed. We present the design for the AO WFS bench and first light results of the PWFS arm of the bench. Using this new testbed in the AO laboratory, we will explore optical gain calibration using the gain scheduling camera (V. Chambouleyron et al, 2021) as well as more exotic ideas to improve the PWFS such as time-resolved wavefront sensing (J. Véran et al 2022). We also present details about the synchronization of the modulation mirror and camera for high-speed operations while supporting dithering. A key design of the bench is the portability of the PWFS arm such that it can be ported to NRC-Herzberg's on-sky AO system, REVOLT, for on-sky testing of the PWFS with the HEART real-time-controller being developed locally. We will present results towards operating the PWFS on REVOLT.

Pyramid wavefront sensor with laser guide star: Photon noise and convolutional model

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Abstract

The new generation of Extremely Large Telescopes (ELTs) will be dependent on artificial laser guide stars (LGS) for their adaptive optics correction systems, given the lack of enough natural guide stars (NGS) to have a good sky coverage. Due to their large mirror diameter, and the cilinder-like structure of the artificial sodium laser stars, instead of having a point source as reference, the image of the artificial star is a 3D object more than three hundred times wider than a diffraction limited spot and over five thousand times larger. On an 80x80 Shack-Hartmann wavefront sensor (SH) for a 40 meter telescope, the laser spot is four times wider and as much as sixty times larger than a diffraction limited spot. This extension means that the SH's detector needs to have a large amount of pixels (e.g. 1600x1600), making it slow and noisy. Given the difficulties of the SH, the Pyramid wavefront sensor (PWFS) has been proposed as an alternative, given its higher sensitivity and lower demand on pixels, as an equivalent 80x80 PWFS would need a detector no bigger than 240x240 pixels, making it possible to use fast, low noise detectors. One of the problems with the PWFS is the depth of focus of the telescope. As the sodium layer where the LGS is generated is about 20 km thick, and the laser beam has a width of 1 arc-second, different portions of the LGS reach the pyramid with different tip, tilt and focus coefficients, hindering the measurements of the atmospheric disturbances. In this work, a study of closed loop operations was made to compare the performance of the PWFS for different sources: NGS, LGS FWHM spot on sky (1 arcsec spot with no thickness)(LGS-SOS) and LGS, and different telescope sizes: 8, 16, 24 and 40 m. The main focus of this research was to test the influence of photon noise in closed loop operation and to compare the end to end (E2E) results with predictions using linear models. To do this, a new method of simulating Fourier filtering wavefront sensors (FFWFS) with LGS was developed, which speeds up the computation over sixty times when compared to traditional methods. Also, a convolutional model (CMod) was validated and then implemented to further speed up the simulations. We found that using the CMod we could compute the interaction matrix (iMat) for every source up to one thousand times faster than compared to the E2E method, allowing us to estimate the photon noise sensitivity and optimize the reconstructor matrix for each case. Then, comparing the E2E closed loop simulations to the sensitivity analysis we found a good agreement, meaning that it is possible to estimate the performance of the AO system by only computing the iMat using the CMod and not having to do all the E2E simulations. Finally, we found that the limiting magnitude for a LGS does not increase as the telescope gets bigger, and the main contributor to the lost sensitivity is the width of the laser, rather than the thickness of the sodium layer.

Recent progress of astronomical piezoelectric deformable mirror technologies at IOE, CAS

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Abstract

Institute of Optics & Electronics (IOE), Chinese Academy of Sciences (CAS) has about 40 years experiences on piezoelectric deformable mirror (DM) technologies research and developing since early 1980s. Several piezoelectric DMs of IOE, CAS have been used in many different application systems. A brief history of piezoelectric DMs development at IOE and several recently achievements, and the main characters, performance and test results of these DMs will be presented in this paper: 1.Wide temperature range deformable mirror. Since 2014, according to the actual testing of piezoelectric actuator characters-temperature relationship and mirror surface error-temperature relationship, an improved structure scheme of wide temperature range DM was proposed. A wide temperature range DM, which could be used in the range of -20■ to 40■ has been fabricated and tested; 2. Piezoelectric deformable secondary mirror. The 73-piezoelectric deformable secondary mirror prototype was docked with 1.8m telescope to obtain its first light. Since 2018, the 1.8m telescope's new piezoelectric deformable secondary mirror with 241 actuators has been developed. The new piezoelectric deformable secondary mirror had been integrated with the telescope in early 2022. In addition, another piezoelectric deformable secondary mirror with 439 actuators for the 1.8m solar telescope (China Large Solar Telescope) has being developed since 2020. It will be integrated with the telescope in mid – 2023; 3.High density deformable mirror. In recent years, high-density deformable mirrors have been widely used in optical communication, retinal imaging, astronomy and other fields. In order to meet the requirements of future extreme large telescopes, a high density deformable mirror prototype with 6400 actuators has been fabricated and tested since 2019.

Reference-star differential imaging on SPHERE

Xie chen [1], Choquet elodie , Vigan arthur , Cantalloube faustine , Benisty myriam , Boccaletti anthony , Bonnefoy mickaël , Desgrange célia , Garufi antonio , Girard julien , Hagelberg janis , Janson markus , Kenworthy matthew , Lagrange anne-Marie , Langlois maud , Menard françois , Zurlo alice

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Abstract

As the primary technique in high contrast imaging, angular differential imaging (ADI) is limited by the self-subtraction effect, which lowers its sensitivity to exoplanets at short angular separations (e.g.,

Results from the Harmoni Laser Guide Star wavefront sensor prototype

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT that will be on sky on 2029. To prepare the final design of the Laser Guide Star Sensors (LGSS), we have developed since few years a full scale prototype of the LGS wavefront sensors implemented in an optical bench to simulate the laser guide star and the turbulence. The WaveFront Sensor (WFS) is a classic Shack-Hartmann that has to sense the wavefront of an ELT (39m pupil diameter). Our prototype is composed of 80x80 double side microlens array, a 6 lenses optical relay to reimage the light coming from the microlens on the detector, and a CMOS camera using a SONY detector with 1608x1104 pixels, RON < 3e- at a frame rate of 500Hz. The choice of the sensor has been motivated by the large number of pixels to provide a field of view larger than 15 arcsec per surbaperture. Our bench has the particularity to use a Spatial Light Modulator (SLM) to emulate the M4 deformable mirror (DM) and its actuators geometry and the atmospheric turbulence. We present our study of the wavefront sensing with this prototype: we show that there is no limitation to use a relay between the microlens array and the detector, the behaviour of the wavefront sensor is similar as more classic components. In addition, we present our implementation of elongated laser spots on the bench. They are used to better understand the effect of elongated and truncated spots on the wavefront sensing (possible presence of bias, impact of stray light, wavefront sensing algorithm on elongated spots, etc). The bench is implemented to mimic the HARMONI LGS AO loop and to validate and optimise the algorithms that will be used on the instrument, in particular the super-resolution concept.

RISTRETTO at the VLT: a pathfinder for ELT-ANDES and ELT-PCS

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Abstract

RISTRETTO is a visible high-resolution spectrograph fed by an extreme adaptive optics (XAO) system, to be proposed as a visitor instrument on ESO VLT. The main science goal of RISTRETTO is the detection and atmospheric characterization of exoplanets in reflected light, in particular the temperate rocky planet Proxima b. RISTRETTO will be able to measure albedos and detect atmospheric features in a number of exoplanets orbiting nearby stars for the first time. It will do so by combining a high-contrast AO system working at the diffraction limit of the telescope to a high-resolution spectrograph, via a coronagraphic 7-spaxel integral-field unit (IFU) feeding single-mode fibers. Further science cases for RISTRETTO include: the study of accreting protoplanets such as PDS 70 b & c through spectrally-resolved H-alpha emission; the kinematics of protoplanetary disks through scattered-light Doppler velocimetry; and spatially-resolved studies of Solar System objects such as icy moons and the ice giants Uranus and Neptune. The project is in an advanced design phase for the spectrograph and IFU/fiber-link sub-systems, and a preliminary design phase for the AO front-end. Construction of the spectrograph and IFU/fiber-link has just started. RISTRETTO is a

pathfinder instrument in view of similar developments at ESO ELT, in particular the SCAO-IFU mode of ANDES and the future PCS instrument.

RISTRETTO: reaching 1E-4 fiber contrast at 2lbd/D in the visible

Blind nicolas [1], Lovis christophe , Shinde muskan , Chazelas bruno , Kuhn jonas

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Abstract

RISTRETTO is a visible, single-mode fiber-fed, High Dispersion Corongraphic instrument for the VLT. Its main target, Proxima b, defines most of the requirements on the Front-End, which are: 1) Planet coupling into SMF at 2 lbd/D > 50%; 2) Average coupling of the star on the planet fiber < 1E-4. We first present our baseline design, which primarily consists in a single-stage 40x40, 2kHz XAO and a modified version of the Phase Induced Amplitude Apodizer as part of a 7-spaxels coronagraphic IFU. We will also present first prototyping activities to demonstrate feasibility of the coronagraphic IFU, as well as a first optical design of the Front-End.

SAXO+ upgrade : second-stage AO system end-to-end numerical simulations

Goulas charles [1], Vidal fabrice [1], Galicher raphael [1], Mazoyer johan [1], Ferreira florian [1], Sevin arnaud [1], Boccaletti anthony [1], Béchet clémentine [2], Tallon michel [2], Langlois maud [2], Chauvin gaël [3], Milli julien [3], Gendron eric [1]

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Abstract

SPHERE+ is a proposed upgrade of the SPHERE instrument on the ESO's Very Large Telescope. It will improve the detection and characterization capabilities of young giant planets. It includes an additional second-stage adaptive optics (AO) system composed of a dedicated near infrared wavefront sensor (WFS) and a deformable mirror (DM). This second stage will remove the residual wavefront errors left by the actual primary AO loop (SAXO). This paper is focused on the numerical simulations of the second stage (SAXO+) and concludes on the impact of the main AO parameters used to build the design strategy. To run these simulations we use COMPASS, an end-to-end AO simulation tool. COMPASS was modified to handle the temporal asynchronism of the two stages. It was also improved to simulate the hybrid wavefront sensing capabilities, namely a Shack-Hartmann for the first stage and a pyramid for the second one. A dedicated coronagraph module was implemented in order to produce coronagraphic images and quantify the system performances with contrast ratios. We present the simulation results in terms of raw contrast curves and compare them to the actual SAXO system. The explored parameter space includes turbulence conditions, star magnitudes and SAXO+ relevant design parameters. The key system choices addressed in these results are the AO control strategy (integrated or stand alone solution), the RTC frequency, the DM choice, WFS

calibration parameters, and photon sharing. We show an improvement of a factor 10 in raw contrast compared to the current system. In the future, a focal plane wavefront control loop will be added to the simulation to minimize the speckles intensities on the coronagraphic images.

SAXO+: Status update of the current design study.

Vidal fabrice [1], Boccaletti anthony [1], Diolaiti emiliano [2], Ferreira florian [1], Langlois maud [3], Loupias magali [3], Mazoyer johan [1], N'diaye mamadou [4], Rousseau sylvain [4], Stadler eric [5], Tallon michel [3], Wildi françois [6], Béchet clémentine [3], Chauvin gaël [4], Feldt markus [7], Galicher raphael [1], Gendron eric [1], Goulas charles [1], Gratton raffaele [8], Kasper markus [9], Kulcsar caroline [10], Mouillet david [5], Raynaud henri Francois [10], Schreiber laura [2], Tallon-Bosc isabelle [3], Milli julien [5], Thiébaut eric [3]

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Abstract

SPHERE+ is a proposed upgrade of the SPHERE instrument at VLT, which will boost the current performances of detection and characterization of exoplanets and disks, and will serve as a demonstrator for the future planet finder (PCS) of the European ELT. The upgrade aims at improving the raw contrast closer to the optical axis and enabling observations of currently inaccessible fainter near infrared stars. The contrast gain improvement will be made possible thanks to a second-stage Adaptive Optics (AO) system (hereafter SAXO+) running at a fast frame rate (2-3 kHz), in addition to the operating first stage system (SAXO). We focus in this paper on the SAXO+ design study which is currently on-going. We present the AO strategy, hardware choices (wavefront sensor, deformable mirror...), real time and software implementation in the context of an already constrained VLT environment. We present the foreseen SAXO+ RTC design using GPU accelerated devices based on the COSMIC platform solution. We focus on the so-called 'integrated strategy' which must be interfaced to the current SAXO real time hardware (HODM and VIS WFS) and discuss the challenges and solutions of such an invasive approach. We expose the AIT plan in Europe and present how it can cope with a simulated first stage hardware together with a comprehensive strategy once the instrument will be shipped to Paranal. We finally conclude on the implementation of a 3rd focal plane loop that will minimize the uncorrected quasi static speckles using the latest state-of-the art dark hole techniques and how it will be embedded into the overall SAXO+ correction strategy.

Science test cases benchmark simulations of the SPHERE XAO system towards SPHERE+ high contrast performances

Langlois maud [1 2], Béchet clémentine [2], Schrieber laura [3], Goulas charles [4], Tallon michel [2], Vidal fabrice [4], Ferreira florian [5], Milli julien [6], Loupias magali [2], Kulcsar caroline [7], Dinis isaac , Thiébaut eric , Raynaud henri Francois , Mazoyer johan , Tallon-Bosc isabelle , Feldt markus [8], Galland nicolas , Ndiaye mamadou [9], Stadler eric , Boccaletti anthony , Chauvin gael [9], Diolaiti emiliano , Gratton raffaele , Wildi françois [10]

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Abstract

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) is a European Southern Observatory exo-planet imaging instrument installed on the 8m Very Large Telescope at Paranal (Chile). It has been operating for over 8 years since its commissioning in 2014. The SPHERE+ project proposes an upgrade of this existing system to expand its science objectives. In particular, the current XAO system (SAXO) main update will consist in the addition of a second stage of correction using a pyramid wavefront sensor operating at near infrared wavelengths. The second stage will take advantage of the fact that the residual phase of the first stage will be already partially corrected and will run at a nominal frequency three times faster than the existing XAO system. As a part of the design process for this new XAO system, we performed E2E XAO simulations using both COMPASS and PAOLA. The numerical simulations are essential in the first place to determine the optimal design for the hardware configurations and the controllers of the considered high contrast instruments and then to estimate their corresponding performance. After refining the current SAXO system parameters we validated its simulated performances (Strehl, PSF profile, contrast) by comparing them to a large selection of on sky data both with and without coronagraph at wavelengths ranging from 0.7 to 2.3 microns. This SAXO study increases the reliability of our E2E models and thus mitigates the risk of incorporating a second stage system onto SAXO. Using the same science cases we perform SAXO+ E2E and analytical simulations including coronagraph, which we will also describe in this presentation. Such well-calibrated benchmark study under identical boundary and parameter conditions provides quantitative comparison of the strengths and weaknesses of the different control methods. Beyond SPHERE+, this is also important for the future high contrast instruments.

Second stage Adaptive Optics with double Zernike mask for future Extreme Adaptive Optics systems on Extremely Large Telescope : theory, simulation and experimental validations

Cisse mahawa [1 2], Chambouleyron vincent [3], Fauvarque olivier [4], Levraud nicolas [2 5 6], Sauvage jean-François [2 5], Neichel benoit [2], Bond charlotte [7], Fusco thierry [1]

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Abstract

The next generation of Extremely Large Telescopes (ELT) will provide high angular resolution and broad sky coverage allowing astronomers to study very faint object such as exoplanets. To do this, an Extreme Adaptive Optics (XAO) systems is required. The Single-Conjugated Adaptive Optics systems of the ELT will be equiped of a Pyramid wave-front sensor, allowing to highly mitigate the atmospheric turbulence. However, a second correction stage is needed to further reduce the AO residuals down to a level compatible with high-contrast performance and to correct the aberrations induced by the telescope itself such as Low-Wind Effect or differential piston. This two-stage correction will provide high angular resolution and allow the coronagraph to increase the contrast and image planets closer to their host stars. To reach this requirement, the second stage has to provide a very fast correction, leading the wave-front sensor (WFS) of the second stage to be as sensitive as possible. For this reason we are considering a Zernike wave-front sensor (ZWFS) as the ideal WFS for this task. Yet high sensitivity in the case of the ZWFS comes at the cost of a small dynamic range. To counterbalance this small dynamic, we combine two Zernike masks in order to double the linearity range of the classical ZWFS. This dual ZWFS with its higher dynamic range and still high sensitivity will increase the efficiency of the AO correction. First, we present a full theoretical description of this double Zernike mask with its characteristics. We will focus on its ability to both measure phase residuals and phase discontinuities such differential piston in the ELT case. We will then present an End-to-End simulation of this two-stage AO system and its performances. To that end we will run a full two-stage correction with a first stage dedicated to the turbulence correction with a modulated Pyramid and the dual ZWFS as the second stage WFS. Finally, we will present the first experimental results of this two-stage AO system obtained on the LOOPS bench. The optical set-up of the cascade AO system for the PAPYRUS bench will also be presented.

Seeing-limited integral field spectroscopy as the tool to simply estimate the outer scale parameter of the atmospheric turbulence

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Abstract

The image quality performed by ground-based large telescopes is frequently better than envisioned from DIMM-measured seeing. This improvement is one of the effects of a finite outer scale (L0) on the wavefront of the light propagating through atmospheric turbulence. Moreover, finite L0 also impacts the wavelength dependence of the full width at half maximum (FWHM) of point-like sources in long-exposure observations, deviating from the natural wavelength dependence of the seeing (lambda^-1/5). Seeing-limited integral field spectroscopic (IFS) data allows checking the FWHM wavelength variation for long-exposure observations by recovering narrow-band filter images of point-like sources. These images are observed homogeneously under the same instrumental and atmospheric conditions. Deviations of such FHWM(lambda) from the natural seeing provide an approach to the L0 during the IFS observation. We present the analysis of FWHM with lambda for point-like sources obtained from the Multi Unit Spectroscopic Explorer (MUSE) in the Wide Field Mode to approach the atmospheric outer scale at the Paranal observatory.

Segment piston estimation using sequential phase retrieval

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Abstract

The Giant Magellan Telescope (GMT) consists of seven 8.4-m diameter circular segments in a petal pattern to create a telescope with an effective diameter of 25.4 m. The Laser Tomography Adaptive Optics system for the GMT uses a Shack-Hartmann Wavefront Sensor guiding on six laser guide stars (LGSs) to measure high-order wavefront aberrations. LGS-based adaptive optics systems also require one or more tip-tilt sensors, since the LGSs affected by tip-tilt errors on the uplink. The wavefront errors also contain segment piston, which can be induced by the atmosphere or the telescope. If the tip-tilt sensor is a Nyquist sampled imager, we can use phase retrieval to measure discontinuities in the wavefront at the full frame rate of the tip-tilt sensor. Two existing algorithms, Gerchberg-Saxton and the Fast & Furious algorithms, are adapted for this purpose. We describe both algorithms in detail, and demonstrate using end-to-end simulations that phase retrieval can be used to measure segment piston and thus improve the delivered image quality over a range of operating conditions.

Segmented pupils and wavefront reconstruction noise propagation for PWFS

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Abstract

In this contribution we analyze the process of wavefront reconstruction over a segmented pupil with particular attention to the case of the pyramid sensor. The study considers different ways of representing the wavefront over the segmented pupil, especially whether to use independant bases for each segment, or a global base capturing all the segments. Using numerical simulation, we analyze each case in terms of noise propagation through the wavefront reconstruction process and evaluate the influence of key parameters such as the pyramid wfs modulation and the wfs bandwidth. Finally the study briefly considers the conventional SH sensor and compares the behavior of the two sensors.

Sequential coronagraphic focal-plane wavefront sensing and control

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Abstract

Coronagraphs are sensitive to low-order aberrations, with performance rapidly degrading with small amounts of wavefront error. Low-order aberration control (including pointing control) at the coronagraphic focal plane is key to attaining optimal performance. Several algorithms have been developed that can control such aberrations, though they require phase diversity techniques (meaning reduced science uptime) or are developed for particular coronagraphic architectures. We present two new methods, an analytical and machine-learning approach, that are based on sequential phase diversity techniques. The analytical method works with all optical systems with even symmetry, and the machine-learning approach works without any symmetry assumptions. Both algorithms do not require dedicated diversity frames, meaning high science uptime. We present simulation and preliminary benchtop implementation.

Shack-Hartmann wavefront sensor design for strong scintillation conditions

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Abstract

In the case of an optical link with a LEO satellite, it is crucial to maximize the duration of the downlink, even at low elevations, in order to transfer the largest amount of data possible at each pass. However, in this context, amplitude fluctuations (or scintillation) are challenging the operation of Adaptive Optics (AO) systems, starting with its wavefront sensing function. Indeed, low elevations implies being in the strong perturbation regime as the propagation distance through turbulent atmosphere layers increases with zenithal angle, causing log-amplitude variance to reach saturation, i.e. with propagation conditions beyond the Rytov's approximation [1]. In the case of a Shack-Hartmann Wavefront Sensor (SHWFS), scintillation induces a wide intensity range across the pupil resulting in some subapertures being saturated and other being extinguished (cf. Figure). Besides, when the intensity distribution is non-uniform in a given subaperture, the slope measurement is shown to be biased [2]. Moreover, some subapertures point-spread functions suffer from diffraction-induced deformations making it difficult to compute the centroids and hence to obtain accurate slope measurements. We have performed propagation simulations through strong perturbations considering Cn^2 profiles with ranging from 4cm to 1cm, and ranging from 0,08 to 0,9. Such diversity enabled us to progressively leave Rytov's regime, and observe the effect of increasing scintillation. We then study the effect on wavefront sensing accuracy of the complex amplitude sampling by the subapertures grid. We compare three SHWFS configurations featuring increasing number of subapertures, in presence of scintillation, considering noise sources and detector dynamic range. We highlight the improvement brought by oversampling the SHWFS in comparison to usual designs. Finally, we present a noise propagation model on

the phase reconstructed from SHWFS data. References [1] Tatarski, V. I. (2016). Wave propagation in a turbulent medium. Courier Dover Publications. [2] Mahe, F., Michau, V., Rousset, G., & Conan, J.-M. (2000, November). Scintillation effects on wavefront sensing in the Rytov regime. In Propagation and Imaging through the Atmosphere IV (Vol. 4125, pp. 77-86). SPIE. https://doi.org/10.1117/12.409307

SHARK-NIR, first results of the commissioning at LBT

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Abstract

SHARK-NIR is an instrument which provides direct imaging, both coronagraphic and non-coronagraphic and with the possibility to perform dual-band imaging and low-resolution spectroscopy in Y, J and H bands, with the main scientific goal of detecting exoplanets, and characterizing already known planets, young stellar systems, jets and disks. SHARK-NIR takes advantage of the excellent performance of the Large Binocular Telescope AO systems, the wavefront sensors of which have been recently upgraded to SOUL. The latter is delivering a very good performance also at faint magnitude, opening to science otherwise difficult to be achieved, as for example AGN and QSO morphological studies. To fully exploit the just mentioned science cases, binocular observations will be performed using SHARK-NIR in combination with SHARK-VIS (operating in B, V, R and I bands) and LMIRCam of LBTI (operating from K to M bands), in a way to exploit coronagraphic observations in three different wavelengths. The instrument has passed the preliminary acceptance Europe in March 2022, being shipped immediately after at LBT, and re-integrated, installed and characterized daytime in three pre-commissioning run at the telescoped. SHARK-NIR had a very successful first light in January this year, and we will report of the results obtained in the three commissioning runs performed in the first half of 2023.

Simulating METIS' SCAO System

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Abstract

METIS, the Mid-Infrared ELT Imager and Spectrograph is one of the four first-generation ELT instruments scheduled to see first light in 2028. Its two main science modules are supported by an adaptive optics system featuring a pyramid sensor with 90x90 subapertures working in H and K-band. During the PDR and FDR phases, extensive simulations were carried out to support the sensing, reconstruction, and control concept of METIS SCAO. We will present details on the implementation of the COMPASS-based environment used for the simulations, the metrics used for analysing our performance expectations, an overview of the main results, and some details on special cases like NCPA and water vapor seeing, the low-wind-effect, the impact of METIS' CFO apodizer, and residual dispersion stemming from METIS' static ADCs.

Simultaneous Control of the Segmented Primary Mirror and Adaptive Optics System with a Pyramid Wavefront Sensor

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Abstract

The phasing of the primary mirror is one of the most critical aspects to the operation of the extremely large class of segmented telescopes. The Thirty Meter Telescope (TMT) and European Extremely Large Telescope (E-ELT) will consist of hundreds of segments which must be phased together to act as a single aperture, and maintaining this phasing through operation will regulate the quality of the wavefront through the rest of the system. The current designs for the TMT and E-ELT primaries utilize sophisticated systems of thousands of edge sensors that will measure the pairwise displacements of each segment, similar in principle to the control scheme for the segmented W. M. Keck telescopes. However, a drawback of these systems is their inability to directly measure the phase of the primary during operation. Indirect measurements of the phasing in the Keck primary estimated static phase aberrations on the order of 60nm rms, which were not detected in the edge sensors. Therefore, we propose incorporating sensing and control feedback of the primary mirror via the adaptive optics system, as a Controllable Segmented Primary (CSP), in order to actively and consistently track its phasing. In simulations of the Keck AO system, we are able to simultaneously monitor the CSP surface and also operate the adaptive optics system using a single shared pyramid wavefront sensor in a closed low-bandwidth loop. By updating the primary segments with the measurements from the PyWFS, we can decrease the phase aberration across the primary by approximately 50%, resulting in a 15% increase in the achievable Strehl. In this work, we discuss the use cases of the CSP methodology in regard to ELT-class telescopes.

Simultaneous wavefront sensor and coronagraph dark hole calibration: real time optical gain tracking with incoherent focal plane speckles

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Abstract

Imaging exoplanets on next-generation extremely large telescopes requires adaptive optics (AO) fed coronagraphs that are exceptionally well calibrated with well-understood control loops. Current wavefront sensing (WFS) and control systems have become sensitive enough to expose an imperfect relationship between the applied corrections. This relationship, known as optical gain, is seen to drift throughout the night due to non linearities and signal loss due to low strehl. Unaddressed, optical gain is an additional unknown in the correction loop and degrades all possible WFS telemetry use-cases (e.g. real time correction speeds, NCPA offsetting capabilities, PSF reconstruction, telemetry based predictive control, and high performance correction at small working angles) due to lower controller gain or incomplete wavefront reconstruction. We will report on a method for characterizing and tracking optical gain in coronagraphic ExAO systems non-destructively. Focal plane speckles can be produced by applying a high frequency sine wave in addition to Deformable Mirror (DM) commands. This reproduces copies of the central star's PSF unobstructed by the coronagraph at the focal plane. When the induced sine wave is given a 90 degree phase offset above the Nyquist sampling rate of the WFS, it no longer interferes with the atmospheric speckles resulting in clearer PSFs for astrometric and photometric calibrations in post processing. This procedure, which is common in high contrast imagers, leaves a consistent high spatial-frequency pattern on the WFS. This existing pattern is perfectly suited to track drifts in optical gain over time without degrading potential coronagraphic dark holes. We propose to use the WFS speckle signal to characterize and track discrepancies between sensed and applied modes. Here we show preliminary results of this optical gain tracking technique as used on the MagAO-X system and discuss how this will be applied to GMagAO-X, and other high-sensitivity AO systems of future telescopes. This work will enable extreme WFS systems of the next-generation to meet their full potential.

Single detector stereo-SCIDAR at the 2.3 m Telescope at Siding Spring Observatory

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Abstract

Site characterisation for atmospheric turbulence analysis is crucial for the development and design of adaptive optics systems, especially for systems for extremely large telescopes. There are many seeing monitors and optical turbulence profilers. Seeing monitors such as the Differential Imaging Motion Monitor (DIMM) often have a simpler design and smaller telescope requirements than optical turbulence profilers at the expense of height resolution limitations and are only able to provide seeing measurements integrated over the entire atmosphere above the instrument, but cannot provide a detailed height resolved atmospheric turbulence profile. Other more complex instruments such as the Multi-Aperture Scintillation Sensor (MASS), Slope Detection and Ranging (SLODAR) or generalised Scintillation Detection and Ranging (SCIDAR) require larger telescope apertures and more complex setups, but can yield a more spatial and time resolved atmospheric turbulence profile. The generalised SCIDAR technique suffers from signal limitation due to its optically overlapping pupil images. This can be overcome with stereo-SCIDAR by separating the pupil images optically making the opto-electronic setup more complex and expensive as two scientific cameras are required to record the optically separated pupil images. Furthermore, as site testing campaigns are expensive to run at large telescopes, there are few campaigns that have been conducted frequently for an extended period of time to reliably investigate detailed seasonal changes. To overcome some of these challenges, the Advanced Instrumentation and Technology Centre of the Research School of Astronomy and Astrophysics at the Australian National University has designed, built and operated a single-detector generalised stereo-SCIDAR. The instrument was commissioned on the 2.3 m Telescope at Siding Spring Observatory in April 2022 and has been operated every month for a year. In this paper, we present the design of the single-detector generalised stereo-SCIDAR instrument as well as the preliminary results of data evaluation focussing around the system's capabilities and the seasonal changes of the atmospheric turbulence patterns at Siding Spring to showcase its potential for site characterisation at other astronomical sites in the world.

SOUL at LBT: commissioning results, science and future.

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3 - Large Binocular Telescope Observatory [Tucson](United States)
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Abstract

The SOUL systems at the Large Bincoular Telescope can be considered as pathfinders for the ELT SCAO systems, bringing together key techncologies as EMCCD, Pyramid WFS and adaptive telescopes. After the first light of the first upgraded system on September 2018, going through COVID-19 and technical stops, we have now all the 4 systems working on sky. Here, we report about the results of the commissioning work, aimed to reach the nominal performances together with reliability for an optimal scientific production. The SOUL upgrade allows now to correct more modes in the bright end and increses the sky coverage on the faint end, opening to extragalcatic targets. Finally, we will shortly review the first astrophisical results, looking forward to the next generation of instuments (SHARK-NIR, SHARK-Vis and iLocater), to exploit the SOUL WF correction.

Sparse Aperture Masking with the ELT: lessons learnt from the VLT/SPHERE instrument

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Abstract

Sparse Aperture Masking (SAM - a.k.a Non-Redundant Masking, NRM) consists in inserting a pupil-plane mask with several apertures in a non-redundant configuration. This mode transforms the single-dish telescope pupil into an set of sub-pupils to be treated as a Fizeau interferometer. This observing mode brings a unique discovery space by improving the angular resolution by a factor 2, at a cost of a lower sensitivity. We used the SPHERE high-contrast instrument currently installed at the VLT to characterise the limitations of its SAM mode with extrem AO simulated data, internal source data and on-sky data. This analyses took into account the lessons learnt from the high-contrast limitations diagnosed beforehand. As two of the ELT first light instruments (namely METIS and MICADO) will include a (non publicly offered) SAM mode, we extrapolated this work to the capabilities of the SPHERE SAM mask with an ELT-like AO system. This work gives information on the consequences of missing M1 segments and large spider width on the ELT.

Spectroastrometry and Imaging Science with Photonic Lanterns on Extremely Large Telescopes

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3 - California Institute of Technology(United States)
4 - The University of Sydney(Australia)
5 - Subaru Telescope(United States)

Abstract

Photonic Lanterns (PLs) are tapered waveguides that gradually transition from a multi-mode fiber geometry to a bundle of single-mode fibers. In astronomical applications, PLs can efficiently couple multi-mode telescope light into a multi-mode fiber entrance and convert it into multiple single-mode beams. The output beams are highly stable and suitable for feeding into high-resolution spectrographs or photonic chip beam combiners. For instance, by using relative intensities in the output cores as a function of wavelength, PLs can be utilized for spectroastrometry. In addition, by interfering beams in the output cores with a beam combiner in the backend, PLs can be used for high-throughput interferometric imaging. When used on an Extremely Large Telescope (ELT), with its increased sensitivity and angular resolution, the imaging and spectroastrometric capabilities of PLs will be extended to higher contrast and angular regimes. We study the potential spectroastrometry and imaging science cases of PLs on an ELT, including study of close-in extrasolar planetary systems, exomoons, and broad line regions of quasars, and examine the requirements for PL system design.

STARLOC: the star tracking algorithm for the MICADO Lyot coronagraphs

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Abstract

The ELT/MICADO instrument will be equipped with a set of classical Lyot coronagraphs: three different sizes of focal plane occulting spots will be available to optimize the observations in the J, H and K spectral bands. Given the complexity of the instrument and the size of the optical elements, a drift of the star image from the coronagraph center is expected during the observations, that would degrade the coronagraph performance. It is indeed likely that the atmospheric dispersion will not be completely compensated due to the wavelength difference between the AO (visible) and the science camera (IR). Mechanical drift due to temperature variation during the night can also induce such drift. We have thus developed the Star Tracking Algorithm for Regular Lyot Occulting Coronagraph (STARLOC), aimed at estimating the centering error of the star image onto the occulting spot of the Lyot coronagraph, with the goal of stabilizing the star image within 0.5 mas of the coronagraph center. This method is based on the analysis of the coronagraphic image, following the principle of QACITS that was developed for vortex coronagraph. When the image of the star is not centered onto the coronagraph (i.e. the occulting spot), there is light leaking through, down to the detector. This unwanted light can be used to estimate the centering error (or tip-tilt error). The estimation is based on the measurement of the flux asymmetry in a selected region, typically an annulus, inferred from the flux integrated in four quadrants. In this presentation, we will report on the performance study of the STARLOC algorithm, in particular under the presence of static aberrations, AO residuals, photon and read-out noises, and Lyot stop shift.

Status of the SCExAO platform - a multi-purpose instrument, testbed, and technological demonstrator for high-contrast imaging.

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Abstract

The Subaru Coronagraphic Extreme Adaptive Optics platform (SCExAO) is a high-contrast imaging (HCI) instrument, installed since 2009 at the Subaru 8.2-m telescope. SCExAO's uniqueness lies in its loosely constrained and highly versatile design, allowing the platform to be used as an instrumental research testbed, as well as an active, science-producing HCI instrument open to the international community. Several scientific and technical modules are deployed within SCExAO, allowing diverse operational configurations, e.g. up to eight cameras simultaneously sharing astronomical light from 400 nm to 2.2 µm for imaging, spectroscopy, and wavefront sensing. At the front-end, SCExAO benefits from a first-stage wavefront correction from the facility AO system, which is currently being upgraded from a 188 actuator correction to a 3224-element DM (AO3K), along with a high-order infrared pyramid wavefront sensor (WFS) and visible light quad-plane curvature WFS, which will enable a high-Strehl beam and to repurpose SCExAO's internal correction only towards HCI features, such as dark-hole digging and coherent differential imaging. The deployment of AO3K's real-time computer will facilitate joint integration with existing WFSs in SCExAO and enable, together with other efforts in sensor fusion and predictive control, a tighter integration to achieve the deepest possible contrasts. At the back-end, we present upgrades to the visible light polarimetric imager VAMPIRES, being redesigned using sub-electron noise CMOS cameras and with multi-band imaging modes, equivalent to a low-resolution, polarimetric IFU. The pupil-remapping interferometric modules FIRST and GLINT leverage the high-Strehl correction to provide high-value sub-diffraction-limit astrophysical measurements, and also pave the way into the world of astrophotonics. We also present recent results from already commissioned modules: the NIR spectro-imager CHARIS, the fast NIR polarimetry, and the MKIDS exoplanet camera. The SCExAO team encourages collaborators and is always willing to share the exceptional availability of the platform for technological demonstrations. Looking towards the future, as science modules and wavefront control techniques reach full maturity, SCExAO, AO3K, and their neighbor instruments at Subaru telescope (IRCS, IRD) are envisioned to together become a complete system-level demonstrator for the Planetary Systems Imager, the future high-contrast platform of the Thirty Meter Telescope, which resolution will allow ground-breaking improvements in high-resolution, high-contrast astronomy.

Status on the Multi-conjugate adaptive optics system on 1m New Vacuum Solar Telescope

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Abstract

A multi-conjugate adaptive optics (MCAO) system was designed as a new instrument of the 1-meter New Vacuum Solar Telescope (NVST) for routine scientific observation in 2017. This system, which includes one tip/tilt mirror, three deformable mirrors, and two multi-direction wavefront sensors, has been mounted on the telescope and tested for more than one year. The new MCAO configuration, that is, high order ground layer adaptive optics (GLAO) combined with low-order high altitude correction, was adopted for the expected effect of high-resolution correction imaging in 1 arcmin field of view. The opto-mechanical design allows for changing the conjugate plane of the two high-altitude DMs independently between two and ten kilometers. The control system is based on Multi-core CPUs platform, which is flexible for testing various control approaches. In this paper we present the integration testing and some of the first experimental results, on the basis of a brief system introduction. The observed results with GLAO close are well, while the MCAO system is under improved for better results.

Status report of the SAXO+ opto-mechanical design concept

Stadler eric [1 2], Diolaiti emiliano [3], Schreiber laura [3], Cortecchia fausto [3], Lombini matteo [3], Loupias magali [4], Magnard yves [5], Derosa adriano [3], Malaguti guiseppe [3], Maurel didier [5], Morgante gianluca [3], Rabou patrick [5], Rochat sylvain [5], Schiavone filomena [3], Terenzi luca [3], Vidal fabrice [6], Ferreira florian [7], Gendron eric [7], Mazoyer johan [7], N'diaye mamadou [8], Langlois maud [4], Tallon michel [4], Rousseau sylvain [8], Gratton raffaele [9], Milli julien [5], Mouillet david [5], Chauvin gaël [8], Wildi françois [10], Boccaletti anthony [7]

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9 - INAF - Osservatorio Astronomico di Padova(Italy)
10 - Observatoire Astronomique de lÚniversité de Genève(Switzerland)

Abstract

SAXO+[1, 2] is the second-stage adaptive optics module for the SPHERE[3] intstrument at VLT, proposed to boost the current performances of detection and characterization of exoplanets and as a pathfinder for the future planet finder (PCS) of the European ELT. It will work in combination with the SAXO[4] first-stage xAO system measuring and reducing the residual wavefront errors. SAXO+ will be implemented on a mezzanine above the main bench and it will be fed by an exchange mechanism deploying a pick-off mirror in order to preserve all the fuctionalities of the original instrument. Optical interfaces at the output are left unchanged for the scientific instruments downstream. We present in this paper the actual status of the SAXO+ baseline opto-mechanical design and its major challenges.

Strategy for sensing petal mode in presence of AO residual turbulence with a pyramid wavefront sensor

Levraud nicolas [1 2 3], Cisse mahawa , Chambouleyron vincent , Fauvarque olivier , Sauvage jean-François , Plantet cedric , Cheffot anne-Laure , Agapito guido , Neichel benoit , Fusco thierry , Pinna enrico , Esposito simone

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2 - ONERA [Salon](France)
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Abstract

The next generation of Extremely Large Telescope (24 to 39m diameter) will suffer from the so-called "pupil fragmentation" problem. Due to their large spiders, differential pistons will appear in the wavefront between the part of the pupil separated by these spiders during observations. The Adaptive Optics (AO) system necessary to compensate atmospheric turbulence appears unable to sense this differential piston leading to bad control by the loop. Hence, such differential pistons, a.k.a petal modes, will prevent the AO system from reaching the diffraction limit of the telescope and ultimately will represent the main limitation of AO-assisted observation with an ELT. All the future single conjugated AO systems for the ELT have a PyWFS that is sensible to differential piston unlike the Shack-Hartmann, but it is not trivial to get a good enough sensitivity. This is particularly true for high contrast observing modes. These differential pistons can evolve quickly, so we are looking for an AO loop scheme able to measure both the atmospheric turbulence and the petal modes. Solutions have been proposed such as the Holographic Dispersed Fringe Sensor (HDFS) for the Giant Magellan Telescope but they are not fast enough to be implemented as WFS of the AO loop and require longer AO sensing wavelength. In this talk we want to study how to make the Pyramid Wavefront Sensor (PyWFS) sensitive to petal mode with visible light. We show that a small modulation radius makes the PyWFS sensitive to petal but unable to measure atmospheric turbulence due to the PyWFS non-linearities. We therefore propose to add dedicated petal sensor as a 2nd path and we study the unmodulated PyWFS as a candidate for this role. We study the reconstruction of the petal mode present in the residuals by this petalometer. We show that the petal mode due to its spatial frequency distribution beeing infinite can be confused with other high spatial frequency modes present in the residual turbulence. We propose a focal plane spatial filter to reduce high frequency residuals. The spatial filter helps in reducing this confusion, improving the petal measurement. In this talk we perform E2E simulations and laboratory tests to demonstrate the validity and performance of this new concept.

Study of the LIFT focal-plane wavefront sensor for GALACSI NFM

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Abstract

The Infrared Low Order Sensor (IRLOS) has recently been upgraded to increase the sky coverage of the Narrow-Field Mode (NFM) of VLT UT4's Adaptive Optics Facility (AOF). The current version of IRLOS uses a 2x2 Shack-Hartmann WaveFront Sensor (WFS) in the J+H band as a baseline solution for low-order wavefront sensing. However, a full-pupil mode of IRLOS was additionally proposed to address the faintest end of the magnitude range by concentrating photons from the full aperture into a single focal-plane Point Spread Function (PSF), avoiding the lenslet-induced flux division. In this context, we are studying the LInearized Focal-plane Technique (LIFT), a phase diversity-based wavefront sensing approach that enables the retrieval of low-order modes from a single closed-loop PSF image of a Natural Guide Star (NGS). We mainly examine this method within the scope of AOF. We analyze the linearity, sensitivity, and stability of LIFT in simulated, experimental, and on-sky scenarios and discuss the practical aspects and challenges of implementing this method as a part of real operations. Additionally, we examine the potential applicability of this technique for future-generation instruments of VLT and ELT, such as MAVIS and MORFEO+MICADO. These instruments will implement the Multi-Conjugate Adaptive Optics (MCAO) correction using multiple off-axis NGSs, that will be probed in a similar fashion to AOF's IRLOS, making LIFT potentially applicable in this case.

Studying the limits of long-short term memory neural networks for wavefront prediction

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Abstract

Atmospheric turbulences can cause huge distortions in ground-based telescopes. To overcome this issue adaptive optics has become an essential tool for improving the quality of images. Measuring light aberrations produced by the rapidly changing turbulent atmosphere, it is possible to correct those images in real time. First of all, turbulence is measured using a Shack-Hartmann wavefront sensor, and then following calculations with reconstruction algorithms, the compensation is performed with deformable mirrors. In this work we try to improve previous non-linear wavefront predictors using a long short-term memory (LSTM) artificial neural network, to this end, a series of significant changes are being implemented in the model, in addition to a higher variability into the generated turbulent data from the atmosphere with variable conditions used to train the neural network. The main goal is to predict slopes measurements of a Shack-Hartmann wavefront sensor several frames in advance instead of just one frame as it was made in prior experiments, so that we can analyze how far such a prediction can go. For this purpose, we will also add a change with respect to previous works, the consideration of smaller temporal sequences to check if the learning of the parameters of the model environment is mainly done in the last frames, and thus reduce the amount of unnecessary and possibly inefficient information that encompasses the trained model. The possibility of predicting a certain number of forward values with different successive models trained specifically for each forward position will also be analyzed.

Subpixel pupil tracking on METIS for ELT

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Abstract

The METIS instrument for ELT will use a pyramid wavefront sensor (WFS) for natural guide star based adaptive optics, instead of the more traditional Shack-Hartmann WFS. The pyramid produces four pupil images, one on each quadrant of the resulting WFS image. One of the dynamic problems that METIS will encounter is a lateral drift on these four exit pupils of the telescope instrument. This drift will occur over time and needs to be corrected for by shifting the Pupil Stabilization Mirror. We aim to create a Pupil Position Control (PPC) algorithm specifically calibrated for the ELT. The lateral shift would need to be measured and corrected for on a subpixel level. The goal is to measure the lateral shift, on both axes, to within 1/10th of a pixel (with regards to the pupil images on the WFS). The observed pupil image in METIS has unique characteristics that can both benefit and hamper attempts to calculate the center. Traditional methods such as center of gravity algorithms are too easily skewed by reflectivity differences or missing segments. Our approach is to build a series of sequential matched filters and correlate these to the pupil image to determine

the level of lateral shift. The PPC algorithm was evaluated for all stages of handover; open-loop prior to handover, closed-loop with 50 modes during handover and full closed-loop after handover. Through a series of simulations and unit tests we show that the PPC algorithm can achieve the desired accuracy, while still offering a level of invariance to rotation, warping, missing segments and luminosity differences in the pupil image.

Tell me where and when and I will tell you your sodium

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Abstract

The sodium column abundance CNa in the mesosphere is one of the crucial parameters that determines the brightness of sodium laser guide stars (LGS). LGS are becoming standard elements of adaptive optics assisted instruments and more powerful lasers as well as systems to generate multiple LGS from one single laser are available now. An accurate knowledge of the possible LGS photon return flux is therefore important to properly dimension the laser power, for accurate performance estimation through adaptive optics simulations, and to design the LGS wavefront sensors. We have been using the telemetry data of the 4-LGS Adaptive Optics Facility at Paranal available since mid-2017 to derive CNa. The automatic logging provides us with an almost unique data set spanning already more than five years and counting. We derive the statistics and variations of CNa on different time scales: hours, days, months, seasons, years, or even decades. With these data, we developed a semi-empirical model of CNa at Cerro Paranal. Moreover, we propose here a global model of CNa, for every location and any time. To do so, we have gathered additional data from various sources and locations, coming from other observatories, Lidars, Earth observation satellites, and Earth atmosphere models. We will present the status of this modelling attempt, showing the challenges and the careful verifications we applied to our data analysis to avoid biases, and give a glimpse at a public domain numerical prediction tool.

Testing and validating HARMONI AO System in Europe

Costille anne [1], Neichel benoit [1], Sauvage jean-François [2], Heritier cedric [2], Dohlen kjetil [1], Fusco thierry [2], Morris tim [3], Bardou lisa [4], Townson matthew [3], Clarke fraser [5]

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT assisted with two adaptive optics mode (SCAO and LTAO) that will be on sky in 2029. The project is preparing for its final design review and in particular the Assembly, Integration and Test period. HARMONI adaptive optics will be tested in Marseille, whilst the IFS will be tested separately in Edinburgh, but these two systems will only be integrated together at the ELT, when the ELT M4 mirror will also be seen by HARMONI for the first time. This changes a lot our approach to test the adaptive optics systems. We propose showing how we will answer this challenging situation for HARMONI. The impact is different for the SCAO and the LTAO modes. While the SCAO mode will be mostly validated at sub-system level with a small telescope simulator, the LTAO mode requires the use of a large telescope simulator with various object as sources (both laser and natural guide stars). The development of this telescope simulator requires a lot of effort and its goal and main capabilities need to be carefully defined. We ask the question of what are the tests that are essential to be done in the laboratory, even without a perfect representation of the M4 mirror, and what are the tests we can can be postponed until the instrument is integrated at the telescope. We will also show the current design of the telescope simulator, which includes the simulation of 6 laser guide stars, 2 natural guide stars, an optical relay between the sources modules and HARMONI entrance and the used of Spatial Light Modulator (SLM) to simulate both the M4 mirror and the turbulence and to compensate for the optical relay aberrations.

The 21,000 Actuator GMagAO-X Parallel DM for the Giant Magellan Telescope: First HCAT Testbed Results with Segment/Petal phasing/AO control of Seven GMT Segments

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Abstract

A key scientific reason we are pursuing the very difficult effort of construction of ELT-class telescopes is for the characterization of habitable exoplanets. Indeed, the recent Astro2020 decadal survey listed this as the number one science goal for the "Worlds and Suns in Context" over the next decade. Currently this goal is extremely difficult with the current generation of D=6.5-10m telescopes (on the ground or in space) but the problem becomes more tractable with ELT-class telescopes. If we enable very high-contrast AO at ~0.8microns on a D=25-38m ELTs then, for example, the habitable planet Proxima Centauri b becomes a reasonable 6-9 lambda/D resolution elements from its star (with a challenging, but theoretically achievable, contrast of ~10 million). The GMagAO-X instrument is motivated by this reflected light direct imaging exoplanet science. GMagAO-X is a first light ExAO coronagraphic instrument for the 25.4m GMT. It is designed for the folded port "D" of the GMT. To meet the strict ExAO fitting and servo error requirement for visible light ExAO (less than 90nm rms WFE), GMagAO-X must have a very high authority 21,000 actuator DM (yielding a sampling of ~14cm on the primary/actuator) capable of ≥2KHz correction speeds. Moreover, the GMT (and likely all ELTs) will suffer from low wind effect, and petal phasing/piston errors. To minimize this wavefront/segment piston error GMagAO-X has a novel seven arm interferometric beam combiner on a vibration isolated table. As well this DM has seven 3,000 actuator MEMS DMs that work in parallel. We call this DM/beam combiner the "21,000 actuator parallel DM" and it is at the heart of the GMagAO-X instrument. Due to the challenges of piston sensing and AO control we have developed a GMT AO testbed called HCAT at the University of Arizona, Center for Adaptive Optics (CAAO) in partnership with the NSF/AURA and the GMT. Piston errors are sensed by a Holographic Dispersed Fringe Sensor (HDFS), a device invented at CAAO and tested in our HCAT testbed. In this talk we will highlight the exciting new HCAT testbed results from the fully phased parallel DM with all seven GMT segments actively co-phased.

We will also report on the first testbed results of feeding this seven segment GMT pupil from the HCAT testbed into the MagAO-X ExAO instrument. This HCAT optical feed effectively makes MagAO-X "believe" it is at the GMT and so we can easily utilize MagAO-X's PyWFS and HDFS to close the AO loop on the GMT pupil. We will report on the current phasing accuracy of the HDFS and the parallel DM on the GMT pupil, and on lessons learned about ELT AO issues with segmented primary mirrors with real hardware. In addition to these exciting testbed results, we will also briefly present our current (post-CoDR) optical-mechanical design for GMagAO-X that satisfies GMagAO-X's top-level science requirements and is compliant with the GMT instrument requirements.

The Arcetri-STILES: introducing two research facilities dedicated to problem solving for the ELTs.

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Abstract

Here we introduce two R&D; facilities we are going to set up at the Arcetri Observatory premises. The framework is the "Strengthening the Italian leadership in ELT and SKA" (STILES) project and the goal is to deepen the knowledge of the next generation of adaptive optics systems on 40m-class telescopes by moving the experimentation from computer-based numerical simulations to the lab. STILES is funded by the "Piano Nazionale di Ripresa e Resilienza" (PNRR) within the Next Generation EU (NGEU) programme. This represents a unique occasion to provide the Arcetri Observatory with state of the art equipment allowing the international community to benefit from two cutting edge facilities that will be set up in the ADONI laboratory. These are the AoCascading and AoPetalometer test benches, the former dedicated to study the Extreme Adaptive Optics (XAO) technique for planet finding instruments at ELT and the latter dedicated to the solution of the piston control on the ELT segmented pupil. In the first part of the paper we will introduce the scientific goals and objectives of the AoCascading experiment, giving also an overview of the layout of the test bench. Briefly, the detection and characterisation of exo-Earths requires a high level of Strehl and image contrast thus it is mandatory to provide planet finders with XAO systems. In the case of ELT this could be achieved by coupling a second deformable mirror in cascade to M4/M5. By implementing an optical relay with two DMs with a large number of actuators and two high-order pyramid WFS in cascade configuration, the AoCascading test bench will simulate in the lab all the aspects of the implementation and control of an XAO system at the ELT. The other test bench, the AoPetalometer, will be dedicated to experiment the most challenging aspect of the ELT control: the phasing of the 6 petals composing M4. Every instrument on ELT will need to control the differential piston between the M4 segments in order to preserve the coherence in the full aperture wavefront, exploiting the spatial resolution of the 39m pupil. Nowaday, the petalometer is an open challenge for the entire AO community working for ELT instruments. The AoPetalometer will implement an optical relay to simulate for the ELT-M4 layout and different wavefront sensors and phasing techniques in order to identify the best petalometer. This will be achieved by building a custom-made segmented mirror mimicking for the M4 petalas and a reference metrology system to validate the petalometer measurements.

The Architecture of the MCAO Real-time Control Computer Cluster for the Daniel K. Inouye Solar Telescope

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Abstract

Long version for review: The real-time control system for the multi-conjugate adaptive optics system for the 4-meter Daniel K. Inouye Solar Telescope will process 11817 subapertures in total, each 20x20 px, received from nine wavefront sensors and control three deformable mirrors with a total of 3452 actuators. The system will run the control loop at a rate of 2000 Hertz. To perform this tremendous amount of processing, we use a cluster of ten x86 Linux servers interconnected with a 200-gigabits-per-second Infiniband network. Identical computers are dedicated to the camera in each of the nine wavefront sensors. These computers process the Shack-Hartmann image with a two-dimensional cross-correlation technique, and they reconstruct their parts of the wavefront modal coefficients using a matrix-vector multiplication. This data is then sent to the tenth computer in the network which sums them up and computes the final actuator commands, using another matrix-vector multiplication. This computer is also performing additional control loop functions and manages the other computers. The cluster hardware is complete, and based around a total of eleven AMD Epyc 7742 64-core processors. We are currently developing the real-time control software which is a clusterized advancement of the KAOS Evo 2 software which is used in Clear at the Goode Solar Telescope. The Infiniband communication layers for all relevant data has been implemented using RDMA (remote direct memory access) technologies for minimal latency, and a simplified control loop is already running at 2000 Hertz. The system can be commanded from a single graphical user interface which displays all nine wavefront sensor images in parallel. The development is ongoing and progress is being made quickly. We will not have a complete optical setup in the lab before deployment at the telescope, and therefore the implementation of the algorithms in the clusterized control system will be tested with simulations. We will use the adaptive optics simulation software Blur that will present the cluster with faked observations, simulating both the wavefront sensor images and the deformable mirror effects in the imaging of the sun through turbulence. On a server with two AMD Epyc 7742 processors, Blur can simulate one loop cycle in about 70 milliseconds. To speed this up even further, we have ordered a server with two AMD Epyc 9654 96-core processors. This computer will be sending the simulated camera images directly into the frame grabbers of the cluster computers using nine CoaXPress 2.0 simulator cards. We expect delivery of this computer in late March. At AO4ELT7, we plan to present the software and hardware architecture of the real-time control system, including synchronization techniques we use for lowest latency, motivate our choices and report on the timing performance and the things we have learned from using 200-gigabits-per-second Infiniband. Overall project status: The Wavefront Sensor System design has passed Final Design Review in February 2023 and the system is being manufactured. Deliveries of the custom-made cameras and of the first high-altitude deformable mirror are expected in the first half of 2023. Fabrication of the second high-altitude deformable mirror is under contract. Note to the organizers: Screenshot for review only, not for public release. Thanks. Short version for program: The real-time control system for the multi-conjugate adaptive optics system for the 4-meter Daniel K. Inouye Solar Telescope will process 11817 subapertures in total, each 20x20 px, received from nine wavefront sensors and control three deformable mirrors with a total of 3452 actuators. The system will run the control loop at a rate of 2000 Hertz. The control system is based on the KAOS Evo 2 software and will run on a cluster of ten x86 Linux servers interconnected with a 200-gigabits-per-second Infiniband network. We will use the adaptive optics simulation software Blur to test the cluster implementation before deployment at the telescope. Blur will present the cluster with faked observations, simulating both the wavefront sensor images and the deformable mirror effects in the imaging of a solar imaging through turbulence. At AO4ELT7, we plan to present the software and hardware architecture of the real-time control system, including synchronization techniques we use for lowest latency, motivate our choices and report on the timing performance and the things we have learned from using 200-gigabits-per-second Infiniband.

The Calibration and Test Unit of MORFEO: the path towards the final design

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1 - INAF - Osservatorio Astronomico d'Abruzzo(Italy)

Abstract

The Calibration Unit (CU) of MORFEO, the Multiconjugate adaptive Optics Relay For ELT Observations, is a complex optomechanical subsystem used to project on the telescope NGS and LGS focal planes a large number of light sources at different wavelengths. These sources are needed to run calibration, verification and test procedures on MORFEO at the Extremely Large Telescope (ELT). This subsystem will play a critical role not only during operations, but also during the Assembly, Integration and Verification (AIV) phase, both in Italy, when it will be used in the Test Unit (TU) configuration, including a Deformable Mirror (DM), and in Chile. This paper intends to define a path towards the final design, describing possible solutions to solve or mitigate the main criticalities identified so far.

The duality of coronagraphy and wavefront sensing: reaching the fundamental sensitivity limit on arbitrary apertures with the Phase Induced Amplitude Apodized Zernike Wavefront Sensor (PIAA-ZWFS).

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Abstract

In the last two decades many people have been searching for the optimal wavefront sensor as it can boost the performance of high-contrast imagining by orders of magnitude on the ELTs (Guyon 2005). Several authors have shown that the optimal sensitivity of a wavefront sensor is ½ radian rms per photon and per mode. The Zernike wavefront sensor is an example of a WFS with high sensitivity. It uses a circular focal plane phase mask that has a similar size to the core of an Airy pattern. Chambouleyron et al. 2021 showed that the overall sensitivity of the ZWFS can be increased by optimizing the size of the phase dot at the cost of low-order sensitivity. In Chambouleyron et al. 2022 and Landman et al. 2022 the authors optimize the full focal plane mask allowing for either purely linear or even non-linear responses. They were able to achieve the fundamental limit at high-spatial frequencies (>5 cycles per pupil) at the cost of lower sensitivity for the low-order modes which are critical for high-contrast imaging. The masks also cover the whole focal plane and are difficult to manufacture because the found phase pattern is continuous. In this work we will show that the limiting factor of the previous masks is mode matching of the focal plane mask and the incoming aperture shape. This can be solved by using lossless aperture apodization with a set of Phase Induced Amplitude Apodization lenses. This sensor is named the Phase Induced Amplitude Apodized Zernike Wavefront Sensor (PIAA-ZWFS). The focal plane mask is optimized together with the apodization and converges to a compact solution (1 lambda/D diameter) that achieves perfect sensitivity for all spatial frequencies for any aperture shape. The PIAA-ZWFS solution is very similar to the PIAA-Complex Mask Coronagraph (PIAA-CMC). The PIAA-CMC is a coronagraph that achieves the fundamental limit of coronagraphy. In this presentation we will show how coronagraphy and wavefront sensing are related and why perfect coronagraphs are also perfect wavefront sensors, by using the PIAA-ZWFS and PIAA-CMC as examples. We will also show how both can be integrated into a single system to completely erase non-common path aberrations at the coronagraph focal plane, which is of extremely high importance in high-contrast imaging.

The Giant Magellan Telescope Wide-field Phasing Testbed

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Abstract

Phasing the seven segment pairs of the doubly segmented Giant Magellan Telescope over an extended field of view requires measuring wavefront piston at multiple field locations. This will be done using a dispersed fringe sensor in each of four identical units of the GMT Acquisition, Guiding, and Wavefront-sensing System (AGWS). To test the methods planned for the GMT, we have constructed a laboratory Wide-field Phasing Testbed (WFPT), as well as a full-sized prototype of a single AGWS unit. The primary mirror of the GMT is represented by a seven-element piston-tip-tilt flat mirror array paired with an ALPAO DM292 deformable mirror. A second segmented mirror array and DM292 are used to represent the GMT's secondary mirror. These four elements are fed by a set of off-axis parabolas at the correct conjugate positions, allowing us to generate the expected off-axis misalignment aberrations over the telescope's 10 arcminute field of view. The testbed also includes elements to simulate atmospheric turbulence and chromatic dispersion. We will present an overview of the designs and results from the WFPT + AGWS experiments.

The HARMONI SCAO system: wavefront control and basis optimisation

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the Extremely Large Telescope (ELT). It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. To achieve diffraction limited performance HARMONI can operate in two Adaptive Optics (AO) modes: Single Conjugate AO (SCAO) and Laser Tomographic AO (LTAO). The HARMONI SCAO system is based on a pyramid wavefront sensor (PyWFS) operating in the visible (700 – 1000 nm). Here we will present an overview of the AO system and control scheme, reporting on end-to-end simulations and demonstrating the performance of the HARMONI SCAO system across a range of atmospheric conditions. We consider the impact of optical gain, PyWFS misregistrations and badly seen 'petal modes' on the performance. We will present on recent efforts to incorporate the force budget of the ELT's deformable mirror (M4) into our simulations and demonstrate how knowledge of the stress response of M4 can be used when building the SCAO control basis to avoid saturation events and optimise performance. Finally, we will combine these functionalities to present a simulated acquisition sequence and analyse its robustness.

The Ingot Wavefront Sensor: Updates from the laboratory test bench

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Abstract

Sodium Laser Guide Stars (LGS) let Adaptive Optics systems to dramatically increase the sky coverage, but at the same time, they suffer from some limitations imposed by their natural geometry, which differently from NGSs, are not point-like sources but more elongated objects in the sky. The Ingot-WFS (Ragazzoni 2017) is a possible solution to overcome these limitations increasing the performance of the AO system. In this work, we report the status of the laboratory activities performed at the INAF – Astronomical Observatory of Padua, in which we have developed a test bench, that in an open loop scenario, aims to investigate the behavior of the I-WFS both in terms of the LGS variation in the sky, and on the sensitivity. In this framework, we show the results obtained with a robust and automatic Python-code alignment procedure of the I-WFS with respect to the movements and density profile variations of the simulated LGS source. In addition, we also report the preliminary analysis of the response of the I-WFS to known low-order aberrations introduced with a deformable lens positioned in the pupil plane.

The LBTI as an ELT pathfinder

Ertel steve [1]

1 - Steward Observatory(United States)

Abstract

The Large Binocular Telescope (LBT) Interferometer (LBTI) is a strategic instrument that combines the two 8.4m apertures of the LBT for sensitive, high-angular resolution imaging and interferometric observations at thermal infrared wavelengths. Through its observing modes making use of Adaptive Optics, Fizeau interferometry, and nulling interferometry, the LBTI makes the LBT in many respects the first ELT. It thus serves as a pioneer for future ELTs in terms of both science (angular resolution of a 23m telescope at thermal-infrared wavelengths) and instrumentation (large, sensitive mid-infrared instrumentation, adaptive secondary mirrors, co-phasing large apertures). LBTI is also the only thermal-infrared interferometer and the only interferometer using 8m-class telescopes in the northern hemisphere and LBT is as of yet the only ELT-like telescope in the northern hemisphere in operation or under construction. LBTI has successfully completed a large survey for habitable-zone dust around nearby main sequence stars exploiting its superior angular resolution to obtain a 100x better sensitivity than space-based, precision-photometric observations. More recently, we have emphasized Fizeau interferometry and executed our first extragalactic and N band observations in this mode, together with high-contrast and precision-astrometric observations. We are now pushing a project to image the first rocky planet in the habitable zone around one of the nearest Sun-like stars. In this talk, we will present an overview of the LBTI's design and capabilities, illustrated by recent science highlights, and will outline future developments and observing projects.

The limits of predictive control under frozen flow turbulence and slope-based wavefront sensing

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1 - Lappeenranta University of Technology(Finland)
2 - Aalto University School of Science and Technology [Aalto Finland](Finland)

Abstract

Time-delay error, or AO servo-lag error, is a significant error source in adaptive optics systems. This error arises from the overall latency between sensing the wavefront and applications of the correction. Predictive control algorithms can reduce the time-delay error, providing significant performance gains, especially for instruments dedicated to direct exoplanet imaging. However, the predictive controller's performance gain depends on multiple factors, such as the type of wavefront sensor, the measurement noise level, the AO system's geometry (aliasing, actuator spacing), and the atmospheric conditions (e.g., seeing, wind speed). This work studies the theoretical limits of predictive control under different imaging conditions through spatio-temporal Gaussian process models. Further, we study the optimal design of predictive filters. We use the optimal experimental design (OED) methods to answer questions like "how long WFS data history a linear predictive filter should consider in different conditions, at given AO system geometry?"

The new Laser Launch Telescopes for Gemini North AO: design, characterization and serial production

Spano' paolo [1], Zuccon sara [1], Piersanti emanuele [1], Girardini marco [1], Marcuzzi enrico [1], Sivo gaetano [2]

1 - Officina Stellare(Italy)
2 - Gemini Observatory - AURA(United States)

Abstract

The new Gemini North AO (GNAO) laser guide star facility (LGSF) needs four Laser Launch Telescopes (LLTs) to enable both wide and narrow field corrections using GLAO and LTAO. Early in 2021

Officina Stellare has been awarded a contract to design and build four LLTs. Based on a preliminary LLT design submitted during the call for tender phase, Officina Stellare performed a one-year design study, starting the manufacturing of an engineering and qualification model (EQM) to validate this design and minimize risks on the production of the four deliverable units. After manufacturing of mechanical and optical parts including the large aspherical lens, made in-house by CNC optical polishing and tested by high-resolution interferometry, the EQM underwent a full set of mechanical and optical tests to validate its performances under representative operating conditions, including gravity, pressure and temperature. The serial production of the other four units, to be installed on the telescope, has started, with all key components already done.

The PACOME algorithm: Multi-epoch combination of direct imaging observations for exoplanet detection

Dallant jules [1], Langlois maud [1], Flasseur olivier [1], Thiébaut eric [1]

1 - Centre de Recherche Astrophysique de Lyon(France)

Abstract

Direct imaging exoplanet detection and characterization require combining extreme adaptive optics with custom differential imaging and dedicated post-processing algorithms to eliminate the residual stellar leakages. Over the last decade, large efforts have been invested on new powerful post-processing algorithms. They currently allow the detection of massive exoplanets down to 10 au but their performance remain limited at shorter angular separations due to the lack of diversity induced by the processing of each epoch of observations individually. The upcoming thirty meters class telescopes such as the ELT, will enable exploring much deeper the inner environment of nearby solar-type stars. The contrast levels to reach will require long exposure times of several tens of hours, that will only be achieved by combining several observations conducted days, weeks, or months apart. At these timescales and separations, the orbital motion of exoplanets will no longer be negligible, and a proper orbital modeling will be crucial to combine multi-epoch observations without drastically degrading the detection confidence and the achievable contrast. Very recently, we proposed the PACOME algorithm that combines optimally several observations of the same star within an end-to-end maximum likelihood based statistical detection formalism. It accounts for the Keplerian orbital motion of the sought exoplanets across epochs and co-adds constructively their weak signals. Its sensitivity and the reliability of its astrophysical outputs (orbital elements and their uncertainties) constitute major advantages in the field to detect new companions at a statistically grounded confidence level. Besides, its implementation is efficient and fully automatized, allowing to test and refine a large number of orbits in a reasonable computation time.

The Phasing and Diagnostic Station of ESO's ELT

Pfrommer thomas [1], Pettazzi lorenzo , Lewis steffan , Abad jose Antonio , Araujo constanza , Bedigan helen , Bourget pierre , Brinkmann martin , Cortes angela , Frank christoph , Gago fernando , Grudzien thomas , Guidolin ivan Maria , Haimerl andreas , Hammersley peter , Haug marcus , Hinterschuster renate , Huber stefan , Jolley paul , Kellerer aglaé , Kiekebusch mario , Kirchbauer jean-Paul , Kolmeder johannes , Kosmalski johan , La Penna paolo , Leveratto serban , Lucuix christian , Mandla christopher , Marchetti enrico , Moins christophe , Paufique jerome , Pfuhl oliver , Popovic dan , Tordo sebastien , Zuluaga pablo

1 - ESO(Germany)

Abstract

The Phasing and Diagnostic Station (PDS) of ESO's ELT provides optical sensing functions needed to phase the 39 meter diameter segmented primary mirror and to characterize the telescope optics and optical performance for maintenance and diagnostic purposes throughout the telescope's lifetime. The PDS is a stand-alone piece of equipment, designed and developed internally at ESO and having external dimensions of approximately 4 m x 1.7 m x 2 m and a total mass of several tonnes. The PDS helps to bring the telescope after the installation of its mirrors to diffraction limited performance and into operational configuration for science by verifying telescope performance with respect to the high level specifications. We report on the current status of the final design, the expected performance and the plans for the assembly, integration, and test of the system.

The photonic lantern wavefront sensor: on-sky and lab demonstration of photonic focal plane wavefront sensing, PSF reconstruction and single-mode fiber-injection with machine learning

Norris barnaby [1], Wei jin [1], Betters christopher [1], Leon-Saval sergio [1], Lin jonathan [2], Xin yinzi [3], Kim yoo Jung [2], Sallum steph [4], Lozi julien [5], Vievard sebastian [5], Guyon olivier [5], Gatkine pradip [6], Jovanovic nemanja [6], Mawet dimitri [6], Fitzgerald michael [2]

1 - Sydney Institute for Astronomy
University of Sydney(Australia)
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4 - University of California - Irvine(United States)
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Abstract

A focal plane wavefront sensor offers major advantages in AO, including removal of non-common-path aberrations and providing sensitivity to blind modes (especially low-wind-effect / petalling modes). This is especially important for ELTs, with petalling anticipated to be an important issue. But simply using the observed PSF is not sufficient for wavefront correction, as only the intensity, not phase, is measured. Here we present the use of an all-photonic device, the photonic lantern wavefront sensor (PLWFS), to sample the PSF's phase and amplitude directly. The device encodes the PSF's complex wavefront information into the intensities of a single-mode fiber output array. Although the encoding function is very stable, it must be learned empirically. Linear control systems can perform this for smaller wavefront errors (see abstract from Jonathan Lin), but a different approach is required for larger wavefront errors as the encoding becomes non-linear. We thus demonstrate the use of a neural network to reconstruct the wavefront using the PLWFS, both in-lab and on-sky with SCExAO at the Subaru Telescope. Accurate reconstruction of petalling and low-order modes, and closed-loop correction, is shown. The PLWFS also optimizes detector usage, needing only one pixel per mode, and output fibers can be easily spectrally dispersed to resolve degeneracies from phase wrapping/scintillation. It could be invaluable in phasing up ELT mirrors, and the PLWFS fits in a standard fiber connector, ideal for MOAO. We also describe the use of the PLWFS to optimally inject

starlight into a single-mode fiber, as desired for single-mode spectroscopy and long-baseline interferometry. A hybrid mode-selective photonic lantern injects starlight into the fundamental mode and uses higher order modes for wavefront sensing. The fundamental mode is then mapped over a wide bandwidth into a single output fiber fed to the science instrument. Wavefront-sensing fibers drive the AO loop to maintain maximum injection, forming a truly zero-non-common-path wavefront sensor. We also demonstrate on-sky PSF reconstruction using the photonic lantern. Finally, we explore the next step - measurement of spatial coherence, phase, and amplitude for full image reconstruction. This disentangles wavefront error/speckle from true astronomical signals, enabling full diffraction-limited performance of an ELT.

The progressive simulations for solar multi-conjugate adaptive optics on 1m New Vacuum Solar Telescope

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1 - The Key Laboratory of Adaptive Optics
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2 - Institute of Optics and Electronics
Chinese Academy of Sciences(China)

Abstract

Multi-conjugate adaptive optics (MCAO) is one of the most promising techniques currently developed to enlarge the corrected field of view (FoV) of adaptive optics in astronomy. The typical configuration in solar MCAO system often consists of two components: the first is an AO system that uses an on-axis wavefront sensor (OAWFS) and a deformable mirror (DM) conjugated at 0 km to correct the low altitude turbulence, the second is a high altitude part (HAC) that uses a multi direction wavefront sensor (MDWFS) to measure the high altitude turbulence under large FoV, and N(N≥1) DMs are conjugated at corresponding atmospheric layers to correct the residual aberrations from the former AO system. As a result, by performing high-order low altitude and low-order high altitude [AO + HAC] correction, such a MCAO system can achieve multi layers correction with a large FoV while also reducing system costs. However, because the ground layer correction based on OAWFS only benefits on-axis direction but penalizes off-axis direction due to anisoplanatic error, the correction effect is typically non-uniform, leading to an obvious issue in solar MCAO: only the central FoV can acquire good quality. In order to overcome the FoV inconsistency, a new configuration of solar MCAO has been proposed and constructed in the 1-meter New Vacuum Solar Telescope (NVST): An GLAO part with an individual high-order MDWFS is employed to replace the conventional AO part to detect the ground layer turbulence for low altitude correction. Similarly, low-order MDWFS provides the wavefront information caused by high layers turbulence through atmospheric tomography for high altitude correction [GLAO + HAC]. In this paper, for the purpose of comparison verification and parameters optimization of the real system, we make both the zonal and modal close loop simulations for various configurations based on object oriented matlab adaptive optics toolbox (OOMAO), including the conventional AO, the GLAO, and the MCAO with the AO + HAC and the GLAO + HAC architectures. The results show that the correction uniform and performance of the new scheme is obviously improved compared to conventional solar MCAO configuration. Furthermore, the system's detailed error budget and trade-off study are still being worked on.

The RTC for METIS SCAO

Bertram thomas [1], Briegel florian [1], Coppejans hugo [1], Correia carlos [2], Kulas martin [1], Steuer horst [1], Neureuther philip

1 - Max Planck Institute for Astronomy(Germany)
2 - Space ODT Porto(Portugal)

Abstract

METIS, the Mid-infrared Imager and Spectrograph for the ELT, is one of three first generation science instruments and has recently completed its final design phase. Its Single Conjugate Adaptive Optics (SCAO) system will provide the performance of an Extreme Adaptive Optics system which enables high contrast imaging observations in the thermal/mid-infrared wavelength domain (3 µm – 13.3 µm). The real-time computer (RTC) is the central component of the SCAO real-time control system. It executes the time critical wavefront control loop as well as associated control tasks by processing the data from the pyramid wavefront sensor and controlling the set of ELT actuators dedicated to Adaptive Optics. A total of 4868 commands to be computed at a loop rate of up to 1 kHz impose a number of demanding constraints in terms of memory throughput and computing power on the Hard Real-Time Core (HRTC), which employs GPU acceleration for the bulk of computations. Several auxiliary functions need to be in place to establish and maintain the quality of the wavefront correction. Among them are the control of the pupil position, the compensation of misregistration and of non-common path aberration, and the adaption of the temporal control parameters. The main wavefront control loop and many of the auxiliary functions have been prototyped to verify timing requirements and to identify the most suitable algorithms. A median RTC computation time of 382 µs was achieved for a 300k samples (5 minutes) run. The results are presented in this paper together with the foreseen RTC hardware and the software deployment within the SCAO Control System.

The Rubin Observatory Simonyi Survey Telescope's Active Optics System

Thomas sandrine [1], Connolly andrew [2], Crenshaw john Franklin [2], Kalmbach bryce [2], Megias guillem [3], Meyers josh [4], Suberlak chris [2], Tsai te-Wei [1], Ribeiro tiago [1], Claver chuck [1], Fiorentino giuliana [5], Savarese salvatore [5], Schipani pietro [5], Schreiber laura [5], Braga vittorio [5], Di Criscienzo marcella [5]

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2 - University of Washington(United States)
3 - Stanford University(United States)
4 - Lawrence Livermore National Laboratory(United States)
5 - Istituto Nazionale di Astrofisica(Italy)

Abstract

The Vera C. Rubin Observatory's Simonyi Survey Telescope (SST) is an 8.4m telescope now in construction on Cerro Pachon in Chile. In order to achieve the Rubin Observatory scientific goals of conducting a decade-long time domain survey of the optical sky, the telescope requires delivering a consistent good image quality over its 3.5 degrees field of view (FoV). This is achieved using a combination of an open-loop and a closed-loop active optics system (AOS). The open-loop AOS will correct for gravity induced wavefront errors while the closed-loop AOS will correct semi-realtime (~30s) system aberrations introduced by temperature gradients, hysteresis and other non-predictable errors. The closed-loop AOS uses a combination of 4 curvature wavefront sensors (CWSs) integrated into the focal plane of the science detector and located on the edge of the SST's field of view. The information coming from the 4 CWSs are combined using tomography techniques to calculate the appropriate corrections to be sent to the three SST's mirrors, all equipped with actuators. The AOS software is composed of a Wavefront Estimation Pipeline (WEP) to estimate the error at each of the wavefront sensors and a control system to reconstruct the state of the 3-mirrors system and find the optimal correction. Because of the large field of view and the off-axis position

of the wavefront sensor detectors, the design brings interesting problematics to the traditional curvature wavefront sensing used in adaptive optics, such as: overlapping donuts, vignetting, pairing versus stacking donuts to measure the wavefront error and others. In the process, we also focussed on new emergent and promising techniques of wavefront estimation/correction such as machine learning and reinforcement learning. Finally, in preparation of on-sky performance evaluation planned for next year, the team is working on developing tools to align the telescope within the range of the wavefront sensor, verify the sensitivity matrix on sky, evaluate the overall AOS performance and also calibrate the non-common path aberrations between the wavefront sensors at the edge of the 3.5 degrees FoV and the detector image PSF. Some of these first steps can be done using PSF moments variations across the entire FoV to understand misalignment but also mirror shape residual errors. In this paper, we describe the algorithms optimization and trade-offs, including the use of PSF variations for wavefront error estimation and we will discuss the commissioning plan. Finally, we will present some preliminary AOS performance using our Auxiliary Telescope, a 1.2 telescope using identical hardware and software as the SST.

The TMT approach to maximizing value from key performance parameters

Trancho gelys [1], Gajadhar sarah [1], Hardie kayla [1], Fordham bart [1], Kleinman scot [1], John miles [1]

1 - Thirty Meter Telescope International Observatory(United States)

Abstract

The community has long used key performance parameters (KPPs) to model and track system performance from concept to design to operations. As designs change, parts are accepted, subsystems assembled, and systems built, we redetermine KPP values and ensure the designed/as-built system meets requirements. As systems become more and more complicated, it becomes harder to track KPPs and understand how they affect and are affected by other system requirements. The Thirty Meter Telescope (TMT) is one such complicated system, with the telescope, facilities, adaptive optics system, and instruments being simultaneously designed and built. To really make our identified KPPs useful, we needed a better set of tools to visualize the web of connections from the top level science cases to multiple levels of requirements and the key performance parameters. The TMT system is ideally suited to benefit from careful KPP analysis. We are able to include the design of the instruments and adaptive optics systems with that of the telescope from day one. As a result, the TMT telescope, the first light adaptive optics system NFIRAOS — a laser guide star multi conjugate adaptive optics system — and its instruments IRIS and MODHIS are designed together to maximize performance. Knowing the relationships between KPPs and the requirements in each of these systems is an important key to successfully optimizing the design. The industry standard DOORS requirements management tool has proven useful for requirements management, but lacked a way to easily determine the connections between them and our KPPs. We therefore developed a visualization tool called TraceTree to help analyze the relationships within the entire requirements flowdown including those between the project's science cases and KPPs. This ability allows us to answer questions like which science cases are most demanding on a particular KPP or which science cases are affected by a change in a KPP value. Being able to visualize this traceability provides insight to the potential impact a change in requirements or predicted performance can have across the observatory. This paper presents the definition and management of system level KPPs and performance budgets at TMT that allows teams to refine estimates as designs mature and proactively identify areas of concern that may need additional analysis or resources.

Thin shell polishing

Ple fabien [1]

1 - Safran Reosc(France)

Abstract

Safran Reosc has developed its thin shell manufacturing process since 1988 up to now through six main programs*. Through these programs, Safran Reosc overcame many technical challenges: reducing thickness from 10mm to

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1 - Safran Reosc(France)

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Tip-tilt anisoplanatism in MCAO systems and its impact on astrometric observations with next-generation telescopes

Carlà giulia [1], Plantet cedric , Busoni lorenzo , Agapito guido

1 - INAF - Osservatorio Astrofisico di Arcetri(Italy)

Abstract

The use of multiconjugate adaptive optics (MCAO) is foreseen for the future observations from the ground, either in the infrared with the Multi-AO Imaging CamerA for Deep Observations (MICADO) at the Extremely Large Telescope (ELT), assisted by the Multiconjugate adaptive Optics Relay For ELT Observations (MORFEO), or in the visible with the MCAO Assisted Visible Imager and Spectrograph (MAVIS) at the Very Large Telescope. Astrometry represents one of the main science cases of these instruments, that are required to provide challenging performance on the astrometric measurements. In this context, among the different astrometric error sources, we investigated the contribution of tip-tilt anisoplanatism that we analytically modelled in case of MCAO-assisted observations. We present the results of our analysis on the impact of MCAO tip-tilt residuals applied to the future astrometric observations with MORFEO and MAVIS.

TipTop4ELT: Toward a single tool for all ELT instruments PSF prediction

Neichel benoit [1], Agapito guido , Rossi fabio , Plantet cedric , Kuznetsov arseniy , Conseil simon , Fetick romain , Cheffot anne-Laure , Correia carlos , Fusco thierry

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Abstract

One crucial aspect for the science observations assisted by Adaptive Optics is the knowledge of the Point Spread Function (PSF). The PSF delivered by AO systems has a complex shape, combining spatial, spectral and temporal variability, such that it is difficult to predict. The AO PSF also highly depends on the atmospheric parameters and the Natural Guide Stars (NGSs) selected. Finally, the AO-PSF can also have a very different behavior depending on the AO flavor. To assist the AO community in preparing their AO observations, we have developed a fast algorithm - called TIPTOP - producing the expected AO Point Spread Function (PSF) for any of the existing AO observing modes (SCAO, LTAO, MCAO, GLAO), and any atmospheric conditions. Called from a simple API, TIPTOP provides the estimated AO-PSFs for any of these AO configurations, in a fast enough way (few seconds per PSF) so that users can predict the performance for as many configurations as needed, at any sampling, position in the field and wavelengths. As such, TipTop will guide you in the best Guide Star asterism selection, and it will be interfaced with an instrument simulator to predict the final SNR expected for your favorite target. And beyond observation preparation, TipTop being fast enough it will also serve for queue scheduling, on-line quality checks and to provide a first PSF estimation associated with each science observation block. This last step is foreseen as a first PSF-Reconstruction approach, simple but accurate enough to serve several science cases. In preparation for the ELT, TipTop is currently deployed and tested for VLT instruments, with ERIS, MUSE (NFM and WFM), CRIRES, SPHERE and eventually MAVIS. It has also been tested with LBT and Gemini AO instruments. The team is currently actively working toward the fine tuning of the algorithm vs. on-sky observations and first results will be presented. TipTop is available for beta-testing, so don't hesitate to play with it, and send feedback!

TIPTOP: cone effect for single laser adaptive optics systems

Agapito guido [1], Plantet cedric , Rossi fabio , Kuznetsov arseniy , Conseil simon , Neichel benoit

1 - INAF(Italy)

Abstract

TIPTOP is a python library that is able to quickly compute Point Spread Functions (PSF) of any kind of Adaptive Optics systems. The goals of this library are several: support the exposure time calculators of future VLT and ELT instruments, support adaptive optics systems design activities, be part of PSF reconstruction pipelines, support the selection of the best asterism of natural guide stars for observation preparation. Here we report one of the last improvements of TIPTOP: the introduction of the error given by a single conjugated laser, the so-called cone effect. Cone effect was not introduced before because it is challenging due to the non-stationarity of the phase. We chose a different approach considering spatial frequency by spatial frequency that the correction corresponds to a measurement done on turbulence above the ground level is associated with a lower spatial frequency. In fact there is a magnification of the beam footprint on the turbulence layer due to the finite distance of the source. Therefore, we estimate the residual power by

computing the difference between two sinusoids with different periods: replicating this for each spatial frequency we obtain the power spectrum associated with the cone effect. We compare this estimation with the one given by end-to-end simulation and we present how we plan to validate this with on-sky data.

Title: Doubled sky coverage, GeMS Upgrade NGS2 in operation

Garrel vincent [1]

1 - Gemini Observatory [Southern Operations Center](Chile)

Abstract

GeMS, the Gemini Multi Conjugated AO System GeMS is operational and regularly used for science observations since 2013 delivering close to diffraction limit resolution over a 2" field of view. Its original NGS WFS was delivering Tip-Tilt correction down to magnitude 15.5. In late 2019, in partnership with the Australian National University (ANU), we installed the NGS2 upgrade in the GeMS Canopus bench. NGS2 is based on an EMCCD detector observing the entire field of acquisition and allowing Tip Tilt and anisoplanatic correction based on the selection of up to 3 regions of interests (mROI) at 800Hz. We introduce the performance of this new system compared to the previous one. While we installed this upgrade, the Slow Focus Sensor integrated in the original NGSWFS was decomissioned. Measuring the relative drifts in the mean sodium altitude is now assumed by one of the Gemini Telescope Peripheral Wavefront Sensor, a 6x6 Shack Hartmann, called PWFS1. We review the hardware and software modifications we brought to PWFS1 to fulfill this new specialized role. The use of NGS2 and PWFS1 had profound implications on the GeMS operational model, we conclude by assessing those changes.

TMT Adaptive Optics Facility Status Repor

Boyer corinne [1], Andersen david [1], Atwood jenny [2], Irarrazaval benjamin [1], Miles john [1], Trubey melissa [1], Veran jean-Pierre [2], Wang lianqi [1]

1 - TMT International Observatory(United States)
2 - Herzberg Astronomy and Astrophysics Research Centre(Canada)

Abstract

The TMT first light AO facility consists of the Narrow Field Infra-Red AO System (NFIRAOS), the associated Laser Guide Star Facility (LGSF) and the AO Executive Software (AOESW). NFIRAOS is a 60 x 60 order laser guide star (LGS) multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H, and K bands over 17-34 arc sec diameter fields with 50 per cent sky coverage at the galactic pole, as required to support the TMT science cases. NFIRAOS includes two deformable mirrors, six laser guide star wavefront sensors, one high order Pyramid WFS for natural guide star AO, up to three low-order, IR, natural guide star on-instrument wavefront sensors (OIWFS) within each client instrument, and up to four guide windows on the science detectors (ODGW). At first light, NFIRAOS will fed two science instruments: the Infrared Imaging Spectrograph (IRIS) and the Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph (MODHIS). The LGSF system includes the sodium lasers and optics required to generate the NFIRAOS and future AO system laser guide star asterisms. In this paper, we will provide an update on the progress in designing, modeling, and fabricating the TMT first light AO systems, the AO components, and the first light NFIRAOS science instruments. This will include

NFIRAOS final design activities, re-baselining the NFIRAOS visible wavefront sensors to commercial detectors, LGSF preliminary design activities, progress in developing the Real Time Controller software and manufacturing the NFIRAOS deformable mirrors, as well as design activities and prototyping for the NFIRAOS science instruments

TMT Laser Guide Star Facility Preliminary Design

Trubey melissa [1], Boyer corinne [1], Ebbers angelic [1], Irarrazaval ben [1], Miles john [1], Santoro fernando [1], Vogiatzis konstantinos [1], Wang lianqi [1]

1 - TMT International Observatory(United States)

Abstract

The Laser Guide Star Facility (LGSF), part of the adaptive optics (AO) system of the Thirty Meter Telescope (TMT), is responsible for generating the artificial guide stars in the mesospheric sodium layer with the brightness, beam quality, and asterism geometries required by the telescope's first light AO system and future AO instruments. It includes up to 8 sodium lasers mounted on the telescope's elevation structure behind the primary mirror, the conventional beam transfer optical system to transport the beams to the top end behind the secondary mirror, and the formatting and launching optical system to generate and project up to 4 required laser guide star asterisms to the sky using a center launch telescope. In this paper, we will present the LGSF preliminary design, including the optical, mechanical, electronics, software and safety designs.

Toward on-sky testing of model-based RL for AO

Nousiainen jalo [1], Kasper markus [2], Engler byron [2], Heritier cedric Taissir [3]

1 - Lappeenranta University of Technology(Finland)
2 - European Southern Observatory(Germany)
3 - Laboratoire d'Astrophysique de Marseille(France)

Abstract

One of the main objectives of the next generation of ground-based telescopes is to directly image Earth-like exoplanets. However, identifying these exoplanets can be challenging as they are located very close to their host stars. To overcome the challenge, a careful design of the adaptive optics (AO) system's control algorithm is necessary. Recently, there has been an emerging interest in improving AO control using data-driven methods such as Reinforcement Learning (RL), a subfield of machine learning where the control of a system is learned through interaction with the environment. In particular model-based RL enables an automated, self-tuning control for AO. It can handle temporal and misregistration errors and adapt to non-linear wavefront sensing while remaining efficient in training and execution. In this study, we apply and adapt a specific RL method called Policy Optimizations for AO (PO4AO) to the GHOST test bench at ESO headquarters, where we demonstrate strong performance on a simulated cascaded AO system. We explore the predictive and self-calibrating capabilities of the method and show that our current implementation using PyTorch introduces only a latency of 300μm. We also discuss and introduce the open-source implementation of the method.

Towards the MICADO@ELT PSF reconstruction with simulated and real data

Simioni matteo [1]

1 - INAF - Osservatorio Astronomico di Padova(Italy)

Abstract

Observations close to the diffraction limit, with high Strehl ratios from AO-assisted instruments mounted on ground-based telescopes are a reality and will become even more widespread with the next generation instruments that equip 30 meter-class telescopes. This results in a growing interest in tools and methods to accurately reconstruct the observed PSF of AO systems . In this presentation, I will discuss the performance of the PSF reconstruction (PSF-R) software developed in the context of MICADO@ELT. In particular, we have recently implemented a novel algorithm for reconstructing off-axis PSFs. I will present the results coming from end-to-end simulations and real AO observations, covering a wide range of observing conditions. Specifically, the spatial variation of the PSF has been studied with different AO-reference star magnitudes. The reconstructed PSFs are observed to match the reference ones with a relative error in Strehl ratio and full-width at half maximum below 10% over a field of view of the order of one arcmin, making the proposed PSF-R method an appealing tool to assist observation analysis, and interpretation. For completeness, I will also discuss the scientific evaluation of the reconstructed PSFs. Fig. 1: The radial profile of a simulated off-axis (30 arcsec) MICADO PSF in Ks band (black solid line) is compared with the associated reconstructed one (red solid line). In this case the Strehl ratio is about 0.12 and 50% of the light is contained inside a circular aperture of ~0.1 arcsec. The cumulative mismatch between observed and reconstructed PSF translates into an error of 15% in this quantity.

Training and Optimizing the Deep Optics Preconditioner for the Pyramid Wavefront Sensor

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Abstract

The Pyramid Wavefront Sensor (PWFS) [1] is one of the preferred choices to measuring wavefront aberrations for adaptive optics in highly sensitive astronomical applications. Despite its high sensitivity, the PWFS offers a limited linear range of operation that can only be extended through the modulation of the pyramid, which involves additional mechanical and movable parts, complicating the optical setup and its calibration and operation. Nevertheless, modulation decreases the sensitivity in exchange of the extended linearity range. Inspired by artificial intelligence techniques, we designed [2] a passive diffractive layer that acts as an optical preconditioner to the PWFS, with the aim of extending the linearity range without the need for modulation. The design of the novel Deep Optics PWFS (DWPFS) is obtained through an End-2-End optimization scheme that involves, firstly, the physical modeling of the optical propagation path of the modified PWFS up to the measured intensity patterns at the detector level, and secondly, the mathematical estimation using a linear model. Then, the estimation error is used to feed the backpropagation through the models to update the diffractive layer. Considering as initial point the PWFS without modulation, the training process is performed using a variety of wavefront maps from realistic turbulence models at different

strengths, most likely situated in the zone where we want to force the response of the sensor to become more linear. As shown in Fig.1, simulation results suggest that the DPWFS excel for estimating turbulence without requiring modulation, being competitive to the PWFS with modulation. On the other hand, the DPWFS is not benefited from modulation as the original PWFS. In this work, we will show our efforts to understand the importance and impact in terms of linearity and sensitivity of selecting the training parameters such as the dataset statistics, turbulence range, adding or not detector or photon noise, enabling beam modulation, calibration set point, and incorporating experimental constraints.

Twentyeight and counting

Ragazzoni roberto [1]

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Abstract

From the introduction of the pyramid wavefront sensor it become evident that diversity translated into an advantage well before that this become a popular sociological mantra. From that time 28 years elapsed, and while I conceived 28 (or maybe more) wavefront sensor, and a similar further order of magnitude appeared in the literature, maybe as a side effect that making things different is actually possible, large deformable mirrors, lasers and reconstructors developed in a similar fashion, although we still lack some of the dreams we traced back in the early days of pushing adaptive optics beyond its conventional limits, refractive correctors remaining a game-changer that never turned out as a solid option. I would revise -with the limits of my personal vision- the development of these almost three decades along with what is of the order of one hundred novel conceptions, trying to trace the path of such development and to guess which and where could be the next milestones, in a context of astronomical knowledge and availability of space based telescopes that dramatically changed in such a span of time.

ULITMATE-Subaru : GLAO system overview and its performance analysis

Ono yoshito [1], Minowa yosuke [1], Tanaka yoko [1], Yoshida hiroshige [1], Terao koki [1], Koyama yusei [1], Tanaka ichi [1], Ali sadman [1], Hattori takashi [1], Okita hirofumi [1], Hayano yutaka [1], Oya shin [2], Motohara kentaro [2 3], Yanagisawa kenshi [2], Yoshida michitoshi [2], Akiyama masayuki [4], Kodama tadayuki [4], Ogane hajime [4], Konishi masahiro [3], Martinez Rey noelia [5], Herrald nicholas [5], D'orgeville celine [5], Rigaut francois [5], Chandler david [5], Haynes dionne [5], Wang shiang-Yu [6], Chou chi-Yi [6], Kimura masahiko [6]

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Abstract

ULTIMATE-Subaru is a next facility instrumentation program at the Subaru Telescope. The goal of this project is to enhance the wide-field capability of the Subaru Telescope at the near infrared (NIR) wavelength using the wide-filed NIR instruments supported by the ground layer adaptive optics (GLAO). The GLAO system will uniformly improve the seeing size down to 0.2" at K-band in FWHM over the 20-arcmin field of view. The preliminary design of the GLAO system has been successfully completed in November 2022. In the preliminary design, we perform the detailed performance analysis using an analytical approach to understand the behavior of the GLAO system and then to specify the requirements of the GLAO sub-systems for their preliminary design. In this presentation, we will briefly introduce the GLAO preliminary design first, then present the basis of our analytical approach, and finally show the result of the GLAO performance analysis, including the GLAO performance and its uniformity over the field-of-view as function of several observation parameters, wavefront error budget, its sensitivity to the Cn2 and wind profile, and sky coverage analysis.

ULTIMATE-START: Subaru Tomography Adaptive optics Research experimenT

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Abstract

ULTIMATE-Subaru Tomography Adaptive optics Research experimenT (ULTIMATE-START) is a laser tomography AO project on the Subaru telescope. The project targets to achieve AO corrections above 600nm and feed multiple instruments on the IR-side Nasmyth platform through the beam switching optics; infrared camera and spectrograph (IRCS), visible IFU (Kyoto-3DII), extreme AO (SCExAO), and midium dispersion NIR spectrograph (NINJA). Tomography AO will be realized with 4 LGSs, corresponding four 32x32 Shack-Hartmann wavefront sensors, and 64x64 deformable mirror, which will be installed in the facility AO system, AO188. In the cource of the project, we have conducted engineering observations with a prototype 32x32 SH-WFS and a turbulence profiling system. Overall status and the results of the observations will be reviewed.

Ultra-high-resolution spectroscopy: Development and results of a real-time controller for an imaging Fourier Transform Spectrometer

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Abstract

Spectroscopy in exoplanet imaging has been used to characterize stars and their companions in astronomy for the last few decades. New imaging spectrograph technologies are needed to optimize new promising techniques, such as using very high-spectral resolution to identify exoplanet molecules in a speckle-limited image. These new techniques are difficult to implement as they require both a large field-of-view to search for hidden exoplanets, and a high-resolution spectrum for every resolution element of the field-of-view. The Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra (SPIDERS) will showcase a new generation imaging spectrograph, using an imaging Fourier Transform Spectrometer (FTS) to acquire a wide FOV from low R40 to high R20,000 spectral resolution. Off-the-shelf FTS devices have few options for speed and scan control. Typical FTS applications with bright sources and plenty of photons can take advantage of faster scan speeds to mitigate mechanical vibration and increase spectral SNR. Implementing new imaging methods and faster techniques, SPIDERS requires an FTS that can scan much slower than usual to prevent the detector read noise impact whilst prioritizing position and velocity stability. Using an off-the-shelf Michelson interferometer, a custom PCB was developed and implemented to facilitate a voice coil driving and metrology feedback circuit to provide complete control over scan speed, length, and shape. A Helium-Neon laser provides fringe quadrature sine waves that are used to determine nanometer-level position feedback. The C based controller generates a 16-bit current command at 50kHz to provide stable scanning and accurate positioning. Closed-loop testing and tuning is underway with first results proving the success of the drive and metrology electronics, the quadrature algorithm, and the closed-loop control. This paper will present the controller design and implementation, along with an analysis of its performance on the bench under real conditions.

Updates from the MICADO PSF reconstruction working group

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Abstract

The Point Spread Function (PSF) of AO-assisted instruments presents a peculiar and more complex morphology compared to seeing limited instruments. Moreover, the majority of ELT instruments will have a relatively modest field-of-view; therefore in many cases there will not be a sufficient number of bright and isolated stars in the observed field to model the PSF with great accuracy; this could strongly hamper the scientific potential of the observations. The PSF Reconstruction (PSF-R) Team of MICADO is currently implementing, for the first time within all ESO telescopes, a software service devoted to the blind reconstruction of the PSF. This tool will work using telemetric data only, both for the SCAO and the MCAO (MORFEO) MICADO modules without using the scientific focal plane data. I will review the general concepts and astrophysical context and present recent results obtained on simulated and real data gathered on instruments similar to MICADO.

Upgrades of FIRST at Subaru/SCExAO for Halpha imaging of protoplanets using photonics

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Abstract

The Fiber Imager foR a Single Telescope (FIRST) is a visible spectro-interferometer (600-850 nm, R~400). FIRST couples light from sub-apertures into single-mode fibers that are interferometrically combined and spectrally dispersed, delivering high accuracy coherence measurements at high angular resolution. Indeed, it provides inner working angles as low as 0.5λ/D, smaller than the typical inner working angles of a few λ/D of classical direct imaging techniques using current ExAO instruments, making it suitable for exoplanet detection and characterization. Installed on the Subaru telescope's extreme adaptive optics platform SCExAO, FIRST is regularly tested on sky. Its potential has already been demonstrated by measuring spectral features of tight binary systems at high angular resolution, below the diffraction limit of the telescope. At present, the contrast limit of FIRST is estimated at 0.01 with a magnitude limit of 6 in the R-band. In this presentation, we will report on the ongoing developments aiming at increasing its spectral resolution, sensitivity and dynamic range which will bring young exoplanets around nearby stars within reach. At their earliest stages of formation, exoplanets are accreting matter, a phenomenon inducing a bright emission in the Halpha line (656.3 nm) which strongly improves the companion-to-star contrast to 0.01 - 0.001 at this wavelength (e.g., PDS 70b&c;). To this end, we are implementing several upgrades to enhance the sensitivity of FIRST: integration of a new spectrograph providing a higher spectral resolution (R~3600 at 656 nm) to detect the Halpha signal, use of metrology sources to monitor instrumental phase variations, design and optimization of the visible photonic beam combiner to provide increased stability and accuracy. In the longer term, FIRST on the ELT would offer unique capabilities. The interferometric phase as measured by FIRST would sense the wavefront and feed the AO system. In particular, we have shown that the low wind and petalling effects can be reconstructed thanks to the spectral phase measurement. Combining wavefront sensing and science measurement, FIRST would offer an integrated solution to perform high contrast at unprecedented high angular resolution (0.5λ/D~2mas on a 38m-telescope at 656 nm), opening up the avenue for potential new exoplanet populations to be probed.

Using numerical models and iterative algorithms to perform non-linear reconstruction of Fourier-filtering wavefront sensor

signals.

Chambouleyron vincent [1], Salama maissa , Guthery charlotte , Fauvarque olivier , Gerard benjamin , Fowler jules , Sengupta aditya , Van Kooten maaike , Delorme jacques Robert , Wizinowich peter , Echeverry dan , Jovanovich nemanja , Xin yinzi , Wallace kent , Dillon daren , Cetre syvain , Jensen-Clem rebecca , Macintosh bruce

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Abstract

Because of their intrinsic high sensitivity, Fourier-filtering wavefront sensors (FFWFS) are becoming key elements for high-performance adaptive optics systems. These sensors exhibit orders of magnitude higher sensitivities than the widely-used Shack-Hartmann wavefront sensor, but this extremely appealing behavior comes with a drawback: such sensors have a limited linear range, which prevent from using them to their full potential (modulation required for the Pyramid wavefront sensor, only second stage adaptive optics with the Zernike wavefront sensor) and introduces significant wavefront control issues. We study a set of methods to invert FFWFS signal in a non-linear fashion, based on a numerical model of the sensor and iterative algorithms (as the Gerchberg-Saxton algorithm for instance). We discuss the improved dynamic range of these methods while comparing noise propagation with respect to linear reconstruction schemes. Polychromatic performance of these reconstructors are also assessed. These inversion techniques are performed in end-to-end simulations but also demonstrated on the adaptive optics SEAL testbed at UCSC and on KPIC instrument at Keck. Focusing on the Pyramid wavefront sensor and the Zernike wavefront sensor, we show that using these kinds of approaches can improve phase estimation from FFWFS signals. Such a class of reconstructors are (for now) not suited for real-time as they require multiple Fast-Fourier-Transform to perform reconstruction. However, we show how such non-linear reconstructors may already play important roles for different wavefront sensing and control applications. Finally, some ideas to improve convergence speed of this technique are presented with the ultimate goal that it could one day be used for real-time purposes.

Using PASSATA for the numerical simulations of the CaNaPy LGS-AO monostatic, pre-compensated system

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Abstract

CaNaPy is a demonstrator of LGS-AO technologies for visible wavelengths. The primary objective of CaNaPy is to advance the maturity of novel LGS-AO concepts by showcasing their feasibility and performance, thereby laying the groundwork for future LGS-AO instruments in the large and extremely large telescopes. CaNaPy offers a platform for verifying several breakthroughs, including complete uplink beam correction aimed at reducing the LGS's size from the 1m OGS ESA telescope, pyramid wavefront sensor utilizing the pre-compensated LGS, and high-power 589nm guidestar laser pulsed operation. In the past, preliminary results regarding the expected performance of CaNaPy have been reported. However, it was lacking a full modelling of the system; a complete simulation of CaNaPy has now been established in PASSATA, an IDL-based object-oriented simulation software for end-to-end numerical simulations of adaptive optics systems. This modelling includes geometrical and physical optics propagation of the upward-propagated guide star laser, extended vertical sodium profile, and Karhunen-Loeve modal gain optimization within the control loop. The LGS-AO system in CaNaPy employs a pulsed 63W CW guidestar laser that propagates through the entire 1-m aperture of the OGS telescope at Teide Observatory using double axicon optics to prevent losses caused by the central obstruction. We will present the expected performance of this monostatic approach, in which the same pupil is utilized for both transmitting and receiving the laser beam. The primary objective of CaNaPy is to verify the effectiveness of its technologies in preparation for their possible implementation in large and extremely large telescopes. To achieve this goal, we have expanded our numerical modelling efforts to explore the feasibility of scaling CaNaPy's system to larger apertures. This work aims to identify the optimum trade-off between complexity and performance gain.

V(WF)²S: Very Wide Field WaveFront Sensor for GLAO

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Abstract

Adaptive optics is an advanced technique developed for large telescopes. It turns out to be challenging for smaller telescopes (0.5~2m) due to the small isoplanatic angle, small subapertures and high correction speeds needed at visible wavelengths, requiring bright stars for guiding, severely limiting the sky coverage. Natural guide star (NGS) SCAO is ideal for planetary objects but remains limited for general purpose observing. The approach we propose is a compromise between image quality gain and sky coverage: our proposition is that it is better to partially improve the image quality anywhere in the sky than to be limited by diffraction around a few thousand bright stars. We therefore propose a new solution based on multiple fundamental AO concepts brought together to enable a whole new field of application: The principle is based on a rotating Foucault test, like the first AO concept proposed by Horace Babcock in 1953, on the Ground Layer Adaptive Optics (GLAO), proposed by Rigaut and Tokovinin in the early 2000s, and on the idea of Layer-oriented MCAO and the pupil-plane wave surface analysis by Roberto Ragazzoni. We propose to combine these techniques to use all the light available in a large field to measure the ground layer turbulence and enable the high angular resolution imaging of regions of the sky (e.g. nebulas, galaxies) inaccessible to traditional SCAO systems. The motivation to develop compact and robust AO system for small telescopes is two-fold: On the one hand, schools and universities often have access to small telescopes as part of their education programs. Also, researchers in countries with fewer resources could also benefit from well-engineered and reliable adaptive optics on smaller telescopes for research and education purposes. On the other hand, amateur astronomers and enthusiasts want improved image quality for visual observation and astrophotography. Implementing readily accessible adaptive optics in astronomy clubs would also likely have a significant impact on citizen science.

Validating Kernel Phase Interferometry on an IFS using SCExAO/CHARIS

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Abstract

Kernel phase interferometry (KPI) is a data processing technique for high-Strehl images that achieves moderate contrast at or within the diffraction limit of the telescope. This allows for the detection of asymmetries arising from companions or disks at higher angular resolutions than those available for current approaches with coronagraphy. Here we show that this technique can be successfully applied to the CHARIS integral field spectrograph (IFS) which sits behind the SCExAO extreme adaptive optics system on the Subaru telescope. Furthermore, by making use of simultaneous wavelength coverage provided by the IFS we are able to demonstrate that a spectral differential imaging (SDI) calibration approach is potentially more sensitive for line-emission searches than a classical reference difference imaging (RDI) approach. This is useful, since current KPI observations are typically limited by instrumental systematics as well as airmass and spectral differences between the science target and calibrator. The use of an SDI calibration is a promising avenue towards achieving photon noise limited KPI observations. Finally even with the greatly improved angular resolutions afforded by the next generation of ELTs, due to the large distances to star-forming regions, KPI will still be a powerful tool for probing the orbital separations where giant planets are known to exist, at thermal-infrared wavelengths where protoplanets are expected to be relatively bright.

Vector Zernike Wavefront Sensor Development: On-Sky and Laboratory Segment Co-Phasing Results

Salama maissa [1], Guthery charlotte [2], Chambouleyron vincent [1], Van Kooten maaike [3], Jensen-Clem rebecca [1], Wallace kent [4], Delorme jacques-Robert [2], Dillon daren [5], Ragland sam [2], Wizinowich peter [2], Echeverri daniel [6], Xin yinzi [6], Xuan jerry [6], Jovanovic nemanja [6], Mawet dimitri [6]

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Abstract

We demonstrate segment position sensing and control on Keck II telescope's primary mirror using the vector-Zernike wavefront sensor. Segment co-phasing errors are a primary contributor to contrast limits on Keck and will be necessary to correct for the next generation of space and ground-based ELTs, which will all have segmented primary mirrors. The Zernike wavefront sensor (ZWFS) is ideal for measuring phase discontinuities from co-phasing errors in a segmented telescope and the low wind effect, as well as sensing non-common path aberrations. It consists of a focal plane mask which imposes a phase offset to the core of the PSF, which then interferes with the remaining PSF, converting phase variations to intensity variations in the pupil image. The vector-Zernike mask imposes two different phase offsets to orthogonally polarized light, producing two pupil images. Compared with the traditional scalar ZWFS, the vector-ZWFS has a superior dynamic range and enables the reconstruction of the wavefront's amplitude as well as phase. We evaluate the performance of these vector-Zernike WFSs in measuring and correcting segment co-phasing errors in the presence of atmospheric turbulence on-sky at Keck and with simulated atmospheric turbulence in the lab on the Santa Cruz Extreme AO Lab (SEAL) testbed and discuss the results in the context of high contrast imaging.

Vortex Fiber Nulling Demonstration at Keck and Predicted Performance on the TMT

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Abstract

Vortex fiber nulling (VFN) is an interferometric method for suppressing starlight in order to observe exoplanets at small angular separations from their star, ■1λ/D. This technique may enable the discovery and characterization of young giant planets at separations smaller than conventional coronagraphs can reach. On the ELTs, this will push direct imaging to unprecedented separations of

Wavefront Control for Improved Starlight Rejection Through a Single-Mode Fiber

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Abstract

Connecting a coronagraph instrument to a high resolution spectrograph via a single-mode optical fiber is a promising technique for characterizing the atmospheres of exoplanets with ground and space-based telescopes. However, due to the small separation and extreme flux ratio between planets and their host stars, instrument sensitivity will be limited by residual starlight leaking into the fiber. To minimize stellar leakage, we must apply a control loop on the wavefront at the fiber input. Implicit electric field conjugation (iEFC) is a

model-independent wavefront control technique in contrast with classical electric field conjugation (EFC) which requires a detailed optical model of the system. We present here the first demonstration of an iEFC-based wavefront control algorithm to improve stellar rejection through a single-mode fiber. As opposed to image-based iEFC which relies on minimizing intensity in a dark hole region, our approach aims to minimize the amount of residual starlight coupling into a single-mode fiber. We present both simulation and lab results demonstrating the effectiveness of this technique. Having no need for an optical model, this fiber-based approach is easier to implement than conventional EFC on future ground and space-based telescope missions.

Wavefront Sensor lab for High-Contrast Imaging

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Abstract

Detecting dim exoplanets close to bright stars with extremely large telescopes will require wavefront sensors that utilize the full spatial coherence of the pupil. This will allow better measurement and correction of low-order spatial modes, which diffract starlight close to the star. We present a closed loop demonstration with three different wavefront sensors: the Shack Hartmann (SHWFS), the three-sided Pyramid (3PWFS), and the non-linear Curvature Wavefront Sensor (nlCWFS), using a new wavefront sensor testbed. The testbed is equipped with a variable three-wavelength source, an atmospheric turbulence simulator (ATS), and an adaptive optics system consisting of a fast-steering mirror and a 10x10 MEMS deformable mirror. We present the ATS calibration procedure and describe the range of turbulence parameters it can model, as well as the calibration process for each of the WFSs and the development of their reconstruction algorithms. We explore the baseline linear and nonlinear response of the 3PWFS and nlCWFS as a means to extend the accuracy of wavefront estimation in a regime of high signal-to-noise ratio. Previous work by Schatz et al. (2022) demonstrated and evaluated closed-loop performance of the 3PWFS. The objective of the new work is to empirically use each of the three WFS types to close an AO loop across a range of atmospheric turbulence profiles and source brightness and to quantify the closed-loop response of each sensor.

ZELDA WFS for the ELT-HARMONI high-contrast module - Calibration of the sensor under realistic observation conditions

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Abstract

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The High Contrast Module (HCM) will allow HARMONI to perform direct imaging and spectral analysis of exoplanets up to 10■ times fainter than their host star. Quasi-static aberrations are a limiting factor and must be calibrated as close as possible to the focal plane masks to reach the specified contrast. A Zernike sensor for Extremely Low-level Differential Aberrations (ZELDA) will be used in real-time and closed-loop operation at 0.1Hz frequency for this purpose. Unlike a Shack-Hartmann, the ZELDA wavefront sensor is sensitive to Island and low-wind effects. The ZELDA sensor has already been tested on VLT/SPHERE and will be used in other instruments. Our objective is to adapt this sensor to the specific case of HARMONI. A ZELDA prototype is being both simulated and experimentally tested at IPAG. Its nanometric precision has first been checked during 2020 in the case of slowly evolving, small wavefront errors, and without dispersion nor turbulence residuals. On this experimental basis, we address the performance of the sensor under realistic operational conditions including residuals, mis-centring, dispersion, sensitivity, etc. Atmospheric refraction residuals were introduced by the use of an Atmospheric Dispersion Corrector, and turbulence was introduced by a Spatial Light Modulator which is also used to minimise wavefront residuals in a closed loop in the observing conditions expected with HARMONI.

"CiaoCiao WFS": sensing phase discontinuities at the Extremely Large Telescope

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Abstract

The upcoming extremely large telescopes will have to deal with the so-called "pupil fragmentation" effect: either the presence of thick spider legs supporting the secondary mirror of the Extremely Large Telescope (ELT), or the segmented mirror of the Giant Magellan Telescope may induce unseen phase discontinuities that could limit the performance of the adaptive optics correction. In this context, we proposed the "CiaoCiao WFS" concept for the ELT: a rotational shearing interferometer to sense phase differences between the pupil islands. In this work, we present the progress of the "CiaoCiao WFS" feasibility study that is being carried out from both a numerical and an experimental point of view. On the one hand, we present the output of the numerical simulations where the phase discontinuities are sensed by the "CiaoCiao WFS" in case the input signal is given by the residuals from the Multiconjugate adaptive Optics Relay For ELT Observations (MORFEO). The residuals of the adaptive optics correction also include the compensation for the low-wind effect. On the other hand, we show the status of the optical setup that we are developing in our laboratories to validate and test the proposed concept of wavefront sensor.