# NEW WAVEFRONT SENSING CONCEPTS FOR ADAPTIVE OPTICS INSTRUMENTATION

K. El Hadi*[a], M. Gray [a], T. Fusco[b, a], B. Le Roux[a].
[a]Aix-Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 38 rue Frédéric Joliot Curie, 13388 Marseille, France;
[b]ONERA, Optics Department, 29 avenue de la Division Leclerc, 92322 Châtillon, France

## ABSTRACT

For the last few years, Laboratory of Astrophysics of Marseille has been carrying out several R&D activities in Adaptive Optics (AO) instrumentation for Extremely Large Telescopes (ELTs). In the European ELT (D = 40 m) framework, both theoretical and experimental studies are jointly led. A new theoretical approach for AO control command law with large degrees of freedom is being developed: it is based on the use of Local Ensemble Transform Kalman Filter (Local ETKF). In parallel, an experimental multi-purpose AO bench is mounted to allow the validation of new wave-front sensing and correction concepts dedicated to the next generation of ELTs. All the main AO components, with a large number of spatial (up to thousand) and/or temporal (up to 1.5 kHz) frequencies, are available. From different combinations of these AO elements, several correction and sensing (low order and high order frequencies) studies are possible. Our AO bench is combining different corrector mirrors (MEMS deformable mirror from Boston Micromachines and Spatial Light Modulator from Holoeye) which can be used with Shack-Hartmann and Pyramid Wave Front Sensors (respectively, SH-WFS and PWFS). For this last type of sensor (PWFS), we will use the world's fastest and most sensitive camera system OCAM$^2$ (developed at LAM), 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, Extremely Large Telescope, Local Ensemble Transform Kalman Filter, MEMS Deformable Mirror, Real Time Controller, Wave Front Sensor, Spatial Light Modulator, OCAM$^2$ camera.

## 1. INTRODUCTION

The development of new instrumentation for the future E-ELT will require new AO developments, in terms of simulation (end-to-end simulator for ELTs), optimisation of control laws (classical Kalman Filter will show limitations because of the computation burden, multi-stages correction will be probably needed) and experimental validation of new Wave Front (WF) concepts. Therefore, developing AO systems for an ELT presents a number of challenges, among which we identified two R&D axes in the AO activities at LAM.

The first objective of our work is theoretical and concerns the study of control laws for Large Degrees of Freedom (LDF) systems. Since the number of degrees of freedom grows as the square of the telescope diameter, the classical Kalman filter based optimal control law [1], known to be one of the best solutions for wide field tomographic AO systems [1, 2], will be not adapted in the case of ELTs, because of the numerical complexity for these real time estimations of the turbulent phase:

- ✓ State vectors and observations vectors will have huge dimensions ( $> 10^4$ ),
- ✓ Real covariance matrices computations and storages will be impossible at high frequencies ( > kHz ),
- ✓ There is no possibility to deal with a non stationary model of the turbulence.

To overcome these limitations, we propose the use of Local Ensemble Transform Kalman Filter (Local ETKF), a new method developed in geophysics. For a detailed description of theoretical aspects of ETKF & AO, and the mains ideas of Local ETKF, you can refer to [3]. In the following, we will only remind the principles of this control law for AO and give some first simulations results of Local ETKF, showing that this method can offer a non stationary model of the turbulence associated with a reduced numerical complexity for complex AO systems on ELTS.

*kacem.elhadi@oamp.fr; phone (+33) 495 044 184; fax (+33) 491 621 190

The second axis of our work is experimental and concerns the development of an AO bench whose objectives could be summarized into three points:

- ✓ Implementation of different WF sensing solutions for validation of new detectors and concepts. The combination of different AO elements allows the study of the main configurations to demonstrate different AO concepts (LDF systems, woofer-tweeter solution, fast AO system with up to 1.5 kHz, Local ETKF, …)
- ✓ Implementation of high order Pyramid WFS [4] using the $OCAM^2$ high speed detector [5].
- ✓ On-Sky tests and validations of these new concepts both in terms of control laws (woofer-tweeter, Local ETKF) and new WF sensing methods (PWFS, …).

In this paper, we present the recent developments of the AO activities for future E-ELT instrumentation carried out in collaboration with ONERA. The Local ETKF based control law, dedicated to the study of LDF systems, is first briefly presented. Then, the multi-purpose AO bench, designed to demonstrate different AO solutions, is described. The status of the undergoing activities, the mean features of our bench, the achievements as well as the remaining work to accomplish our goals are given.

## 2. LOCAL ETKF & FIRST SIMULATIONS RESULTS

The two main ideas of ETKF are based, first on the creation of an initial ensemble of m members (m << n & p, the dimensions of state & observation vectors) in order to compute this ensemble representing a propagation of different trajectories and giving an estimation of the turbulence phase, and second on the substitution of the real covariance matrices by the empirical covariance matrices calculated from the m members estimates of this ensemble.

As the Kalman gain is calculated at each update stage (actually the original equation is re written), this control law enables to take into account *non stationary behaviors of the turbulence* during all the observation time and to reduce the numerical complexity of the computations compared to those involved in the use of a classical Kalman Filter in the same non stationary situation.

But for computational reasons, the number of members in the ensemble must remain much lower than the values of n and p [3]. When the diameter of the telescope is increasing (from 8 m to 40 m), we absolutely need to use an extension of ETKF in order to keep the same performances in terms of AO corrections and reduced numerical complexities.

This new version is called Local ETKF and is based on the use of localization by domain decomposition.

The assimilation is split into local domains in which the update data assimilation is performed independently. Figure 1 shows the locations of the actuators (blue dots where the phase is estimated) on the pupil of a 16 m diameter telescope sampled by a 32×32 SH-WFS with a Fried geometry (the square areas between 4 dots represent the sub apertures). In this basic example, the decomposition is made of 25 red estimation domains, each of them composed by a fixed number of actuators. During the update stage, data assimilation (slopes given by the SH-WFS) is performed locally on an observation region around each estimation domain: for instance, the observation region for the central estimation domain is the green one. This kind of assimilation enables parallel computation of much less data during this update stage and enables to have update estimations which tend to lie in a subspace of much lower dimension.

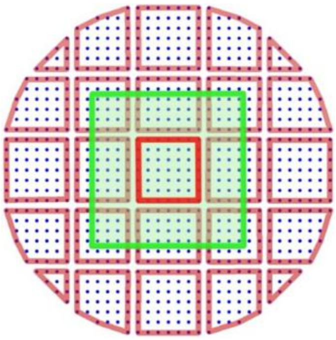

Figure 1. Decomposition of the 25 estimation domains (red) and one observation region (green) for the central estimation domain.

For the simulation of the atmosphere, we consider a Von Karman turbulence: $r_0 = 0.525$ m, $L_0 = 25$ m, $\lambda = 1.654$ µm (for both WFS's and observation's wavelengths). Using Taylor's hypothesis under OOMAO Matlab environment, we can generate a superimposition of 3 turbulent phase screen layers moving at 7.5 $ms^{-1}$, 12.5 $ms^{-1}$, 15 $ms^{-1}$, with a relative strength of 0.5, 0.17, 0.33 respectively. For this zonal Single Conjugate AO (SCAO) system simulation with Local ETKF, we consider a telescope with 2 values for the diameter: 16 m and 32 m with respectively a 32×32 SH-WFS and 64×64 SH-WFS and a transmission factor equal to 0.5. Each AO system works in a close loop at 500 Hz and there is two-step delay between measurement and correction. We assume that the DM has an instantaneous response and the coupling factor of the actuators is 0.3. Phase screens are generated respectively on a 320×320 or on a 640×640 grid, with 10 times 10 points per each sub aperture. With a zonal basis, the phase is estimated only on the actuators' locations (the number of valid actuators is 877 or 3325 for respectively the 16 m or the 32 m telescope). For the turbulence model in the Local ETKF based control law, we have chosen a first order AR model ($a_1 = 0.98$ for D = 16 m and $a_1 = 0.985$ for D = 32 m). The number of members in the ensemble is fixed to a value of 197 in both cases.

The measurement noise variance is fixed to 0.04 Rad² and each value of the Strehl ratio has been calculated with a simulation of 5000 iterations (10 sec).

The following curves (figure 2) obtained with the first simulations of Local ETKF show the performances (Strehl ratio) for different kinds of domain decompositions in function of the width of the observation regions. The point giving the best performance is circled in red: the relevant largest value of the dimensions of the estimation vectors ($n_{max}$) for all the estimation domains and the relevant largest value of the dimensions of the observation vectors ($p_{max}$) for all the observation regions are written in the red box. These values must be compared to these written in the black box and used with the classical Kalman Filter or with ETKF.

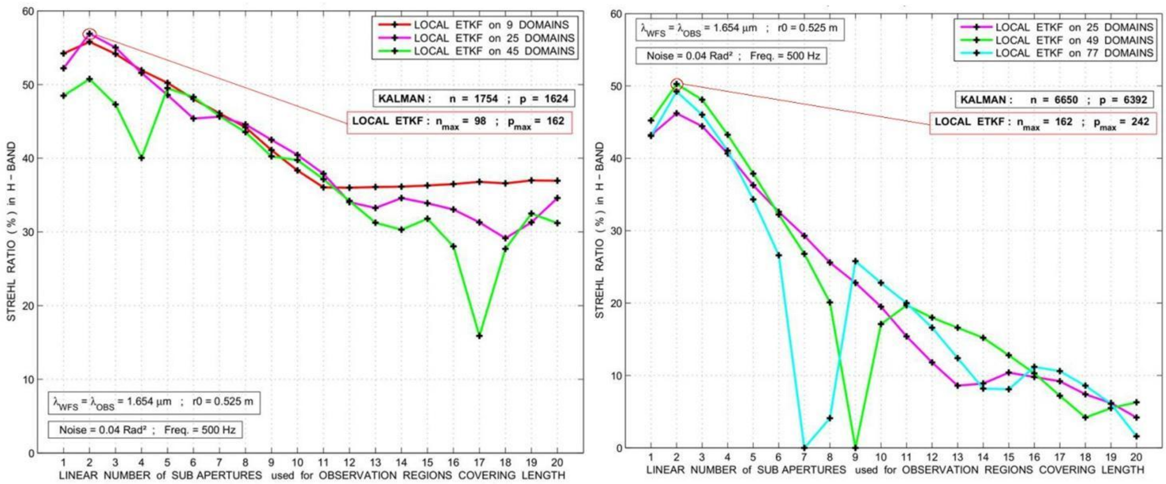


Figure 2. Strehl ratios in the case of Zonal SCAO simulations given by Local ETKF and 3 different domain decompositions. Left side: 16 m diameter telescope with a 32×32 SH-WFS. Right side: 32 m diameter telescope with a 64×64 SH-WFS.

Therefore, in the case of an ELT with Local ETKF based control law, the value of m (number of members in the ensemble), of $n_{max}$ and of $p_{max}$ will remain small in comparison to the initial values of n (dimension of the turbulent phase estimation vector on the whole pupil) and p (dimension of the observation vector on the whole pupil) used with the classical Kalman Filter or ETKF based control laws. The numerical complexity can be therefore dramatically reduced.

As a short conclusion, we remind that, using Local ETKF based control law for complex AO systems on ELTs, we can:

- ✓ Keep the *KF formalism* which enables to obtain an optimal control law,
- ✓ Have a *non stationary model* of the turbulence which enables to deal with the evolution of the turbulence,
- ✓ Have the possibility of a *non linear* state-space model which enables to deal with DM hysteresis or Pyramid WFS (we didn't make simulations with a PWFS but non linear models are already used in geophysics).

And finally, Local ETKF enables to have linear complexity over a reduced number of the parameters of the system [3]. As the values $n_{max}$ and $p_{max}$ are smaller than n & p, with *distributed parallel environment (MPI)* and efficient matrix-vector multiplications on *GPUs*, there will be therefore faster real time identifications of the turbulence.

Of course, the work in progress is to improve these simulations by decreasing the present number of members in the ensemble (197) with better values of Strehl ratios. This will be obtained with an AR2 model for the turbulence model in the Local ETKF based control law and with a change of basis for the factorization of the turbulent phase.

## 3. EXPERIMENTAL ADAPTIVE OPTICS ACTIVITIES

The LAM experimental AO bench has been designed and built around the idea of being a versatile tool for demonstration of new wave-front sensing and control solutions for future E-ELT instrumentation. With the availability of the main AO components (MEMS DM, high density SLM, SH-WFS, PWFS), our Multi-purpose and open bench makes several AO studies possible.

In this section, we will present the AO bench objectives and, its design scheme, simulation and key points, the characterization or status of the different AO elements as well as the next developments to achieve our goals.

### 3.1 Objectives

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

- **New wave-front control concepts test for ELT instrumentation**

The first objective concerns the experimental study of control solutions for validation of new detectors and concepts. The use of low order (LO) and high order (HO) correctors (respectively MEMS DM and high density SLM mirror) and wave-front sensors (respectively SH-WFS and PWFS) is useful to demonstrate different AO studies (Multi stage AO, LDF systems, woofer-tweeter solution, fast AO system with up to 1.5 kHz, Local ETKF) for AO instruments on E-ELT.

- **New wave-front sensor scheme (HO Pyramid with $OCAM^2$ high speed detector ).**

The second goal is the experimental validation of the Pyramid Wave Front Sensor (PWFS) in ELTs conditions with a Laser Guide Star (LGS). Furthermore, using the world’s fastest and sensitive camera $OCAM^2$[3],we will demonstrate new ultra-sensitive and fast sensor in AO environment. The PWFS laboratory validation is planned by the end of 2013.

- **On-Sky tests and validation**

The On-Sky demonstration of these new concepts both in terms of control laws (woofer-tweeter, Local ETKF) and new WF sensing methods (mainly the PWFS) is essential and makes naturally the end step before their complete validation. This preparation of On-Sky tests is planned in collaboration with ONERA and will take place by the end of 2014 at OCA (Observatory of Côte d’Azur).

### 3.2 Design, simulation and key points

The description of the AO setup we designed to reach the objectives defined in the previous paragraph is shown in figure 3. The left side illustrates a schematic overview of the LAM AO bench while the right side shows its simulation under ZEMAX optics software.

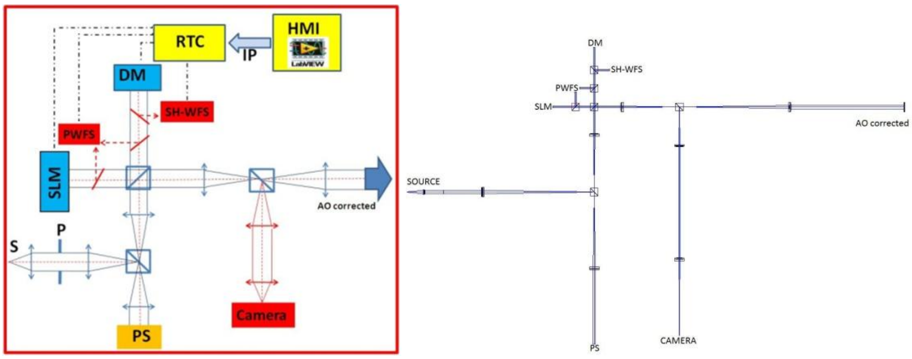


Figure 3. Left side: Schematic representation of LAM AO bench (left side). S (Source), P (Pupil), PS (Phase Screen), DM (Deformable Mirror), SH-WFS (Shack-Hartman Wave Front Sensor), SLM (Spatial Light Modulator), PWFS (Pyramid Wave Front Sensor), RTC (Real Time Calculator), IP (Internet Protocol address) and HMI (Human Machine Interface). Right side: AO bench simulation under Zemax optics software showing the "low orders" and "high orders" correction stages and a third arm for imaging purpose.

In terms of functionalities, the LAM AO bench is based on a 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 and 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 SLM corrector and HO Pyramid sensor for fast AO studies .

### 3.3 LO control stage (MEMS DM + SH-WFS)

- **Presentation**

Based on the use of a 140 actuators MEMS DM and SH-WFS, this wave-front control stage (or woofer) 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 has been fully characterized using many as shown in table 1 (12x12 array without 4 corners with 4.95 mm square of active area, 450 µm actuator pitch, 16-18nm RMS surface data, around 20% actuator coupling and 2.3 µm optical deflection). The figure 2**,** shows some other characterizations in terms of original deflection, linearization of mirror deformation and spatial linearity. One can notice, on the DM deflection graph (figure 4, left side), 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,center, blue curve). Moreover, the spatial linearity has been also measured (figure 4, right side).

Table 1: Main characteristics for our MEMS deformable mirror.

| Different characterizations | Values | Notes |
|---|---|---|
| Dimensions & Actuator pitch | 4.95 mm square & 450 µm | Microscopy measures |
| Surface quality | 16 nm RMS<br>18nm RMS | MiniFiz interferometry<br>Zygo interferometry |
| Actuator coupling | 22 % | WFS measure and analysis |
| Stroke (for single actuator) | 2.3 µm | WFS measure and analysis |

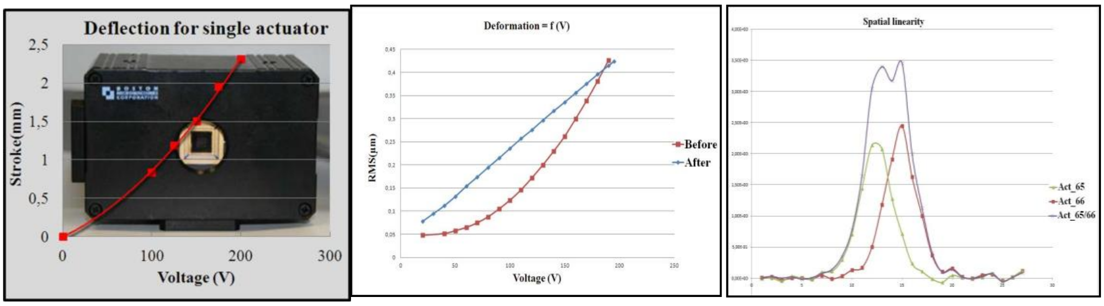


Figure 4. Left side: Graph showing original mirror deformation as a function of applied voltage. Centre: Graph showing mirror deformation before (red) and after (blue) linearization process. Right side: Spatial linearity is shown (addressing both consecutive actuators is equivalent to their addition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

In terms of wave-front sensors components, we have in house several SH-WFS type with different characteristics (summarized in table 2).

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$^2$ |

- **Integration and 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). 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 $\lambda_{max}$ corresponds to the eigenvalue of actuators number and $\lambda_{min}$ is the eigenvalue corresponding to the number of filtered modes). Figure 6 shows an example of closing loop operation for the LO stage.

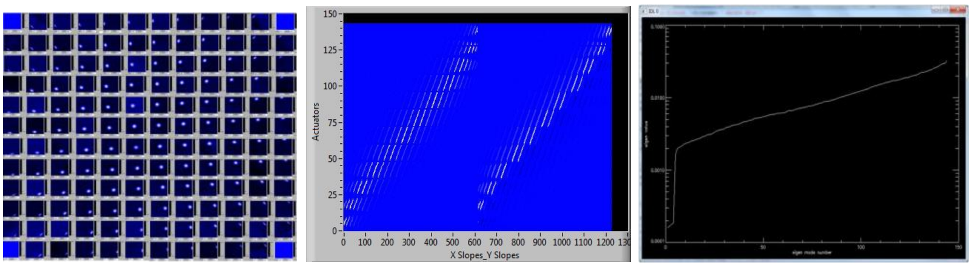


Figure 5. Left side : Influence functions for the 140 DM (12x12 without 4 corners) corresponding to a voltage of +/- 10 V. Center: Corresponding Interaction Matrix showing X and Y slopes (613x2). Right side: Graph showing the SVD (singular values decomposition) corresponding to the IM (conditioning factor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

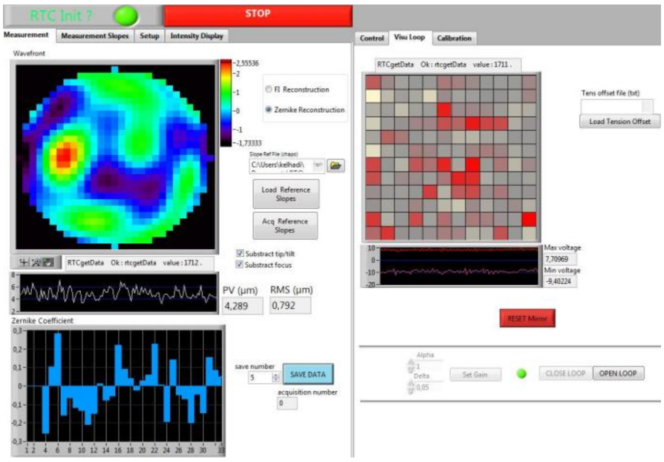


Figure 6. Example of closed loop operation

### 3.4 HO control stage (SLM mirror + PWFS)

- **Presentation**

Combining a high density SLM mirror and a HO Pyramid sensor, this HO AO loop (or tweeter) is dedicated to correct for the high order residuals aberrations coming out from the LO control stage. This HO loop is still under construction. However, we present, its status in our laboratory.

- **High density SLM characterization**

Concerning the High density SLM mirror (up to 10 000 actuators), 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 Factor | 87 % |

The setup presented in figure 7 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 $\lambda$ RMS, due to the polarizer (0.11 $\lambda$ without and 0.12 $\lambda$ with polarizer). Considering the light reflected back from the SLM, we measured 0.16 $\lambda$ with SLM OFF and 0.08 $\lambda$ with SLM ON.

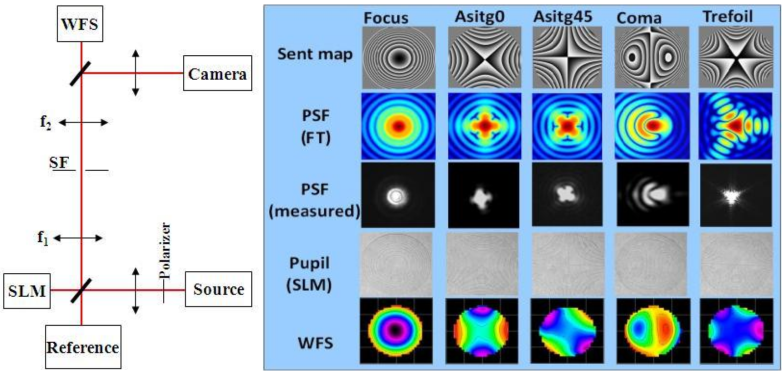


Figure 7. Left side : Schematic setup used for our SLM characterization. A reference mirror is used for comparison. Right side: Different SLM characterizations. Example of different maps (sent to the SLM) and corresponding measurements in the focal and pupil planes with the camera. The wave-fronts are also given in the pupil plane (WFS).

- **High Order PWFS simulation**

Using the world's fastest and most sensitive camera system OCAM$^2$ (240x240 pixels detector). with the pyramid concept, we plan to demonstrate a homemade fast (1.5 kHz) and hyper-sensitive PWFS (up to 100x100 sub-pupils) dedicated to the first generation instruments for ELTs.
In figure 8, are presented the desired configuration (with 4 sub-pupils on detector) and the pyramid concept we obtained from Zemax in the plane of the OCAM detector.

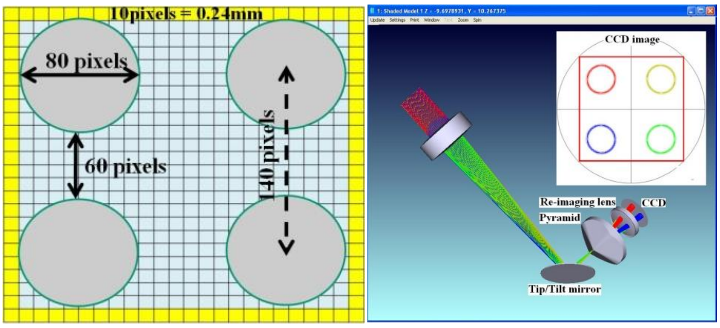


Figure 8. Left side : Configuration Design showing 4 sub-pupils (80 pixels each) located 10 pixels from the edge and separated by 60 pixels. Right side: Pyramid concept design under Zemax. Inside figure represents the obtained sub-pupils on OCAM2 detector (red square).

The pyramids have been optimized and ordered. The PWFS concept will be demonstrated in our laboratory early in the coming months and implemented in the AO bench in 2013. Then, we plan to perform LGS tests on sky in collaboration with ONERA by the end of 2014.

### 3.5 LAM AO means and possible AO studies.

- **Different AO components**

The main components necessary for an AO bench are available. In table 4, we present the LO and HO wave-front correctors (MEMS and SLM mirrors) and sensors (SH and PWFS types) with different spatial and temporal frequencies. One of the main features and important AO component of the LAM/ONERA facilities, is the versatile Real Time Controller (with up to 2.4 kHz, upgradable, multi DM, multi WFS) which has been tested and validated both in laboratory and On-Sky conditions by ONERA at OCA.

Table 4. The different elements used for the LAM AO bench . MEMS DM: MEMS deformable mirror, SLM: Spatial Light Modulator, SH-WFS: Shack-Hartmann wave-front sensor, PWFS: Pyramid wave-front sensor and RTC: Real Time Computer.

| Elements | Spatial frequency | Temporal frequency |
|---|---|---|
| MEMS DM | 12x12 | > 1 kHz |
| SLM | 1920 x 1080 | 60Hz |
| SH-WFS | 10x10 to 64x64 | 100 Hz |
| PWFS | 80 x 80 (100x100) | 1.5 kHz |
| RTC | Versatile | |

- **Possible AO studies**

The availability of all the different AO elements in house makes the possibility, from different combinations, of several AO concepts demonstration. In table 5, we give a spectrum of the AO studies and the corresponding experiments for their implementation.

Table 5. The different AO studies with the corresponding experiment that could be used for their demonstration. MEMS DM: MEMS deformable mirror, SLM: Spatial Light Modulator, SH-WFS: Shack-Hartmann wave-front sensor, PWFS: Pyramid wave-front sensor and RTC: Real Time Computer.

| AO Studies | Experiments | |
|---|---|---|
| | **Corrector** | **Sensor** |
| Woofer-Tweeter | MEMS DM + SLM | with SH-WFS (PWFS) |
| HO Pyramid | SLM | Pyramid |
| Multi-stage AO | SLM<br>MEMS DM | Pyramid<br>SH-WFS |
| Fast AO | MEMS DM | Pyramid |
| On-Sky Tests (ONERA bench) | MEMS DM | SH+OCAM demonstrated<br>Pyramid + OCAM Coming soon |

## 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 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 are ordered. Next developments of the LAM AO bench can be summarized, from short to long term, as follow:

- ✓ 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.

LAM is developing an Adaptive Optics bench dedicated to the future instrumentation for ELTs. Both theoretical and experimental studies are being carried out in parallel for demonstration of new wave-front control and sensing solutions. As joint equipment, a laboratory versatile and multipurpose AO bench (LAM) and an On-Sky test bench (at ONERA, Observatory of Cote d'Azur) are available. With the main AO components, HO & LO correctors (MEMS and SLM mirrors) and HO & LO wave front sensors (Shack-Hartmann and Pyramid types), added to a versatile Real Time Controller, tested and validated both in laboratory and On-Sky, several AO configurations studies are then possible.

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. For the LAM made Pyramid WFS, the concept design is done. Its implementation and integration on our AO bench is then planned in 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.

## AKNOWLEDGEMENT

Authors are grateful to all the people who have been involved in the work presented in this paper (J. L GACH and P. BALARD from LAM, D.RABAUD and F. CHAZALET from SHAKTIWARE, P. JAGOUREL and C. CHAUMONT from GEPI-Observatoire de Paris).
These studies were partially funded thanks to the support of FP7-OPTICON program, the French CSAA INSU financial support and Région PACA funds.

## REFERENCES

[1] Le Roux B. et al., "Optimal control law for classical and multiconjugate adaptive optics," JOSA A, **21**, 1261-1276 (2004).
[2] Petit C. et al, "LQG control for adaptive optics and MCAO: experimental and numerical analysis," JOSA A, **26**, 1307-1325 (2009).
[3] Gray M., Le Roux B., "Ensemble Transform Kalman Filter, a non stationary control law for complex AO systems on ELTs: theoretical aspects and first simulation results," SPIE paper, **8447-65** (2012).
[4] Ragazzoni R., "Pupil plane wavefront sensing with an oscillating prism," Journal of Modern Optics, **43**, 289-293 (Feb.1996).
[5] Gach J.L., "OCAM$^2$," AO4ELT-2, Wave-front sensing talk (2011).