Toward an experimental validation of new AO concepts for future E-ELT instrumentation

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ABSTRACT

For the last few years, LAM has been carrying out several R&D activities in Adaptive Optics (AO) instrumentation for Extremely Large Telescopes (ELTs). In the European ELT framework, a multi-purpose AO bench is developed to allow the experimental validation of new instrumental concepts dedicated to the next generation of ELTs. It is based on the use of a Shack-Hartmann wave-front sensor in front of a 140 actuators micro-deformable mirror (Boston Micromachines), dedicated to "low orders" modes, while a Pyramid wave-front sensor (PWFS) will be combined to a Liquid Crystal Spatial Light Modulator for "high orders" correction. Both systems could be merged in a two stages AO concept allowing to study the coupling of a telescope pre-correction using a dedicated large M4 deformable mirror and a post focal high order AO system. Analysis and optimisation of the spatial and temporal splits of the AO correction between the two systems is therefore essential.

Finally, we will use the world's fastest and most sensitive camera system OCAM^2 (developed at LAM) coupled with the pyramid , to demonstrate the concept of a fast and hyper-sensitive PWFS (up to **100x100** sub-pupils) dedicated to the first generation instruments for ELTs.

Keywords: Adaptive Optics, Deformable Mirror, Real Time Controller, Wave-front sensor, Spatial Light Modulator, LCoS Mirror, Extremely Large Telescope, OCAM^2 camera.

1. INTRODUCTION

The development of new instrumentation for the future European Extremely Large Telescope (E-ELT) will require new developments in adaptive optics in terms of simulation (end-to-end simulator for an ELT), optimisation of command laws (traditional Kalman filter methods will show limitations because of the required computing power, multi-stages correction) and experimental validation of new wave-front concepts.

Then, developing AO systems for an ELT presents a certain number of challenges, among which we identified two short-average term and a longer term objectives that could be demonstrated on the LAM AO bench.

The first one concerns the experimental study of control solutions for two levels of correction systems, such as woofer-tweeter systems. Indeed, the use of two consecutive deformable mirrors (DM), mandatory for most of AO instruments on E-ELT, rises correction and command issues to be optimized.

The second goal is the experimental validation of the Pyramid Wave Front Sensor (PWFS [1]) in ELTs conditions with a Laser Guide Star (LGS). These studies are pursued in collaboration with ONERA and University of Bologna. The design of our PWFS is undergoing and the LGS tests will take place by the end of 2014 with the On-Sky validation of the PWFS concept. Finally another and long term application is the experimental validation of an optimized control law, ETKF (Ensemble Transform Kalman Filter [2]), dedicated to the large number of degrees of freedom, based on recent Kalman filtering and developments studied at LAM.

In this paper, we define the main objectives of our AO bench, present its optical design and the status of the undergoing activities as well as the remaining work to accomplish our goals.

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2. MULTI-STAGE ADAPTIVE OPTICS BENCH

In this section, the main objectives and the design of the LAM multi-stage AO bench are presented.

2.1 Objectives

Our AO bench is being developed around the three following objectives:

- **Command concepts test for ELT test de concepts de commande pour ELT**

The first objective concerns the experimental study of control solutions for two stages of correction system, such as **woofer tweeter** aspects. Indeed, the use of two consecutive deformable mirrors (DM), necessary for most of AO instruments on an ELT, rises correction and command issues to be optimized. Our two mirrors (a 140 actuators DM and an LCD mirror) are, respectively, dedicated to low order and high order correction. Furthermore, using the world's fastest and sensitive camera $OCAM^2$[3],we will demonstrate new ultra-sensitive and fast sensor in AO environment .

- **New wave-front sensor scheme (High order Pyramid or modified version of Pyramid for NGS and LGS).**

The second goal is the experimental validation of the Pyramid Wave Front Sensor (PWFS) in ELTs conditions with a Laser Guide Star (LGS). The PWFS laboratory validation is planned by the end of 2013.
Finally, the last step concerning the PWFS implementation, is its On-Sky demonstration. This preparation of on sky tests is planned in collaboration with ONERA and will take place by the end of 2014 at OHP (Observatoire de Haute Provence).

- **ETKF experimental validation.**

For the last two years, LAM was also studying an optimal control law dedicated to the large number of degrees of freedom (for complex AO systems on ELT), based on Kalman filtering: ETKF (Ensemble Transform Kalman Filter) and its variant Local ETKF.
Then, the third and longer term application is the experimental validation of these two recent developments of new control laws (ETKF & Local ETKF) in the case of SCAO on ELT (future steps will be for wide field tomographic AO on ELT).

2.2 Design

The **description** of the AO setup we designed to reach the objectives defined in the previous paragraph is shown in figure 1. The left side illustrates a schematic overview of the LAM AO bench while the right side shows its simulation under ZEMAX optics software.

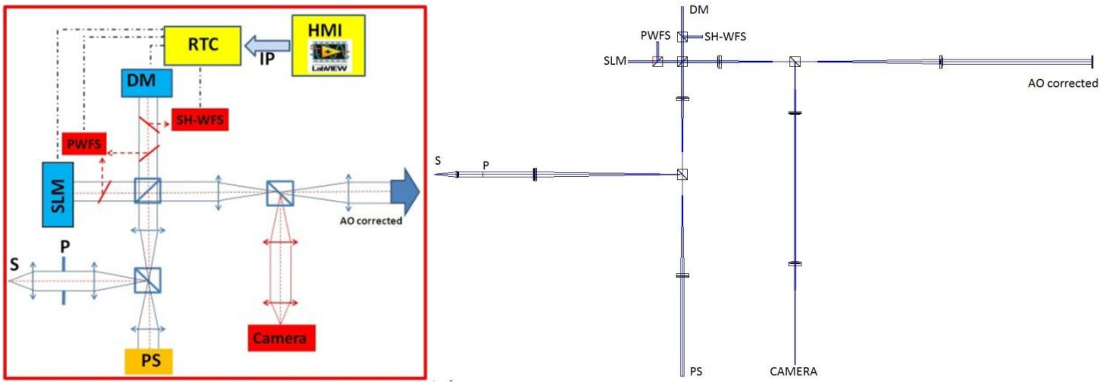

Figure 1. Left side: Schematic representation of LAM AO bench (left side). S (Source), P (Pupil), PS (Phase Screen), DM (Deformable Mirror), SH-WFS (Shack-Hartman Wave Front Sensor), SLM (Spatial Light Modulator), PWFS (Pyramid e Wave Front Sensor), RTC (Real Time Calculator), IP (Internet Protocol address) and HMI (Human Machine Interface). Right side: AO bench simulation under Zemax optics software showing the “low orders” and “high orders” correction floors and a third arm for imaging.

In terms of **functionalities,** the LAM AO bench is based on two wave-front sensing and correction stages. The first stage is dedicated for low frequencies correction. The second stage, combining a spatial light modulator and pyramid wave-front sensor (PWFS), is placed in series to correct for the residual “high frequencies” coming out from the first loop. Moreover, The PWFS can analyze simultaneously both the low (DM) and high (LCD) order mirrors, which would simulate a real ELT behavior.

The **mean features** of the LAM AO bench can be resumed in the following:

- ✓ It includes a versatile Real Time Controller, based on ORCA concept, whose development (by SHAKTIWARE), was partially funded in the frame of FP7-OPTICON program.
- ✓ It is an open bench, easy to modify.
- ✓ It gives access to a state of the art detector with $OCAM^2$ (and other new large CCD development undergoing).
- ✓ It uses a high density DM through LCD mirror.

3. AO BENCH INTEGRATION AND CALIBRATION

3.1 “Low Order Loop: LOL” (WOOFER LOOP)

Based on the use of a 140 actuators deformable mirror (DM) and Shack-Hartmann wave-front sensor (SH-WFS), this wave-front control stage, named “low orders” loop (or woofer loop) , is dedicated to correct for the low frequencies aberrations. In this section, we present the specifications and characterization for the wave-front sensing and correction elements which compound this first woofer loop.

Our DM is a 140 actuators continuous surface model from Boston Micromachines (12x12 array without 4 corners; active area is 4.95 mm square and actuator pitch is 450 µm). It has been fully characterized using many facilities. In figure 2, are presented the actuators geometry (microscopy) and the surface quality (16 nm RMS form MiniFiz and 18nm RMS from Zygo interferometry). While the figure 3 shows a gaussian shape influence function shape, an actuators coupling around 20% and an optical deflection of 2.3 µm for a single actuator..

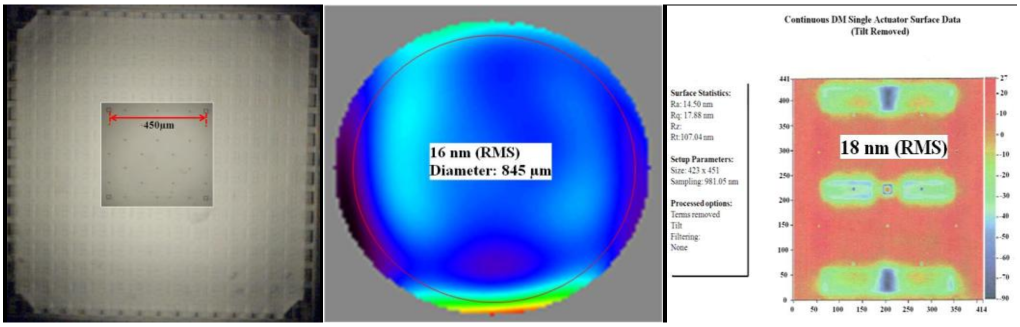

Figure 2. Left side : Boston 140-DM geometry. Center: surface data from MiniFiz interferometer. Right side: surface data obtained with ZYGO interferometer.

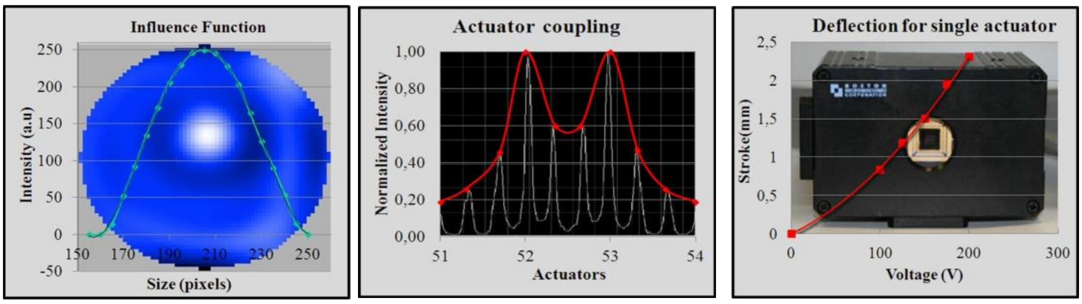

Figure 3. Left side: Influence Function shape. Center: graph illustrating an actuators coupling. Right side: Optical deflection.

One can notice, on the DM deflection graph (left side of figure 3), that the deformation is not linear with the applied voltage. This quadratic evolution, which is quite normal for an electrostatic force, is ,however, a problem for the DM control in an AO system. To overcome this situation, we did work on the control command software on the RTC to linearize the actuators displacement with the voltage (figure 4, right side). Moreover, the spatial linearity has been also measured (figure 4, right side).

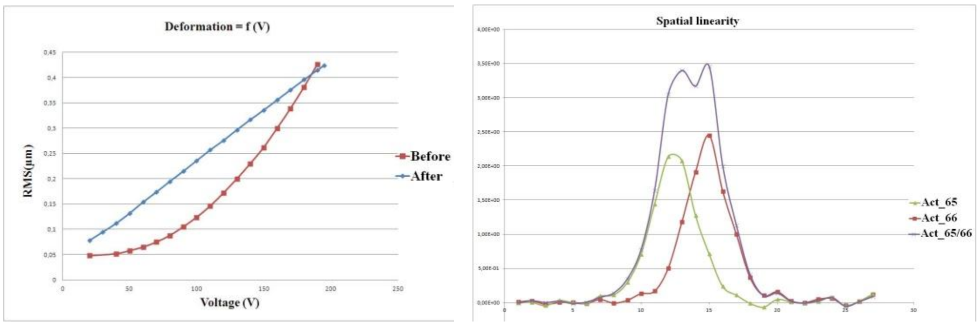

Figure 4. Left side: Graph showing mirror deformation as a function of applied voltage before (red) and after (blue) linearization process. Right side: Spatial linearity is shown (addressing both consecutive actuators is equivalent to their addition when addressing them individually).

For the woofer loop wave-front sensing, we use SH-WFS type. In table 2, are summarized all the characteristics for the ones we have in house.

Table 2. Characteristics for the Shack-Hartmann wave-front sensors for the LAM AO bench. MLA (Micro Lens Array), OCAM[2] (LAM homemade fast camera).

SH-WFS	Characteristics	Detector
HASO64 (Imagine Optics)	64x64 MLA (λ/100 RMS)	12.5x12.5 mm^2, CCD
WFS10-K2 (Thorlabs)	41x29 MLA (λ /30 RMS)	6.37x4.75 mm^2, CMOS
WFS-LAM (Homemade)	11x11 and 22x22 MLA	5.76 x5.76 mm^2, OCAM[2]

3.2 LOL calibration

To work efficiently, an AO system has to be calibrated. Then, the DM deformation has to be related perfectly to the quantity measured on the wave-front sensor to establish this interaction relationship, “Interaction Matrix” (IM), which will be inverted to obtain the Command Matrix (CM). To calibrate the woofer loop system, we used approximately the same setup as shown in figure 9, we only replaced SLM by DM and changed the lenses ratio for beam size adaptation. On figure 5, are shown the DM influence functions, the corresponding Interaction Matrix (IM) and the obtained singular values when performing a Command Matrix (CM). Different modes filtering has been done to optimize the conditioning factor $C_f = \lambda_{min} / \lambda_{max}$ (where λ_{max} corresponds to the eigenvalue of actuators number and λ_{min} is the eigenvalue corresponding to the number of filtered modes). Figure 6 shows an example of closing loop operation for the LOL stage.

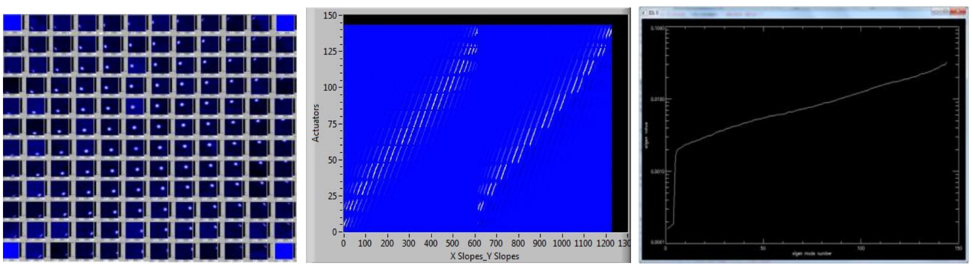

Figure 5. Left side : Influence functions for the 140 DM (12x12 without 4 corners) corresponding to a voltage of +/- 10 V. Center: Corresponding Interaction Matrix showing X and Y slopes (613x2). Right side: Graph showing the SVD (singular values decomposition) corresponding to the IM (conditioning factor is 15).

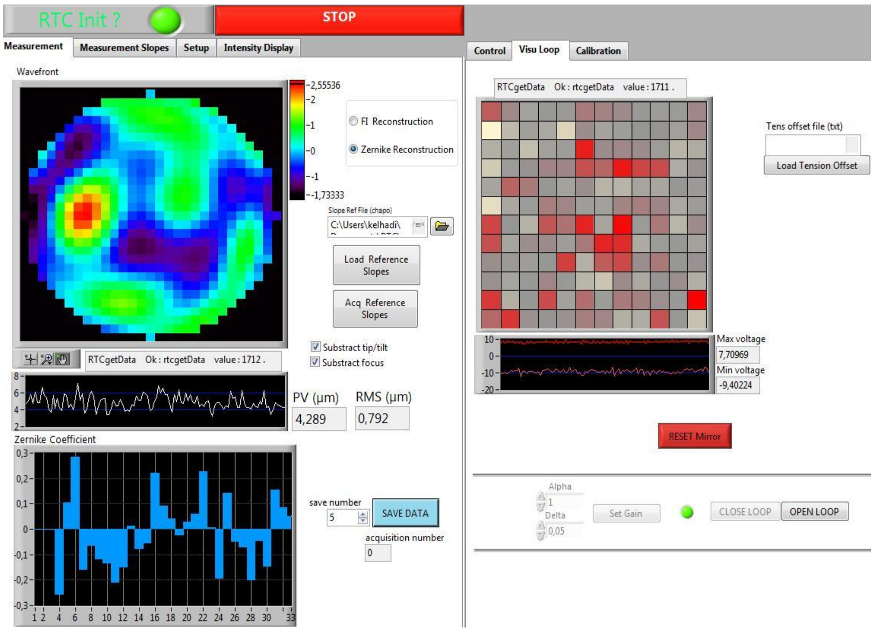

Figure 6. Left side : Influence functions for the 140 DM (12x12 without 4 corners) corresponding to a voltage of +/- 10 V. Center: Corresponding Interaction Matrix showing X and Y slopes (613x2).

3.3 "High Order Loop: HOL" (TWEETER LOOP)

For the tweeter loop, dedicated to high order aberration control, a Pyramid wave-front sensor (PWFS) will be associated to a Liquid Crystal mirror for phase modulation (SLM: Spatial Light Modulator). This tweeter loop is still under construction. However, we present in this section, its state of the art in our laboratory.

One of the advantages of the PWFS, in comparison with the competitive SH-WFS, is that it needs detectors with less pixels. Thus, it offers the possibility of using existing detectors. In our case, we will use the world's fastest and most sensitive camera system OCAM^2 with the pyramid concept to demonstrate a homemade fast and hyper-sensitive PWFS (up to **100x100** sub-pupils) dedicated to the first generation instruments for ELTs.

In figure 7, are presented the pyramid concept and the desired design using OCAM^2 detector (240x240 pixels). While in figure 8, we present the results of the corresponding design obtained from Zemax simulation.

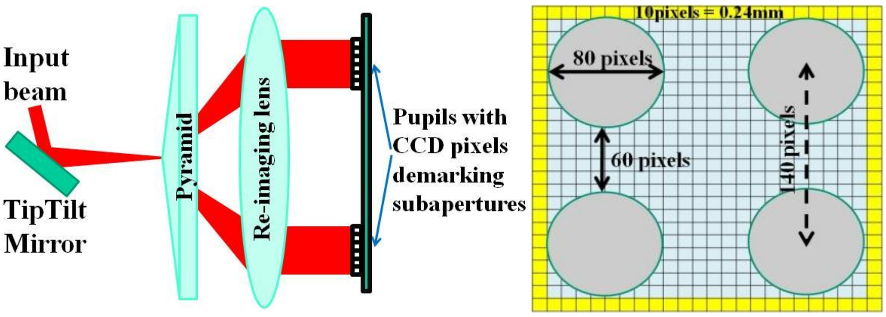

Figure 7. Left side : Pyramid concept. Right side: Example of desired design showing 4 sub-pupils (80 pixels each) located 10 pixels from the edge and separated by 60 pixels.

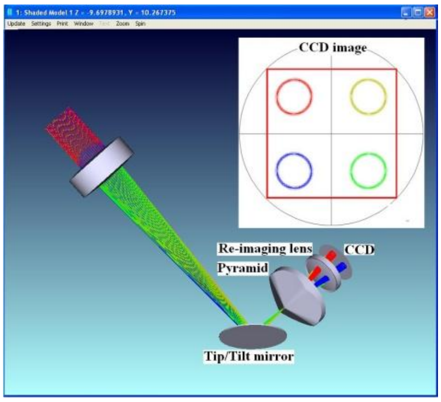

Figure 8. Pyramid concept design under Zemax. Inside figure represents the obtained sub-pupils on OCAM^2 detector (red square) .

Concerning the High density DM, with up to 100x100 actuators, using a liquid crystal SLM mirror (PLUTO-VIS model from HOLOEYE), the main characteristics are shown in table 3.

Table 3. Characteristics for the PLUTO-VIS Phase Only Modulator from HOLOEYE.

HOLOEYE SLM	PLUTO-VIS Model
Display type	Reflective LCoS
Resolution	1920x1080
Pixels Pitch	8.0 µm
Frame rate	60 Hz
Adressing	8 bit
Fill Fcator	87 %

The setup presented in figure 9 has been used for different SLM characterizations both in the pupil and focal planes. Moreover, we performed some aberration measurements for this setup at 695 nm. From the reference bracket, we obtained a value of 0.01 λ RMS, due to the polarizer (0.11 λ without and 0.12 λ with polarizer). Considering the light reflected back from the SLM, we measured 0.16 λ with SLM OFF and 0.08 λ with SLM ON.

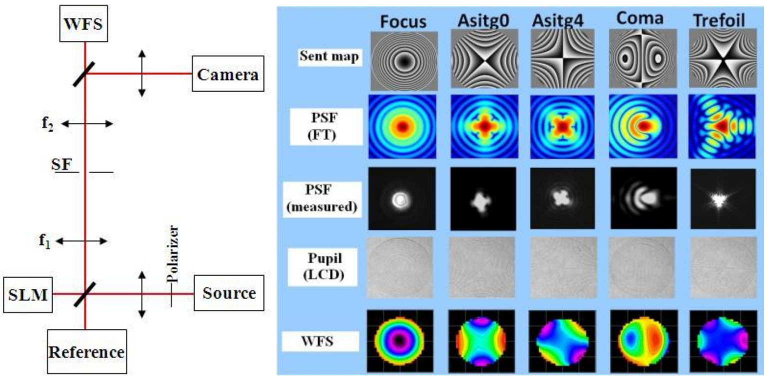

Figure 9. Left side : Schematic setup used for our SLM characterization. A reference mirror is used for comparison. Right side: Different SLM characterizations. Example of different maps (sent to the SLM) and corresponding measurements in the focal and pupil planes with the camera. The wave-fronts are also given in the pupil plane (WFS).

There is still a lot of work to do on the tweeter loop. We have to optimize specifications and order pyramids fabrication, setup and demonstrate the PWFS concept in our laboratory in 2013. Then, we plan to perform LGS tests on sky in collaboration with ONERA by the end of 2014. On the SLM mirror, we have to work on the command control interface to use it as a high order DM. A convenient pixels binning should be found to start, for example, by generating easier influence functions (piston and Tip/tilt modes).

4. SHORT AND LONG TERM DEVELOPMENT.

As described before, the LO stage (made with a12x12 DM and SH-WFS) was integrated and calibrated. For the HO stage, only the high density LCD mirror has been partially characterized. The work on its RTC interfacing and command control is still undergoing. Concerning the hypersensitive homemade Pyramid WFS, using $OCAM^2$ detector, the concept has been already simulated. The pyramids fabrication will be soon ordered. Next developments of the LAM AO bench can be summarized, from short to long term, as follow:

- ✓ Woofer tweeter experiment (2012).
- ✓ Implementation of high order Pyramid with $OCAM^2$ (2013)
- ✓ Implementation of the Multi-stage WFS / DM strategies (end of 2013).
- ✓ Pyramid On-Sky validation (end of 2014).
- ✓ Experimental validation of the ETKF optimized control law (2013 to 2015).

5. CONCLUSION AND PERSPECTIVES.

At Laboratoire d'Astrophysique de Marseille, we are developing an AO bench dedicated to the future instrumentation for ELTs. Indeed, our bench is a multi stage version and an open bench (easy to modify). It is based on the use of a versatile RTC and two stages of wave-front control using a LO loop (140 actuators DM and a 29x29 Shack-Hartman WFS) and a HO loop (high density DM through an LCD mirror with up to 10000 actuators in front of a Pyramid WFS). Using $OCAM^2$, we have access to the state of the art detector to realize a hypersensitive homemade PWFS dedicated to the next generation of instruments for ELTs.

As presented in this paper, the LO WF control stage has been fully characterized and calibrated. For the HO stage, only the characterization of the high density DM, using an LCD mirror offering the possibility of up to 10000 actuators, has been presented. Work on its interfacing and command control with the Real Time Controller is still undergoing. In a short term time scale, the woofer-tweeter concept has to be demonstrated. For the LAM made Pyramid WFS, the concept design is done.. Its implementation and integration on our AO bench is then planned in a second time (by the end 2013). Then the Multi-stage WFS/DM strategies has to be implemented. After all these laboratory demonstrations, the PWFS On-Sky validation will take place by the end of 2014.

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REFERENCES

[1] Ragazzoni R. "Pupil plane wavefront sensing with an oscillating prism," Journal of Modern Optics, 43, 289-293 (Feb.1996).
[2] Gray, M., "Ensemble Transform Kalman Filter, a non stationary control law for complex AO systems on ELTs: theoretical aspects and very first simulation results", SPIE paper, 8447-65 (2012).
[3] Gach. J.L., "$OCAM^2$," AO4ELT-2, Wave-front sensing talk (2011).