Wavefront sensing and control in the VLT/ELT era, 3rd edition

Monday, October 22, 2018 - Wednesday, October 24, 2018

Paris

Book of Abstracts

Contents

Laser Guide Star / 0

PPPP on-sky experiment design

Author: Huizhe Yang[1]

Co-authors: Nazim Bharmal [1]; Richard Myers [1]

[1] *Durham University*

Corresponding Author: huizhe.yang@durham.ac.uk

Summary:

For the next generation of extremely large telescopes with the primary mirrors over 30m in diameter, focal anisoplanatism renders single laser guide star AO useless. The laser tomography AO (LTAO) technique demonstrates an effective approach to reduce focal anisoplanatism, although it requires multiple LGSs & WFSs, and complex tomographic reconstruction. A novel LGS alternative configuration, termed Projected Pupil Plane Pattern (PPPP), associated with its corresponding wavefront sensing and reconstruction method has been demonstrated from Monte-Carlo simulation and a laboratory experiment. An on-sky experiment is now under design to verify this new technique, using a 1.8m telescope and 720W laser at 1064nm, including a site-related simulation, optical & hardware design and an implementation of SH WFS as a comparison.

Laser Guide Star / 2

The MAORY Laser Guide Star Wavefront Sensor Design Status

Author: Laura Schreiber[1]

Co-authors: Chistophe Verinauld [2]; Emiliano Diolaiti [3]; Eric Stadler [4]; Fausto Cortecchia [3]; Jean-Jacques Correia [4]; Laurence Gluck [4]; Laurent Jocou [4]; Lorenzo Busoni [5]; Paolo Ciliegi [3]; Patrick Rabou [4]; Philippe Feautrier [4]; Roberto Ragazzoni [6]; Simone Esposito [5]; Sylvain Oberti [2]; Sylvain Rochat [4]; Yves Magnard [4]

[1] *INAF - OAS*

[2] *ESO*

[3] *INAF - AOS*

[4] *IPAG*

[5] *INAF - Osservatorio Astrofisico di Arcetri*

[6] *INAF - OAPD*

Summary:

MAORY will be the multi-conjugate adaptive optics module feeding the high resolution camera MICADO at the European Extremely Large Telescope (E-ELT) first light.
In order to ensure high and homogeneous image quality over the MICADO field of view and high sky coverage, the baseline is to operate wavefront sensing using six Sodium Laser Guide Stars.
The Laser Guide Star Wavefront Sensor (LGS WFS) is the MAORY sub-system devoted to real-time measurement of the high order wavefront distortions. In the current design, six Shack-Hartmann Wavefront Sensors of order 80×80, operate at 500Hz. In case of a phased E-ELT approach, the LGS WFS may also work with only four reference sources.
The light from the E-ELT is propagated through the MAORY common path optics. Upon wavefront compensation by the Post-focal deformable mirrors, the light is split by a Dichroic beamsplitter: the light of wavelength shorter than about 600 nm is propagated to the LGS Path Optics and then to the LGS WFS sub-system.
For each LGS WFS channel, a fast tip-tilt compensation of the Laser jitter, probably at the laser launcher level, and a slower focus correction of the Sodium altitude variation are foreseen.
Since the LGS WFS detector size seems to be limited to about 800X800 pixels, a critical aspect that could

impact the MAORY performance is related to the Shack-Hartmann sub-aperture field of view: it should be large enough to contain the projected elongated spot, but avoiding an exaggerated spot undersampling that could introduce strong non-linearities.
In this paper we describe the MAORY LGS WFS current design, including opto-mechanics, trade-offs and possible future improvements.

High Contrast Adaptive Optics / 3

HOT news

Author: Markus Kasper[1]

[1] *ESO*

Corresponding Author: mkasper@eso.org

Summary:

co-authors: N. Cerpa, P. Pathak, C. Verinaud, S. Stroebele, T.C. Heritier (all ESO), A. Puglisi, S. Esposito, E. Pinna (all Arcetri)

ESO's high order testbench (HOT) was designed more than a decade ago and implements extreme adaptive optics on a test bench with optical turbulence generation, an ALPAO woofer DM, a BMM 1k MEMS tweeter and a pyramid wave front sensor built by the team of the Arcetri Observatory. A scientific arm feeds an optical CMOS camera of the HAWAII 1 near-infrared (JHK) test camera. HOT has recently been refurbished (~1.3x oversampling of DM by WFS, spectral and spatial filters, improved cailbration methods) to optimize the PWS performance. HOT now corrects for up to 600 K-L modes providing diffraction limited performance at optical wavelengths in good seeing conditions. We provide details on the new hardware and algorithms and quantitatively investigate the achieved performance gains. We also provide an outlook on further XAO R&D planned to support the ELT Planetary Camera and Spectrograph (PCS).

Pyramid Wave-Front Sensor / 5

Design of the MagAO-X Pyramid Wavefront Sensor

Author: Lauren Schatz[1]

Co-authors: Alexander Hedglen [2]; Alexander Rodack [2]; Chris Bohlman [1]; Jared Males [3]; Jennifer Lumbres [2]; Joseph Long [4]; Justin Knight [2]; Kelsey Miller [2]; Kyle Van Gorkom [2]; Laird Close [4]; Madison Jean [2]; Maggie Kautz [2]; Michael Hart [2]; Olivier Durney [4]; Olivier Guyon [5]

[1] *University of Arizona*

[2] *University of Arizona College of Optical Sciences*

[3] *Unviersity of Arizona Steward Observatory*

[4] *University of Arizona Steward Observatory*

[5] *Subaru Telescope / University of Arizona*

Corresponding Author: lschatz@email.arizona.edu

Summary:

Adaptive optics systems correct atmospheric turbulence in real time. Most adaptive optics systems used routinely correct in the near infrared, at wavelengths greater than 1μm. MagAO-X is a

new extreme adaptive optics (ExAO) instrument that will offer corrections at visible-to-near-IR wavelengths. MagAO-X will achieve Strehl ratios greater than 70% at H%\alpha$ when running the 2040 actuator deformable mirror at 3.6 kHz. A visible pyramid wavefront sensor (PWFS) optimized for sensing at 600-1000 nm wavelengths will provide the high-order wavefront sensing on MagAO- X. We present the optical design and an update on the alignment of the MagAO-X pyramid wavefront sensor.

Wave-Front Sensing Techniques / 6

The WOLF ANR : Wave-front sensors for adaptive Optics on Extremely Large telescope using Fourier filtering

Author: Thierry Fusco[1]

Co-authors: Benoit Neichel [2]; Carlos Correia ; Eric Gendron ; Gerard Rousset ; Roberto Ragazzoni [3]; Simone Esposito [4]; Tim Morris

[1] *ONERA / LAM*

[2] *LAM*

[3] *INAF / Padova*

[4] *INAF / Arcetri*

Corresponding Author: thierry.fusco@onera.fr

Summary:

Europe has just launched the construction of the largest ground-based telescope: the ELT. In operation by 2024, this giant of 40m opens a new era in astronomy. It will answer fundamental questions from the search and characterization of extra-solar planets (the ultimate goal being the exo-earth imaging) to the formation and evolution of the first galaxies of the Universe.

In order to achieve these ambitious objectives, telescopes has to correct in real time aberrations introduced by the atmosphere, this is the role of Adaptive Optics [AO]. Wavefront sensors wfs[s] are at the heart of this state-of-the-art instrumentation and their characteristics are the key to achieving the ultimate performance of ground-based telescopes. For the characterization of exo-planets or the study of distant galaxies, gains of an order of magnitude on the accuracy, the measurement speed and the robustness of the WFSs are required. This is the goal set by the WOLF project.

For this, we will rely on a new family of WFS - Fourier filter Wavefront Sensors [FFWFS]. Our group (ONERA and LAM) has recently proposed a rigorous mathematical formalism which allows to describe and study both qualitatively and quantitatively the quite remarkable properties of these sensors. The WOLF project will use this formalism to design innovative FFWFS optimized according to the conditions of use (sensitivity, ultimate performance, linearity, robustness …).

WOLF must therefore provide a set of new sensors, fully tested, validated and ready to be implemented on the future instruments of the ELT. To achieve these ambitious goals, the work plan was divided into three stages of increasing complexity - each representing a key milestone of the project:
1. Theoretical and conceptual developments based on comprehensive simulation tools. This first step will allow to propose the concepts of innovative FFWFS and to quantify their theoretical performance;
2. An implementation of prototypes which will then be validated in laboratory using a unique experimental bench developed at LAM. This step will enable the performance of the sensors to be established as well as the calibration processes and the operating modes to be developed;
3. On-sky validation using the 4-m William Herschell Telescope [WHT] and its AO CANARY platform. The FFWFS prototypes will be tested under the most realistic conditions possible. This step, although entailing risks inherent to any demonstration on an astronomical telescope, has a huge potential gain since it allows to reach a level of maturity compatible with a future use of these sensors into operational astronomical instruments.

The team involved in WOLF brings together European experts in the field around 3 French institutes - ONERA, LAM (Marseille Observatory) and LESIA (Paris Observatory) - and 3 associated European

partners: INAF Arcetri, INAF Padova and University of Durham. The project will benefit from ONERA and LAM simulation tools and infrastructure for laboratory testing and a privileged access to WHT through LESIA and the University of Durham.

In conclusion, the WOLF project benefits from a unique synergy between European laboratories. It fits perfectly into the national strategy of instrumental development related to the ELT. It will be the ideal complement to the design studies of new OA systems and will push them to their ultimate limits in terms of performance and robustness. Thus, WOLF will be a key step in the development of the next generation of OA systems for the next 20 years that will allow to observe objects and phenomena inaccessible to date.

I this presentation I will give an overview of the WOLF project and the main probelematics we will tackle during the project. I will also describe the various opportunities offered to young researchers in the frame of the WOLF ANR.

Wave-Front Sensing Techniques / 7

MAVIS: How to ”LIFT” the sky coverage ?

Author: Yoann Brûlé[1]

Co-authors: Benoit Neichel [2]; Carlos Correia ; Cédric PLANTET [3]; François Rigaut [4]; Simone Esposito [3]; Thierry Fusco [5]

[1] *Laboratoire d'Astrophysique de Marseille*

[2] *LAM*

[3] *INAF - Osservatorio di Arcetri*

[4] *ANU College of Science*

[5] *ONERA / LAM*

Corresponding Author: yoann.brule@lam.fr

Summary:

MAVIS (which stands for MCAO Assisted Visible Imager and Spectrograph) is a proposed instrument for the ESO's VLT Adaptive Optics Facility (AOF - UT4 Yepun). From the ESO's call which includes Top Level Requirements (TLRs), this instrument shall provide diffraction-limited images in the V-band to z-band on a 30 arcsec field of view, in the visible range, under seeing condition < 1 arcsec.
A very challenging aspect of these TLR, is the sky coverage that shall be at least 50% (TBC) of the pointings at the Galactic pole.

To satisfy the requirements, a Multi-Conjugate Adaptive Optics (MCAO) system is used. It is based on a tomographic reconstruction of the atmospheric turbulence phase volume associated to the involvement of several deformable mirrors, optically conjugated at different altitudes of the turbulent volume, that are stacked to perform a uniform 3D correction beyond the limitation of natural angular anisoplanatism. The tomographic reconstruction is performed using information provided by multiple guide stars (Natural NGS and Laser LGS).
Two problems appear regarding LGS wavefront sensing. Firstly, LGS does not sense turbulence's Tip/Tilt modes. Secondly, there is an uncertainty regarding the LGS mean height, which corresponds to a focus error on the LGS wavefront sensing. Thus, the correction of these different aberrations has to be retrieved from the information given by three NGS infrared low order (Tip/Tilt/Focus) sensors. Three bright enough stars has to be found in a 120 arcsec diameter circle around the scientific field of view which drastically constrain the instrument sky coverage. Hence, MCAO instruments like MAVIS require very sensitive NGS low order WFS.

In order to reach the required sky coverage for MAVIS, the use of LIFT (Linearized Focal-Plane Technique) focal plane sensor, which is based on the concept of phase diversity, will be studied. Its linearity and sensitivity will be analyzed for low orders (Tip/Tilt/Focus). This technique is very well adapted in

the MAVIS case where scientific performance is optimized in the VIS and the NGS wavefront sensing is made in the IR. Consequently, NGS will be very well corrected and LIFT could be use in its optimal regime (small phase approximation).

In this communication, we will compare in the MAVIS context LIFT and more classical Shack-Hartmann based WFSs. We will describe the specific adjustments and optimizations proposed with respect to the original LIFT concept in order to match the MAVIS specifications. Finally, we will demonstrate that LIFT low order NGS infrared wavefront sensing could be a way to "LIFT" the sky coverage of the MAVIS instrument.

Phase reconstruction and predictive control / 8

Tensor-based predictive control for large-scale AO

Author: Baptiste Sinquin[1]

Co-author: Michel Verhaegen [1]

[1] *TU Delft*

Corresponding Author: b.sinquin@tudelft.nl

Summary:

We propose a data-driven predictive control algorithm for large-scale single conjugate adaptive optics systems. At each time sample, the Shack-Hartmann wavefront sensor signal sampled on a spatial grid of size $N \times N$ is reshuffled into a d-dimensional tensor. Its spatial-temporal dynamics are modeled with a d-dimensional autoregressive model of temporal order p where each tensor storing past data undergoes a multilinear transformation by factor matrices of small sizes. Equivalently, the vector form of this autoregressive model features coefficient matrices parametrized with a sum of Kronecker products between d factor matrices. We propose an Alternating Least Squares algorithm for identifying the factor matrices from open-loop sensor data. When modeling each coefficient matrix with a sum of r terms, the computational complexity for updating the sensor prediction online reduces from $\mathcal{O}(pN^4)$ in the unstructured matrix case to $\mathcal{O}(prdN^{\frac{2(d+1)}{d}})$. Most importantly, this model structure breaks away from assuming any prior spatial-temporal coupling as it is discovered from data.
The algorithm is validated on a laboratory testbed that demonstrates the ability to decompose accurately the coefficient matrices of large-scale autoregressive models with a tensor-based representation, hence achieving high data compression rates and reducing the temporal error especially for large Greenwood per sample frequency ratio.

Tip-Tilt & Vibration Control / 9

Vibration Mitigation in Adaptive Optics of Large Telescopes Using Model Predictive Control

Author: Martin Glück[1]

Co-authors: Jörg-Uwe Pott [2]; Oliver Sawodny [1]

[1] *University of Stuttgart, Institute for System Dynamics*

[2] *Max Planck Institute for Astronomy*

Corresponding Author: martin.glueck@isys.uni-stuttgart.de

Summary:

Large telescopes such as the Extremely Large Telescope (ELT) will suffer on the influence of structural vibrations to reach the diffraction limited performance. In the ELT a deformable mirror (DM) and tip-tilt mirror (TTM) are in the optical path of the telescope to compensate for the atmospheric turbulences and structural vibrations. Under specific condition as strong atmospheric turbulences and vibrations, the compensation mirrors in large telescopes can reach their stroke limits due to the mechanical dynamics. In this scenario the proportional-integral-derivative (PID) or linear quadratic Gaussian (LQG) control approach cannot reach the optimal performance of the adaptive optics system. Therefore, we propose a model predictive control (MPC) to consider the mirror dynamics and the corresponding actuator constraints in the control law. In a simulation study we analyze the performance in comparison to the PID and LQG control. To show the applicability we tested the optimization algorithms of the MPC on a real time environment. Furthermore, we improve the state estimation of the structural vibrations by using additional accelerometers from the telescope structure in a sensor fusion concept. The sensors are combined in a multi-rate observer. The observer is operated with the fastest sample rate and changes its observer gain dependent on the incoming sensor signal. Therefore, the wavefront sensor can be operated with a slower sample rate for a better signal to noise ratio and the high frequency vibrations can be detected by additional accelerometers, where the optical performance can be increased. In a simulation study we could show that as well the MPC control as the multi-rate observer can improve the performance for astronomical observations.

High Contrast Adaptive Optics / 10

First Electric Field Conjugation wavefront control on the THD2 bench

Author: Axel Potier[1]

Co-authors: Pierre Baudoz [1]; Raphaël Galicher [1]

[1] *LESIA*

Corresponding Author: axel.potier@obspm.fr

Summary:

Direct imaging is crucial to increase our knowledge on extrasolar planetary systems. Yet, as exoplanets are 10 3 to 10 10 fainter than their host star in visibles and near-infrared wavelengths, direct imaging requires extremely high contrast imaging techniques. First, a coronagraph is used to reject the diffracted light of an observed star and to obtain images of its circumstellar environment. Second, a wavefront control system is mandatory because coronagraphs are efficient only if the wavefront is flat. Yet, an adaptive optic setup is insufficient because it does not correct non common path aberration and the wavefront sensor has to be settled directly in the science camera. To study and compare different focal plane wavefront sensor, we developed a high contrast imaging bench at LESIA - the THD2 bench. We recently started a complete study of the practical implementation of the Electric Field Conjugation to estimate and control the phase and amplitude aberrations on the THD2 bench. We will present the first results in this presentation.

In the Lab / 11

Development of the adaptive optics testbed LOOPS for Fourier-based wavefront sensors demonstration and analysis.

Author: Pierre Janin-Potiron[1]

Co-authors: Benoit Neichel [2]; Olivier Fauvarque [3]; Thierry Fusco [4]

[1] *ONERA*

[2] *LAM*

[3] *Institut Fresnel*

[4] *ONERA / LAM*

Corresponding Author: pierre.janin-potiron@lam.fr

Summary:

Development of the adaptive optics testbed LOOPS for Fourier-based wavefront sensors demonstration and analysis.

Astrophysical observations from earth-based telescopes are affected by the atmosphere turbulences. The angular resolution of these instruments is therefore highly reduced. Adaptive Optics (AO) allows, by estimating the wavrefront deformations thanks to a WaveFront Sensor (WFS) and correcting it with one or more Deformable Mirror(s) (DM), to restore the optical performances.

From the beginning of the 90s and until recently, the AO dispositives have been using Shack-Hartman WFS. New WFS based on **optical Fourier filtering** (such as the **Zernike** or **pyramid WFS**) are now starting to being used while still under study and development. A **mathematical formalism** of these kind of WFS has been proposed and deeply formalized in O. Fauvarque's thesis, opening the path toward a better formal comprehension of their operation (especially in terms of sensitivity and linearity) and therefor a way to develop new WFS.

The **transposition of this theoretical work into real-life implementation** and testing will be done at Laboratoire d'Astrophysique de Marseille (LAM) on the **pre-existing AO bench entitled LOOPS** (standing for LAM-ONERA On-sky Pyramid Sensor). For now on, the bench can operate in closed-loop conditions using a 4-sides glass pyramid, a turbulence simulator and a Boston DM (12x12 actuators). Actually under upgrade, the bench is receiving a **Spatial Light Modulator (SLM)** in order to **produce all flavours of WFS**. The SLM is a high-resolution LCD display (~1k x 1k pixels) capable of producing arbitrary phase screen that will modify the wavefront. This versatile instrument allows, for example, the **creation of pyramids with variable number of faces** (see Fig. 1) as well as **adjustable faces angles** (see Fig. 2), opening the way to **innovative** and hopefully **more powerful WFS designs**. Sensitivity and linearity measurements of new WFSs (inspired from the pyramid WFS) will be presented and compared to the results obtained in simulations. The complete setup of the LOOPS bench will also be given to provide an exact overview of the on-going the community.

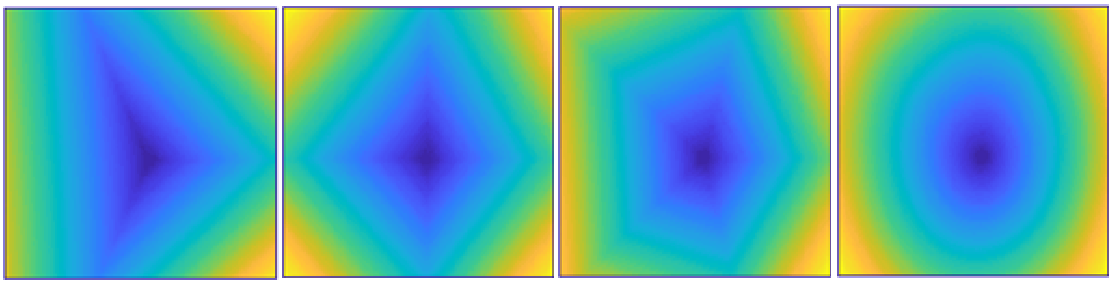

Figure 1:

Fig. 1 - Measured phase on pyramids created with a SLM for different number of faces (from left to right : 3, 4, 5 faces and an axicon).

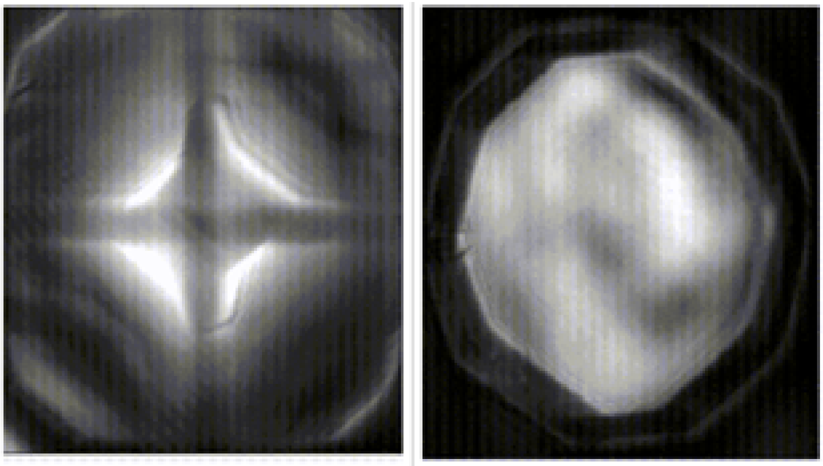

Figure 2:

Fig. 2 - Pyramid WFS images obtained with a SLM for a classical pyramid (left) and a flattened pyramid (right).

Pyramid Wave-Front Sensor / 12

Pseudo-Synthetic Interaction Matrix with Pyramid WFS: focusing on the mis-registrations identification.

Author: Cedric, Taïssir Heritier[1]

Co-authors: Alfio Puglisi [2]; Benoit Neichel [3]; Christophe Verinaud [4]; Enrico Pinna [5]; Guido Agapito [5]; Johann Kolb [4]; Markus Kasper [4]; Nelly Cerpa Urra [4]; Pierre-Yves Madec [4]; Runa Briguglio [6]; Simone Esposito [5]; Sylvain Oberti [4]; Thierry Fusco [7]

[1] *LAM/ONERA - INAF - ESO*

[2] *INAF-Osservatorio di Arcetri*

[3] *LAM*

[4] *ESO*

[5] *INAF - Osservatorio di Arcetri*

[6] *INAF- Osservatorio di Arcetri*

[7] *ONERA / LAM*

Corresponding Author: cedric.heritier@lam.fr

Summary:

Future Extremely Large Telescopes (ELT) will include large Deformable Mirrors (DM) directly located inside the telescope. This characteristic will be constraining for the AO calibration as the registration between the DM and the wavefront sensors (WFS) may evolve during the operations. These so-called mis-registrations highly affect the performance of the AO system and have to be monitored and compensated, for instance by updating the interaction matrix of the system. In the case of the future ELT, considering the large number of actuators, re-acquiring a whole interaction matrix will be problematic in terms of telescope operations (especially with no artificial calibration source). It becomes then necessary to optimize the AO calibration procedures.

At the VLT-Adaptive Optics Facility (AOF) working with a Shack-Hartmann WFS, the strategy consists of developing synthetic models of the AO systems to generate noise-free interaction matrices, injecting mis-registrations parameters identified from telemetry data. This Pseudo Synthetic approach relies on

two key-ingredients: the ability to model accurately the WFS and DM and the accuracy of the mis-registrations parameters.

Considering that the future instruments of the ESO-ELT will all include a Pyramid WFS (PWFS) for their SCAO mode, there is a need to investigate the feasibility of such a strategy working with PWFS. In this communication, we will present the experimental validation of such a pseudo synthetic model for the AO systems of the Large Binocular Telescope. We will then focus on our current activities and preliminary results to optimize/develop mis-registrations tracking methods with PWFS, eventually using the ESO High Order Test-bench (HOT).

Pyramid Wave-Front Sensor / 13

A modal approach to optical gain compensation for the PWFS

Author: Vincent Deo[1]

Co-authors: Eric Gendron [1]; Fabrice Vidal [1]; Gerard Rousset [1]; Jean-tristan Buey [1]

[1] *LESIA*

Corresponding Author: vincent.deo@obspm.fr

Summary:

A major PWFS issue is the so-called Optical Gain (OG) effect: PWFSs experience a nonlinearity-induced sensitivity reduction – of 50% or worse at the fitting error on median atmospheric conditions, and this sensitivity loss worsens as the turbulence residual increases. OG affects system performance, jeopardizes loop stability and prevents efficient non-common path aberration compensation.

We present a theoretical definition of our own modal approach to OG impact mitigation, and investigate its impact on nonlinearity error depending on the AO control basis, demonstrating a Karhunen-Loëve inspired basis is the better choice for PWFS operation.
We also evidence that scalar gain compensation of the OG is insufficient on high order systems, as the high spatial frequency range spanned covers high OG discrepancies over the controlled basis. We quantify the performance improvements obtained with OG modal compensation through end-to-end numerical simulations, evidencing a considerable AO performance improvement over a non-modal method, in particular for faint guide stars and in tough seeing conditions.

Finally, we present a sky-ready method for tracking the modal OG across the control basis: analyzing the propagation of a short-lived sinusoidal excitation of preselected DM modes, we are able to recover the instataneous optical gain and extrapolate this information to all the modes of the system.

Pyramid Wave-Front Sensor / 14

(Semi-)analytical and non-linear approaches towards optical gain compensation for pyramid sensors

Author: Victoria Hutterer[1]

Co-authors: Iuliia Shatokhina [2]; Ronny Ramlau [1]

[1] *Johannes Kepler University*

[2] *RICAM Linz*

Corresponding Authors: victoria.hutterer@indmath.uni-linz.ac.at, shatokhina@indmath.uni-linz.ac.at

Summary:

The pyramid wavefront sensor relates the incoming wavefront and the corresponding sensor signal in a non-linear way. If the sensor is operated around a non-zero setpoint, a non-linearity induced sensitivity loss, known as optical gain effect, can result in over- or under-applied corrections when using linear wavefront reconstructors. The optical gain effect varies especially with the modulation amplitude of the sensor, the statistics of the sensed phase and spatial frequencies contained in a given mode. We describe several concepts to take into account the non-linearity effects of the pyramid sensor in order to obtain an improved reconstruction quality.

One possibility is to measure or (semi-)analytically compute a non-linearity factor. The common idea of these approaches is to retrieve the non-linearity of the pyramid sensor and apply necessary adaptions as a variable (frequency dependent) gain in the reconstruction process. This can be performed, e.g., by registration of the measurements, by analyzing the response to fed frequencies in numerical simulations or by calculating the parameter analytically. Miscellaneous optical gain compensation methods using non-linearity measurements have already been introduced in order to enhance the reconstruction quality.
The analytical approach consists in a linearization of the non-linear pyramid sensor model around a non-zero phase followed by an application of already existing model-based linear reconstructors. Here, we are particularly interested in the adaption of the P-CuReD algorithm.

As an alternative, we investigate non-linear wavefront estimation for which we introduce two new methods called LIPS (Landweber Iteration for Pyramid Sensors) and KLIPS (Kaczmarz-Landweber Iteration for Pyramid Sensors). Especially for the non-modulated sensor, we attain accurate wavefront reconstruction by still keeping the numerical effort feasible for large-scale AO systems.

Additionally, in the context of linear wavefront estimation using pyramid sensors, we present the core ideas of a new wavefront reconstruction method based on an augmented steepest descent approach that takes the reconstructed wavefronts of previous steps in an AO loop into account. For this attempt, we experience a faster convergence to high Strehl ratios in closed loop applications.

Tip-Tilt & Vibration Control / 15

Analytical and numerical simulations of a two-stage controlled AO system

Author: Nelly Cerpa[1]

[1] *European Southern Observatory- Institut d´Optique*

Corresponding Author: ncerpaur@eso.org

Summary:

Co-authors: Markus Kasper(ESO), Miska Le Louarn (ESO), Caroline Kulcsar(Institut d´Optique), and Henri-Francois Raynaud (Institut d´Optique)

We present here a new system architecture, where an already existing low order system is followed by a high order, fast system. The benefits of such a design is to reduce temporal error by using small and fast deformable mirror, minimizing the interventions in the hardware and software of the existing system, while increasing the number of degrees of freedom and speed of the combined system. The system is described and the methodology is presented, where an analytical model was used to roughly determine system parameters, and then, a numerical simulation were performed using Octopus for verification.

Wide Field Adaptive Optics / 16

MAVIS AO, promises and challenges

Author: Francois Rigaut[1]

Co-authors: Benoit Neichel [2]; Cresci Giovanni [3]; Richard McDermid [4]; Robert Sharp [1]; Roberto Ragazzoni [3]; Simon Ellis [5]; Simone Esposito [3]; Thierry Fusco [6]; Valentina Viotto [3]; lorenzo Busoni [3]; maria bergomi [3]

[1] *ANU*

[2] *LAM*

[3] *INAF*

[4] *Macquarie*

[5] *AAO-MQ*

[6] *ONERA*

Corresponding Author: francois.rigaut@anu.edu.au

Summary:

MAVIS is a Multi-Conjugate Adaptive Optics system to serve compensated visible images to an imager and a spectrograph. ESO released a Phase A call for proposal in May, with a phase A likely to start early 2019. On behalf of the MAVIS consortium, including Australian nodes (AAO-Stromlo and AAO-MQ) and European nodes (INAF & LAM), I will present the main characteristics of this ambitious instrument, its promises and its challenges.

High Contrast Adaptive Optics / 17

Hot COFFEE news: a status of the coronagraphic phase diversity.

Author: Olivier Herscovici-Schiller[1]

Co-authors: Arthur Vigan [2]; Fabien Patru [3]; Jean-François Sauvage [4]; Jean-Michel Le Duigou [5]; Kjetil Dohlen [2]; Laurent Mugnier [1]; Laurent Pueyo [6]; Lucie Leboulleux [7]; Pierre Baudoz [3]; Rémi Soummer [6]; Thierry Fusco [8]; raphaël galicher [9]

[1] *ONERA*

[2] *LAM*

[3] *LESIA*

[4] *ONERA & LAM*

[5] *CNES*

[6] *STScI*

[7] *ONERA, LAM & STScI*

[8] *ONERA / LAM*

[9] *Paris University 7*

Corresponding Author: olivier.herscovici@onera.fr

Summary:

Imaging exoplanets is a challenging task. Current ground-based exoplanet imagers such as SPHERE reach contrast levels of 10^{-6} in H-band at 0.5 arcsec; and future space-based instruments will aim for contrast levels better than 10^{-9}.

Such high contrast imaging is enabled by the use of coronagraphs, devices which reject the on-axis starlight but let out-of-axis light from disks or planets pass through. However, any optical aberration in the instrument causes light to leak through the coronagraph, which results in speckles appearing in the focal plane of the telescope. Consequently, it is necessary to measure the optical aberrations after the coronagraphe in order to compensate them. Several methods have been developed in order to measure the wavefront aberrations, such as the low-order coronagraphic wave-front sensor, Zelda, the self-coherent camera (SCC), and the coronagraphic phase diversity.

In this presentation, we will give an overview of the coronagraphic phase diversity from its inception to its recent extensions.
We will recall the principle of the method, and its application to the compensation of aberrations on SPHERE using an internal source. We will expose its extension to the measurement of quasi-static aberrations through post-AO residual turbulence, which enables the use of COFFEE on-sky during observations. We will present its adaptation to the calibration of both phase and amplitude aberrations calibration for space-based instruments. We will present how it adapts to segmented mirrors. Finally, we will discuss how it can complement other wavefront sensing or control techniques, with a focus on recent experimental results concerning the "non-linear dark hole".

Wave-Front Sensing Techniques / **18**

May Mice help scientists to develop a Smart Wave Front Sensor?

Author: Fernando Pedichini[1]

Co-authors: Gianluca Li Causi [2]; Marco Stangalini [3]; Massimiliano Mattioli [1]; Roberto Piazzesi [1]; Simone Antoniucci [1]; Vincenzo Testa [1]

[1] *INAF OAR*

[2] *INAF IAPS*

[3] *INAF-OAR*

Corresponding Author: fernando.pedichini@inaf.it

Summary:

The worldwide used PC Mouse has inside it the technology to become a powerful element in the development of large format Shack-Hartmann wavefront sensors for night and day time use. Indeed, its small smart
camera, used to detect differential movements of the device and to drive the PC pointer, may be employed as a
basic tile for the building of a sensing cell for the acquisition of the centroid movement of stars or extended objects.
In this work we present preliminary results, from laboratory experiments, that provide a first assessment of the
capabilities of a smart wavefront sensor based upon such off-the-shelf and cost-effective technology and a detailed optical layout for the next European Solar Telescope . Furthermore the team has layout a trade-off analysis towards the implementation of a research pool to start the fabrication of experimental devices with a preliminary forecast of costs, efforts and benefits.

Non Common Path Aberrations / **20**

Wavefront sensing for NCPA mitigation in high contrast imaging: SHARK-VIS simulations

Author: Marco Stangalini[1]

Co-authors: Fernando Pedichini [2]; Massimiliano Mattioli [2]

[1] *INAF-OAR*

[2] *INAF OAR*

Corresponding Authors: fernando.pedichini@inaf.it, marco.stangalini@inaf.it

Summary:

Non-common path aberrations (NCPAs) represent one of the major limitations in high contrast imaging. Studying and applying optimized mitigation strategies is therefore mandatory to achieve the high contrasts needed to fulfil the science requirements.
In the framework of SHARK-VIS, the LBT high contrast imager at visible wavelenght that will see the first light in 2019, we have studied, through numerical simulations, different wavefront sensing approaches (e.g. holographic masks, extrafocal image analysis, phase diversity) aimed at the measurement of NCPAs and the optimization of their mitigation strategy. Here we present preliminary results of NCPAs sensing under different operational conditions and observing modes of SHARK-VIS, and discuss the results in terms of the expected performances of the instrument.

Laser Guide Star / 21

INGOT WFS for LGS: on-going feasibility study

Author: Valentina Viotto[1]

Co-authors: Dima Marco [1]; Elisa Portulari [1]; Farinato Jacopo [1]; Greggio Davide [1]; Magrin Demetrio [1]; Marafatto Luca [1]; Maria Bergomi [1]; Ragazzoni Roberto [1]

[1] *INAF - Padova*

Corresponding Author: valentina.viotto@inaf.it

Summary:

As LGSs come from an excited cigar-shaped region in the sodium layer, they do not behave as point-like sources, therefore a new class of WFSs has been proposed to account for such elongation: the Ingot WFSs, the LGS-counterparts of a pyramid WFS. As they appear to be very promising, their implemetation in the framework of MAORY is being considered. In the talk, we aim to present the current plan for Ingot performance simulations, which require a different approach with respect to Shack-Hartmann WFS or Pyramid WFS simulations. This happens because the Ingot WFS key component, which allows to discriminate the first derivative of the incoming wavefronts, lays in an inclined focal plane and its geometry is differently projected into the directions of different pupil sub-apertures. Finally, we want to present a plan for Ingot WFS prototyping activities in the laboratory at INAF-Padova, with the goal to preliminarly investigate the concept feasibility and practical implications.

High Contrast Adaptive Optics / 22

Experimental demonstration of a pupil-modulated PDI with broadband light.

Author: Nicolas Dubost[1]

Co-authors: Nazim Ali Bharmal [1]; Richard Myers [1]

[1] *Durham University*

Corresponding Author: nicolas.s.dubost@durham.ac.uk

Summary:

In high-contrast adaptive optics systems, non-common path aberrations between the wavefront sensing and the science paths need to be highly corrected. To perform an improved calibration, we have developed the Calibration and Alignment Wavefront Sensor (CAWS), a pupil-modulated point-diffraction interferometer (m-PDI). Here we report the results of the integration of CAWS into CHOUGH, the Durham high-order adaptive optics system. Closed-loop experiments with static aberrations were performed with both monochromatic and polychromatic light. With monochromatic light, the residual error RMS is brought down to 55 nm across the entire pupil and 12 nm within a smaller area around the centre. Independently, PSF measurements showed Strehl ratio increases from 0.20 to 0.66. Preliminary broadband light tests with a FWHM of Δ⍰=12% (80 nm) also showed a reduction of residual errors and an improvement of Strehl, which proves the polychromatic capabilities of CAWS.

Wide Field Adaptive Optics / **23**

Deep observations with an ELT in the Global Multi Conjugated Adaptive Optics perspective

Author: Elisa Portaluri[1]

Co-authors: Carmelo Arcidiacono [1]; Davide Greggio [1]; Demetrio Magrin [1]; Jacopo Farinato [1]; Marco Dima [1]; Maria Bergomi [1]; Roberto Ragazzoni [1]; Valentina Viotto [1]

[1] *INAF - Osservatorio Astronomico di Padova*

Corresponding Author: elisa.portaluri@inaf.it

Summary:

Sky surveys are one of the symbols of the modern astronomy because they can allow big collaborations, exploiting multiple facilities and shared knowledge.
We investigated how the new generation of extremely large telescopes will perform in this field of research. In fact they will play a key role because of their angular resolution and their capability in collecting the light of faint sources.
Our simulations combine technical, tomographic and observational information, and benefit of the Global-Multi Conjugate Adaptive Optics (GMCAO) approach, a well demonstrated method that exploits only natural guide stars to correct the scientific field of view from the atmospheric turbulence. By simulating K-band observations of 6000 high redshift galaxies in the Chandra Deep Field South area, we have shown how an ELT can carry out photometric surveys successfully, recovering morphological and structural parameters. We present here a wide statistics of the expected performance of a GMCAO-equipped ELT in 22 well-known surveys in terms of SR.

Wide Field Adaptive Optics / **24**

MAORY LO sensors control strategy and sky coverage assessment

Author: Cedric Plantet[1]

Co-authors: Emiliano Diolaiti [2]; Guido Agapito [1]; Lorenzo Busoni [1]; Michele Bellazzini [2]; Paolo Ciliegi [2]; Philippe Feautrier [3]; Simone Esposito [1]

[1] *INAF - Osservatorio Astronomico di Arcetri*

[2] *INAF - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna*

[3] *Institut de Planétologie et d'Astrophysique de Grenoble*

Corresponding Author: plantet@arcetri.astro.it

Summary:

The future E-ELT instrument MICADO will benefit from a wide-field correction provided by MAORY, a Multi-Conjugate Adaptive Optics (MCAO) module. The sky coverage of the whole system will be limited by the performance of the 3 natural guide star (NGS) sensors, that will estimate low-order modes (tip/tilt, focus and astigmatism). In a preliminary work, we fixed the design of these sensors to 2x2 Shack-Hartmann working in H band. Then, the performance mostly depends on the high-order correction that is applied in the NGSs' lines of sight and on the wavefront control strategy. In the presented study, we evaluate the sky coverage for different configurations of the system: number of post-focal Deformable Mirrors (DM), size of the technical field of view, use of a dedicated DM in each LO sensor's path (so-called Dual AO) … The method to compute the overall system performance with any NGS asterism uses a combination of analytical formulas and end-to-end MCAO simulations, as well as a first assessment of the error budget terms that do not depend on the AO control itself. We will discuss on the relative performance of the different configurations, as well as the limitations of this study.

In the Lab / **25**

GTCAO calibration tools and laboratory results

Author: Iciar Montilla[1]

Co-authors: Alastair Basden [2]; Jose Marco [1]; Marcos Reyes [1]; Marta Puga [1]; Miguel Núñez [1]; Oscar Tubio [1]

[1] *IAC*

[2] *Durham University*

Corresponding Author: imontilla@iac.es

Summary:

The adaptive optics system for the 10-m class Gran Telescopio Canarias consists on a 21 x 21 actuators deformable mirror conjugated to the telescope pupil and a Shack-Hartmann wavefront sensor with 20 x 20 subapertures, using an OCAM2 camera. The expected Strehl ratio @ K-band with bright natural guide stars is 0.65.
The system is now in integration and verification phase at the AIV hall at IAC. The wavefront sensor has been integrated in the optical bench alongside the deformable mirror. A calibration system is also integrated in order to characterise and calibrate the whole system. It simulates the atmospheric turbulence and the telescope, delivering an aberrated wavefront used to debug the RTC.
We will discuss the different calibration tools we have developed to test the system, the advances on the NCPAs calibration, and will present the last results we have obtained in the lab.

High Contrast Adaptive Optics / **26**

Precision emulation of high-contrast images using the low-order wave front sensor telemetry

Author: Garima Singh[1]

Co-author: Ashmeet Singh [2]

[1] *LESIA*

[2] *California Institute of Technology*

Corresponding Author: garima.singh@obspm.fr

Summary:

High performance small inner working angle (IWA) coronagraphs equipped with ground-based extreme adaptive optics (ExAO) systems are capable of imaging exoplanets in the inner regions (< 10 AU) of extrasolar systems. However, the challenge is to gain access to the immediate neighbourhood of a star. Apart from improving coronagraphs design, an important factor that rules the system performance is the nature of wavefront control, especially the correction quality of the low-order wavefront aberrations. Low-order errors lead to starlight leak around the edge of a focal plane mask (FPM), thus further contributing to speckle noise in the science image. Such errors are capable of overwhelming a possible signal from a faint companion.

With a dedicated low-order wavefront sensor (LOWFS), the starlight leak can be measured and controlled, however, with an adjustable gain factor and after a processing delay. The non-zero low-order residuals per control loop iteration always leave some residual starlight in the final science image, especially at < 3 λ/D. This is the region where the current post-processing techniques such as Angular/Reference differential imaging cannot enhance the detection sensitivity. Addressing this issue, we propose an algorithm based on the Gaussian process modelling. Our model uses the telemetry of low-order residuals in closed-loop and calibrate the sub nanometric residuals in post-processing by emulating the given science images. A significant improvement in detection sensitivity at small angles is noticed in simulations. I will present the preliminary simulation and laboratory results of point spread function calibration using the Lyot-based LOWFS measurements (tip-tilt errors only) for a vector vortex coronagraph.

Wave-Front Sensing Techniques / **27**

Past, present and future of the generalized Optical Differentiation Wavefront sensor

Author: Sebastiaan Haffert[1]

[1] *Leiden Observatory*

Corresponding Author: haffert@strw.leidenuniv.nl

Summary:

We have recently developed a new wavefront sensor with high-sensitivity and high-dynamic range, the generalized Optical Differentiation Wavefront sensor (g-ODWFS). These properties make it suitable for adaptive optic systems where a large range of phase aberrations have to be measured with high precision. The g-ODWFS is implemented with patterned liquid-crystals which make the wfs very efficient. The g-ODWFS has replaced the Shack-Hartmann wavefront sensor as our standard wavefront sensor in the Leiden EXoplanet Instrument (LEXI). I will show the first on-sky demonstration and the on-sky performance from our previous observing run in December 2017 on the William Herschel Telescope at La Palma. As LEXI is an high-contrast imager, we need to offload non-common path errors to the wavefront sensor for optimal performance. And because the g-ODWFS is an intrinsically non-linear wavefront sensor we may have to choose an operation point where the response is non-linear. To counter this we are developing a data-driven approach to non-linear wavefront reconstruction using convolution neural networks. I will show and discuss the results from simulations and lab work where we have successfully implemented neural networks that substantially improve the non-linear reconstruction error.

Instruments for Today & Tomorrow / 28

Commissioning Multi-Conjugate Adaptive Optics with LINC-NIRVANA on LBT

Author: Tom Herbst[1]

[1] *MPIA*

Corresponding Author: herbst@mpia.de

We report on early commissioning of LINC-NIRVANA (LN), an innovative Multi-Conjugate Adaptive Optics (MCAO) system for the Large Binocular Telescope (LBT). LN uses two, parallel Multi-Conjugate Adaptive Optics (MCAO) systems, each of which corrects turbulence at two atmospheric layers, to deliver near diffraction-limited imagery over a two-arcminute field of view. We discuss our strategies for wavefront sensor calibration, target acquisition, and science observing. This is followed by a detailed update on MCAO commissioning, with a focus on on-sky performance since First Light. We conclude with an outlook to early science exploitation and lessons learned from bringing such a complex adaptive optics instrument into operation.

Summary:

Early MCAO with LINC-NIRVANA on LBT

Wave-Front Sensing Techniques / 29

Pupil plane wavefront sensing with 3D perturbators

Author: Roberto Ragazzoni[1]

[1] *INAF - Astronomical Observatory of Padova*

Corresponding Author: roberto.ragazzoni@inaf.it

Summary:

Pupil plane wavefront sensing, in contrast with the formerly ubiquitous Shack-Hartmann where the detector is located at the focal plane position, is succeeding to conquer more and more share of the Natural Guide Stars based Astronomical Adaptive Optics systems. The extension of such an approach to reference sources that deploy in 3D (namely, largely elongated Laser Guide Stars) has been the subject of a brief burst of developments in the past (mostly around the PIGS idea) and is now being the focus of a series of concepts (revolving around the INGOT approach). It is important to describe such a devices as "conventional" pupil plane wavefront sensors with the introduction of perturbators that deploy in a 3D copy of the source images in a specific volume close to the focal plane. While it is pointed out the analogy with the layer-oriented approach we try to classify these kind of concepts in a manner that taxonomy could help to identify uncovered concepts. At the same time this can be of help, along with rules like the Scheimpflug one, to describe these device in a manner that can be useful to derive -at least at the first order, or in a comparative manner with other more conventional devices- properties like the expected sensitivity.

Non Common Path Aberrations / 30

Correction of NCPAs using a deformable lens in pyramid wavefront sensor-based AO systems: preliminary lab results

Author: Stefano Bonora[1]

Co-authors: Demetrio Magrin [2]; Maria Bergomi [2]; Martino Quintavalla [3]

[1] *CNR-IFN*

[2] *INAF-Padova*

[3] *CNR-IFN -Padova*

Corresponding Author: maria.bergomi@inaf.it

Summary:

Pyramid wavefront sensors are widely used in adaptive optics systems, and in particular in extreme adaptive optics applications, due to their advantages in terms of sensitivity with respect to other wavefront sensors such as Shack-Hartmann. In particular, as it is well-known, when the adaptive optics loop is closing, the reference star image size gets smaller on the pyramid tip, providing increased sensitivity. However, NCPAs (due to the different optical elements in the wavefront sensor and scientific arms) cause image distortions that can hinder the scientific throughput. NCPAs are usually corrected introducing offsets on the pyramid closed-loop control systems, but the consequent increase in size of the star image on the pyramid tip, leads to a decrease in sensitivity that compromises the aforementioned advantages.
A test-bench has been realized realized at CNR-IFN Institute in Padova, with the collaboration of INAF-Padova, aiming NCPAs correction inserting a multi-actuator deformable lens in the sensing path, in order to recover the optimal working conditions and the ideal magnitude gain of the pyramid. The adaptive lens is composed by two thin glass plates bonded to two piezoelectric rings with multiple actuators and the actuation of the lens allows a wavefront modulation up to the 4th order of Zernike polynomials with a relatively fast time response (frequency up to 500Hz). In particular, we present the laboratory results to show the correction of NCPAs when inserting and driving the multi-actuator deformable lens in the sensing arm, while the main adaptive optics loop is working, thus maximizing the scientific image sharpness. The use of this lens avoids changes in the optical configuration, providing a simple, yet effective way, to correct for NCPAs in existing instruments.

Non Common Path Aberrations / 31

Phase diversity as a tool to sense non-common path aberrations in SHARK-NIR: strategies and simulated performance.

Author: Daniele Vassallo[1]

[1] *INAF-Osservatorio Astronomico di Padova*

Summary:

Phase diversity is a focal plane wavefront sensing technique that allows to retrieve the instrumental aberrations starting from two images of whatever object, one of which (the diverse image) is intentionally corrupted by a known aberration. We present here the results of a simulation campaign aimed at assessing the validity of this approach for sensing non-common path aberrations (NCPA) in the SHARK-NIR instrument, the second-generation high-contrast imager for the Large Binocular Telescope. NCPA have been modeled on a realistic error budget of the instrument and introduced as input to an end-to-end Fresnel simulator to generate the two images required by the algorithm. Two approaches are compared, one using natural light in closed-loop and one using the instrument internal calibration source. Both a modal and zonal reconstruction algorithm have been tested. The reconstructed phase is projected onto the actuator space of SHARK-NIR internal deformable mirror (the corrector) in order to account for the fitting error introduced by the mirror itself.

Phase reconstruction and predictive control / 32

Update on pyramid topics: spiders, LWE, NCPAs, M4, sensitivtiy, K vs R band, …

Author: Andreas Obereder[1]

Co-authors: Iuliia Shatokhina [1]; Ronny Ramlau [2]; Victoria Hutterer [3]

[1] *RICAM, Austrian Academy of Science*

[2] *JKU*

[3] *Johannes Kepler University Linz*

Corresponding Author: iuliia.shatokhina@ricam.oeaw.ac.at

Summary:

We summarize our experience on the performance of several wavefront reconstruction algorithms under a variety of real-life phenomena.

We compare several approaches solving the spiders problem (pupil fragmentation), and focus on illumination and modulation as parameters influencing the result. Also, we analyze the severity of the pupil fragmentation problem in different bands and the related sensitivity or optical gain of the pyramid sensor.

We demonstrate results including the real M4 geometry. Additionally, we show first tests to evaluate the performance of the suggested reconstruction algorithms in the presence of non-common path aberrations.

Tip-Tilt & Vibration Control / 33

Supression of spurious vibrations by online loop shaping and H-infinity control in Adaptive Optics

Author: Alberto Rigamonti[1]

Co-authors: Alireza Karimi [2]; François WILDI [3]

[1] *EPFL / CERN*

[2] *EPFL*

[3] *University if Geneva*

Corresponding Author: francois.wildi@unige.ch

Summary:

A new approach for a robust controller for Adaptive Optics systems is proposed. The traditional Optimal Gain Integrator controller is only weakly able to mitigate the effect on the images of spurious external mechanical vibrations present on real-world telescopes. The new controller is designed with the objective of suppressing these vibrations. The controller is synthesized by loop-shaping in the Nyquist diagram by minimization of the weighted infinity norm of the sensitivity function. The new controller is a gain-scheduled H-infinity controller that can be updated in real time as a function of the perturbation frequencies. In addition to the controller, a recursive least square algorithm for online identification of the vibration frequencies is also derived.
The estimation and the controller performances are studied in the case of a sum of sinusoidal perturbations with one, two and three vibrations and compared to the standard integrator controller. The estimator and controller are implemented on the NIRPS instrument via the off-the-shelf ALPAO ACE toolbox for MATLAB.

In the Lab / 34

A Shack-Hartmann based setup to study deformable mirrors dynamics at very high framerates

Author: Prashant Pathak[1]

Co-authors: Markus Kasper [1]; Nellz Cerpa [2]; Stefan Ströbele [1]

[1] *ESO*

[2] *European Southern Observatory - Intitut d´Optique*

Corresponding Author: ppathak@eso.org

Summary:

The Extremely Large Telescope (ELT), will play an important role in the direct imaging and characterization of habitable exoplanets. Xtreme adaptive optics (XAO) is one of the key driving technique for enabling high-contrast imaging from ground-based telescopes. The accuracy of the wavefront correction in the regime of XAO is limited by poor understanding of the deformable mirrors (DM) surface response in the temporal domain.

As a part of technology development for ELT Planetary Camera and Spectrograph instrument and to make further advances in the field of XAO, we plan to study the dynamical behavior of the DM surface in the regime of several kHz. We present a setup based on Shack-Hartmann sensor and a high-speed visible camera, and progress on the characterization of surface profiles of a high-speed DM.

Wave-Front Error & Performance Evaluation / 35

A few words about AO control performance evaluation

Author: Caroline Kulcsar[1]

Co-authors: Henri-François Raynaud [1]; Jean-Marc Conan [2]; Rémy Juvénal [3]

[1] *Laboratoire Charles Fabry - CNRS - Institut d'Optique Graduate School*

[2] *ONERA*

[3] *Imagine Optic*

Corresponding Author: caroline.kulcsar@institutoptique.fr

Summary:

In this presentation we will tackle performance comparison of several AO controllers when only WFS data are available. The goal is to present some simple variance computations and to illustrate the issue of reliable performance evaluation using simulation data. This should lead to interesting discussions with the public.

Laser Guide Star / 36

On-sky ELT-elongated LGS wavefront-sensing using CANARY

Author: Lisa Bardou[None]

Co-authors: Alastair Basden [1]; Andrew Reeves [2]; Damien Gratadour [3]; Deli Geng [1]; Domenico Bonaccini Calia [4]; Douglas Laidlaw [1]; Eric Gendron [3]; Fabrice Vidal [3]; Fanny Chemla [3]; Gerard Rousset [3]; James Osborn [1]; Jean-Luc Gach [5]; Jean-tristan Buey [3]; Matthew Townson ; Mauro Centrone [6]; Richard Myers [1]; Tim Morris ; Zoltán Hubert [7]

[1] *University of Durham*

[2] *DLR*

[3] *Observatoire de Paris - LESIA*

[4] *ESO*

[5] *LAM*

[6] *INAF - Osservatorio Astronomico di Roma*

[7] *IPAG*

Corresponding Author: lisa.bardou@obspm.fr

Summary:

Six Laser Guide Stars (LGS) are included in the design of the European Extremely Large Telescope (ELT), with all of its current Adaptive Optics (AO) systems taking advantage of them using Shack-Hartmann (SH) wavefront sensors (WFS). However, the implementation of LGS wavefront sensing on the ELT raises new concerns. Indeed, the SH images of the LGS will present unprecedented elongation resulting from the perspective effect caused by the size of the ELT aperture combined with the thickness of the sodium layer.

In order to investigate wavefront sensing with an elongated LGS on a SH WFS, the Multi-Object AO demonstrator CANARY and ESO's 20W transportable Wendelstein LGS unit are used in a configuration reproducing the extreme elongation that will be reached on the ELT. The elongated LGS is superimposed on a Natural Guide Star (NGS) and each guide star has its dedicated SH WFS. The comparison between the wavefronts measured with each guide star is used to build an error breakdown of elongated LGS wavefront sensing.

In this presentation, this error breakdown will be described as well as the corresponding results obtained with data acquired during the latest run of observations in September 2017. The error breakdown is used to compare the performances of correlation and center of mass as centroiding methods. Finally, these performances are evaluated for different SH designs, to explore which compromises can be reached with respect to pixel scale and sub-aperture field of view.

Wave-Front Error & Performance Evaluation / 37

Numerical estimation and modeling of the wavefront error breakdown in adaptive optics

Author: Florian Ferreira[1]

[1] *LESIA*

Corresponding Author: florian.ferreira@obspm.fr

Summary:

For ground-based telescopes, Adaptive Optics (AO) systems aim to correct the wavefront disturbances due to atmospheric turbulence.The Point Spread Function (PSF) is one of the metrics of the AO system correction performance when compared to the diffraction limited one. Estimating the AO corrected PSF is important for image inversion which requires accurate estimation of the PSF over the scienti c field. This estimation relies on the knowledge of the AO system error budget. Establishing the various contributions of this error budget is an issue because of the propagation process of errors through the AO loop filtering. We have developed a model for SCAO system residual error breakdown which includes temporal error, anisoplanatism, aliasing, noise and tting terms. Thanks to GPU acceleration, it leads to

PSF estimation at ELT scale in half a minute

Phase reconstruction and predictive control / 38

Phase prediction under Taylor hypothesis using zonal models in LQG AO control

Author: Léonard PRENGERE[1]

Co-authors: Caroline Kulcsar [2]; Henri-François Raynaud [3]; Jean-Marc Conan [4]

[1] *IOGS*

[2] *Institut d'Optique Graduate School*

[3] *Institut d'Optique Graduate School-Lab. Charles Fabry*

[4] *ONERA/DOTA*

Corresponding Authors: leonard.prengere@institutoptique.fr, caroline.kulcsar@institutoptique.fr

Summary:

The upcoming AO systems for VLTs and ELTs will feature a huge number of WFS measurements and DM actuators, and the design of high-performance controllers is a real challenge. In this context, the distributed Kalman filter (DKF) has been proposed as a massively parallelizable observer for LQG wide-field AO control. It is based on a turbulence model that has to be defined both in a zonal basis (spatially sampled phase points) and in the spatial Fourier domain.
To evaluate an upper bound control performance, we need to define a turbulence model as close as possible to that of the simulated system, and extendable to a DKF formulation.
A multilayer turbulence model defined in a zonal basis with known wind directions and Cn2 profile is the natural candidate. The corresponding minimum variance controller, a Linear Quadratic Gaussian (LQG) regulator, will thus feature a Kalman filter build from this model. However, a turbulence model based on the frozen flow assumption has to face, in each layer and at each iteration, the appearance of a crescent of zeros when layers are estimated on the pupil support and then shifted according to the wind direction. These edge effects induce a performance degradation, that we propose to quantify in a single-conjugated AO configuration. We then propose different solutions to counteract these effects, based on the estimation of phase points outside the telescope pupil. At last, we compare this zonal-based LQG regulator with the standard integral action controller and with an LQG regulator based on an auto-regressive model of order two (boiling turbulence model) defined in a Zernike basis, an approach that was used on sky on the CANARY pathfinder.

Instruments for Today & Tomorrow / 39

Visible adaptive optics challenges for the new THEMIS solar facility

Author: Maud langlois[1]

Co-authors: Bernard Gelly [2]; D. Laporte [2]; Eric Thiébaut [3]; Gilberto Moretto [3]; Michel Tallon [3]; Richard Douet [2]

[1] *cnrs cral*

[2] *THEMIS*

[3] *CRAL*

Summary:

The THEMIS solar telescope is implementing a classical adaptive optics system operating in the visible. The Adaptive optics system is designed to operate on extended object (solar granulation) for wavefront sensing with a Strehl goal of more than 20% and shall remain stable @ r0> 7cm. The target field of view for adaptive optics correction is ~ 10-20". This adaptive optics system has been integrated at CRAL and its integration to the telescope has started in June 2018. The next phases of telescope performance testing and optimization have already started. This talk will present the design parameters, expected performances of the adaptive optics system, the lab integration results as well as preliminary on sky commissioning data.

In the Lab / 40

The ELT Emulator - MELT - an Optomechanical Test Bench for Wavefront Control, Phasing, and Telescope Control

Author: Thomas Pfrommer[1]

Co-authors: Anne-Laure Chaffot [2]; Christoph Franck [2]; Henri Bonnet [2]; Jason Spyromilio [2]; Johan Kosmalski [2]; Nick Kornweibel [2]; Paolo La Penna [2]; Samuel Levêque [2]; Steffan Lewis [2]

[1] *European Southern Observatory*

[2] *ESO*

Summary:

We present an optomechanical test bench setup for testing and validating key functionalities to be used on the Extremely Large Telescope (ELT) during the period of verification, commissioning, and up to the handover to science.

The main objectives of the minuscule extremely large telescope (MELT) are to deploy and validate the telescope control system, to deploy and validate wavefront control for commissioning and operations, as well as to produce and validate key requirements for the phasing and diagnostics station of the ELT.

MELT hosts optomechanical key components such as a segmented primary mirror, which is the Active Segmented Mirror (ASM) with its piezo-driven 61 segments and a diameter of 15 cm, designed for the Active Phasing Experiment APE. It also deploys a secondary mirror on a hexapod, an adaptive fourth mirror, and a fast tip/tilt mirror together with their control interfaces that emulate the real telescope optomechanical conditions.

Several beam paths after the telescope optical train on MELT are conditioned and guided to wavefront sensors and cameras sensitive to wavelength bands in the visible and infrared to emulate wavefront commissioning and phasing tasks. This optical path resembles part of the phasing and diagnostics station (PDS) of the ELT, used to acquire the first star photons through the ELT and to learn the usage and control of the ELT optomechanics.

The ELT main axis control is emulated with a moveable diffraction-limited source that emits white light from the visible up to the K band through a turbulence generator. A single conjugate adaptive optics system is used with an ELT real time computer to test and validate offloading scenarios to M5 and the main axis. In addition, it is used to deploy and validate wavefront control algorithms and the influence of adaptive optics on M1 phasing using the baseline SH high order WFS. The bench also allows to test different phasing concepts that will support this baseline. A pyramid WFS will also be deployed at a later stage.

Purposely misaligned optics will emulate the optically imperfect telescope with its optics mounted with mechanical tolerances after assembly and integration. Pupil rotation and derotation optomechanics create a realistic beam stability that needs active pupil stabilization used to meet the stringent pupil registration requirements.

Instruments for Today & Tomorrow / 41

SOUL: upgrading the SCAO systems at LBT

Author: Enrico Pinna[1]

Co-authors: Alfio Puglisi [2]; Amali Vaz [3]; Armando Riccardi [2]; Cedric Plantet [4]; Fabio Rossi [2]; Guido Agapito [2]; Luca Carbonaro [2]; Manny Montoya [3]; Marco Bonaglia [2]; Marco Xompero [2]; Olivier Durney [3]; Paolo Grani [2]; Phil Hinz [3]; Runa Briguglio [2]; Simone Esposito [2]; Tommaso Mazzoni [2]

[1] *INAF OSSERV. ASTROFISICO ARCETRI*

[2] *INAF - Osservatorio Astrofisico di Arcetri*

[3] *Steward Observatory, University of Arizona*

[4] *INAF - Osservatorio Astronomico di Arcetri*

Corresponding Author: plantet@arcetri.astro.it

Summary:

Nowaday, 4 SCAO systems named FLAO are operating at LBT. All of them are composed by an Adaptive Secondary Mirror (672 actuators) and a Pyramid Wavefront Sensor (30x30 sub-apertures). Two of these SCAO systems feed the interferometric focal stations of LBTI, while the remaining two provide the correction for the two LUCI spectro-imagers. SOUL is upgrading the 4 AO systems replacing the current wavefront sensor camera (CCD39) with an Electron Multiplied CCD (OCAM2k). SOUL will provide: a faster read out and framerate (2kHz instead of 1kHz) at lower noise (< 1e- instead of ~ 10e-) for better rejection of disturbances, and a higher spatial sampling (40 sub-aps on the pupil diameter) for an improved reduction of aliasing error and alignment sensitivity.

We will report here the project status together with the updated estimation of SOUL performances. Two WFSs have been already upgraded and the commissioning of the first system started on September 2018. We updated the numerical simulation using the measurement results obtained in laboratory tests. These results confirm the gain around 1.5-2 magnitudes at all wavelengths in almost all the range of reference star brightness (7.5 < mR < 18). This improvement will open the SCAO correction to a wider number of scientific cases from high contrast imaging in the visible to extragalactic source in the NIR.

Tip-Tilt & Vibration Control / 43

Tip/tilt control strategies of E-ELT

Author: Babak Sedghi[1]

[1] *ESO*

Summary:

The image motion (tip/tilt) of the telescope is dominated by two types of perturbations: a) atmospheric b)
wind load. The wind load effect on E-ELT can be an order of magnitude higher than the atmospheric effect.
Part of the image motion due to the wind load on the telescope structure is corrected by the main axis control
system (mainly large amplitude, low frequency errors). The residual tip/tilt is reduced by M5 and M4 mirror
units. M5 with its large stroke and relative low bandwidth (higher than main axes) corrects for large amplitude
and low frequency part of the image motion and M4 unit takes the higher frequency parts with smaller stroke
availability. In this talk control strategies, in particular a two-stage control strategy for decoupling M4-M5, are presented and the results are discussed.

Phase reconstruction and predictive control / 44

Predictive Tomographic Turbulence Estimation in Zonal Basis

Author: Jesse Cranney[1]

Co-authors: Francois Rigaut ; Jose De Dona [1]; Visa Korkiakoski [2]

[1] *University of Newcastle*

[2] *ANU*

Summary:

Predictive turbulence control schemes are capable of compensating for servo-lag error in adaptive optics systems, both in single and multiple conjugate arrangements. We present a general predictive estimation strategy for tomographic applications, and also a specific solution for off-axis correction in single-LGS, high slew-rate applications (such as satellite tracking).