High speed and High precision pyramid wavefront sensor.

In labs validation and preparation to on sky demonstration

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ABSTRACT

Since the introduction of the pyramid wavefront sensor [P-WFS] concept (Ragazzoni), numerous investigations have clearly shown its ability to achieve better performance (sensitivity, dynamic range) than the standard Shack-Hartman [SH-WFS]. It has recently been successfully implemented on LBT and has already been provided very interesting results (Esposito et al). Then, most of the future adaptive optics [AO] systems, mainly for ELT instrumentation, will probably integrate one or several pyramidal sensors. However, the pyramid behavior still needs to be extensively studied in order to ensure its optimization in real conditions of operation. So, the coupling in an AO loop and the control of this type of sensor is fundamental for an efficient implementation in the future AO systems.

At LAM, we recently carried out in labs demonstration of an extremely performant pyramid sensor (up to 60x60), using particularly an OCAM² detector (1.5 kHz, RON close to zero). Both modulated and fixed configurations are investigated and compared with numerical models. The P-WFS is being coupled with a dedicated RTC and a 12x12 DM to achieve a first AO closed loop operation. For modulation, a fine control is needed: a specific electronic module, interfaced with the RTC, is being developed to drive the TT mirror (OCAM² triggering). Then, various TT mirrors are under test to determine a suitable one. After tests of the pyramid specificities (optimiziation, calibration and operation procedures), the P-WFS will be tested on-sky and compared wih an already existing SH-WFS (using the same OCAM²) on the ONERA bench.

Keywords: Extremely Large Telescope, E-ELT, adaptive optics, wavefront sensing, Pyramid wavefront sensor, deformable mirror, OCAM2 camera.

1. INTRODUCTION

In the European Extremely Large Telescope [E-ELT] studies, several instruments are in preparation[1,2,3]: such as HARMONI, MICADO for the first generation or still EPICS in a more long term range. Most of the adaptive optics [AO] systems will probably integrate one or several pyramidal wavefront sensors [P-WFS], original idea of R. Ragazzoni[4,5]. Indeed, the concept seems to combine very good ultimate performance (mainly for systems dedicated to high contrast), a robustness to noise allowing to observe faint objects (increased sky coverage fundamental for high-resolution ground astronomy) and a simplicity of calculation to retrieve the incident wavefront (allowing to manage large number of degrees of freedom) what makes it very attractive for wide ELT applications.

Then, since its appearance in the mid 90s, the pyramid sensor aroused a lot of interest and numerous investigations [5, 6, 7], both theoretical and experimental, have clearly shown its ability to achieve better performance (sensitivity, dynamic range) than the standard Shack-Hartman [SH-WFS]. However, even though it has recently been successfully implemented on LBT and has already been provided very interesting results, the pyramid behavior still needs to be extensively studied in order to ensure its optimization in real conditions of operation. So, the coupling in an AO loop and the control in laboratory (then on sky) of this type of sensor (optimization of measurement processes, calibration and operation on the telescope) is fundamental for an efficient implementation in the future AO systems on the E-ELT. In particular, the P-WFS behaviour in "typical" conditions of use (particularly for weak flux and turbulence limited regime) is fundamental to be able to reach the ultimate performances of the AO systems and thereby those of the telescope itself.

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At Laboratory of Astrophysics of Marseille (LAM), we recently carried out several studies[6,7] (optical design, testing, specific control algorithm and performance evaluation) to achieve in labs demonstration of an extremely performant, high speed and hypersensitive P-WFS (up to 60x60) based particularly on the use of an OCAM² camera[8] (1.5 kHz and a RON close to zero).

After a deep analyze of the WFS itself (coupled with extensive comparison with end-to-end models) in both modulated and diffraction-limited modes, the P-WFS has been coupled with a dedicated RTC and a first AO loop has been closed using a 12x12 BMM deformable mirror.

After tests of the P-WFS specificities, and an optimiziation of the calibration and operation procedures, the P-WFS and its associated RTC will be integrated in the ONERA AO bench permently located at Observtoire de la Cote d'Azur in order to be tested on-sky and compared wih an already existing SH-WFS (using the same OCAM²).

In this paper, the first experimental results are presented. Both modulated and non modulated configurations are investigated and compared with numerical models to fully characterize the pyramid behavior. Various Tip-Tilt [TT] mirrors are under test in order to control the modulation, in particular, in the high frame rate regime of the $OCAM^2$ camera.

2. NUMERICAL MODELS

Since the very interesting results obtained recently on the LBT, the choice of the pyramid WFS as baseline for the first light AO system on E-ELT is becoming natural. The pyramid WFS is naturally better than SH for aliasing and sensitivity (gain increasing with telescope size). The graph[9] shown on figure 1 illustrates a typical gain of 2 mag on VLT (small loss of final sensitivity with pyramid). This gain is supposed to increase with the diameter of the telescope, and should therefore be even higher with E-ELT. As shown on figure 1, the gain in term of limiting magnitude R is expected to be varying with the amplitude of modulation. But even with a modulation of 3 diffraction size, the gain in magnitude is higher than 2.

In the E-ELT studies framework, particularly for the SCAO-HARMONI system, we have been developing numerical simulations tools (figures 2, 3) in order to fully investigate the pyramid behavior in terms of performance, linearity, sensitivity, effect of modulation. For now the main question we are studying concerns the capacity of pyramid wave-front sensor to deal with Non Common Path aberrations. This question directly translates into characterizing the linearity of the PWFS, which means its capacity to estimate a wave-front whatever its amplitude.

The numerical simulation we have performed are therefore concerning linearity range. The simulation tool we developed in IDL for simulating PWFS measurement in different conditions assumes :

- Fourier-based propagation,
- F/50 optical beam
- Pyramid with perfect optical optics
- Phase only aberrations
- Modal basis is Zernike, Karuhnen-Loeve, influence functions, or pixel basis.

The figure 2 shows the typical product of this simulation tool : four pupil planes on the detector, with no modulation (left) and with 3 lambda/D modulation (Lambda being the wavelength for WFS and D being the diameter of the telescope).

An interaction matrix is recorded and inverted in order to reconstruct the PWFS phase from any measurement. The figure 3 then shows linearity curves of the PWFS for the reconstruction of one single mode (Tip in this case). The left case shows the limited linearity range when PWFS is not modulated. For phase aberrations larger than 0.3 radians (which is 33nmRMS), the linearity curve deviates from more than 10% from the expected one. With the modulated case, the linearity range is greatly enhanced and reaches more than 2 radians with 1.35 lambda/D amplitude modulation (which is 220nmRMS). The modulation enhances the linearity range, this is of course a known result of PWFS[9], but allows us to be confident that the PWFS will be a good option to deal with NCPA aberrations.

The perspective of this work is off course to continue on linearity study:

- Linearity study of a mode, in the presence of residual turbulence
- End-to-end simulation of PWFS with NCPA scheme compensation

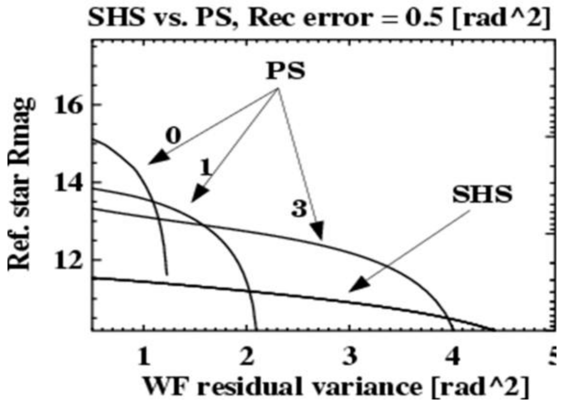


Figure 1. Comparison of SH and pyramid sensors performance (from Esposito et al, 2000)

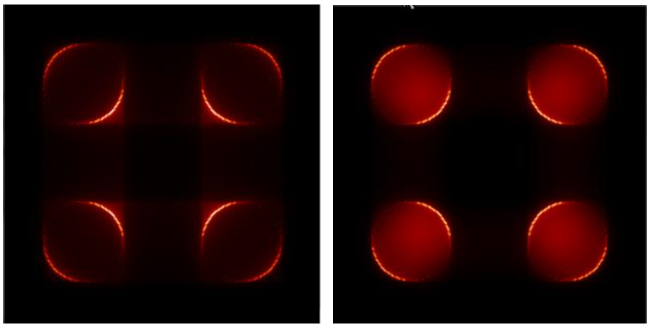


Figure 2. Illustrations from simulation showing unmodulated (left) and modulated (right) pyramid cases.

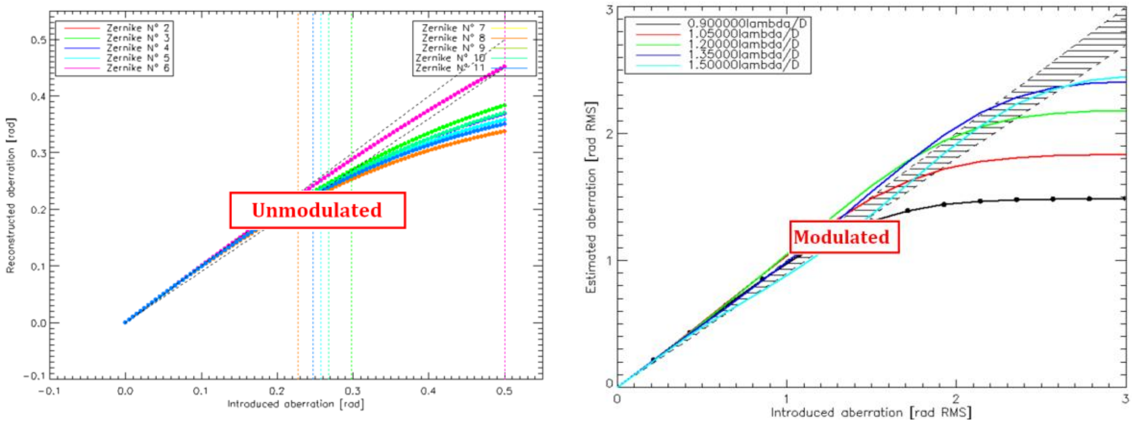


Figure 3. Comparison of unmodulated (left) and modulated (right) pyramid modes for various amplitude (lambda/D).

3. PYRAMID SENSOR DEVELOPMENT: FROM DESIGN TO IMPLEMENTATION

3.1 Optical and opto-mechanical designs.

Using a state of the art detector with the OCAM2 camera (table1), we first designed optically a desired configuration (Zemax software) of the pyramid concept (an opto-mechanical design has been also done). All the pyramid parameters (material, angle, thickness, back face angle, edge width, faces orthogonality, etc) were then optimized. An illustration of the pyramid concept as well as a pyramid image are shown in figure 4.

Table 1. OCAM^2 camera specifications.

OCAM^2 Detector (First Light Imaging)	EMCCD from E2V
Pixels	240 x 240
Pixel size	24 mm
Frame	1500 fps
QE	94%@650 nm
Noise(@1300fps)	0.55 e
Dark signal (@1300fps)	0.01 e/pix/frame

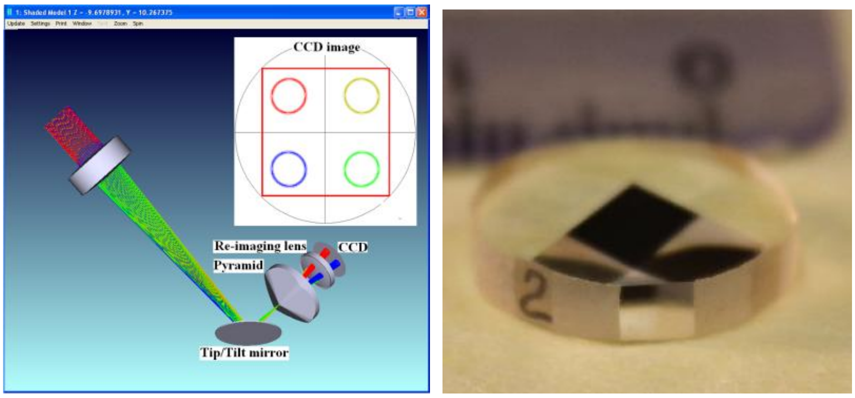


Figure 4. [Left] Pyramid concept under zemax with image on CCD (medallion). [Right] Pyramid view

3.2 Assembly and test.

After optical and opto-mechanical designs, interfacing the OCAM2 camera and the TT mirror (for modulation) with the RTC, we assembled the pyramid sensor in different configurations to be tested. Both unmodulated and modulated pyramid experimental setups are shown in figure 5.

3.3 Pyramid control algorithm development

Naturally, we have also developed control algorithms to process the pyramid signals with two objectives using (for this first step, real time aspects were ignored).

- Matlab program to determine all the parameters of the four pupils(centers, diameters, averaged intensities, number of “sub-pupils”), calculate the pyramid signals (slopes) and retrieve the wavefront (figure 6).

- Labview interface (figure 7) for the control and the display of the pupils parameters.

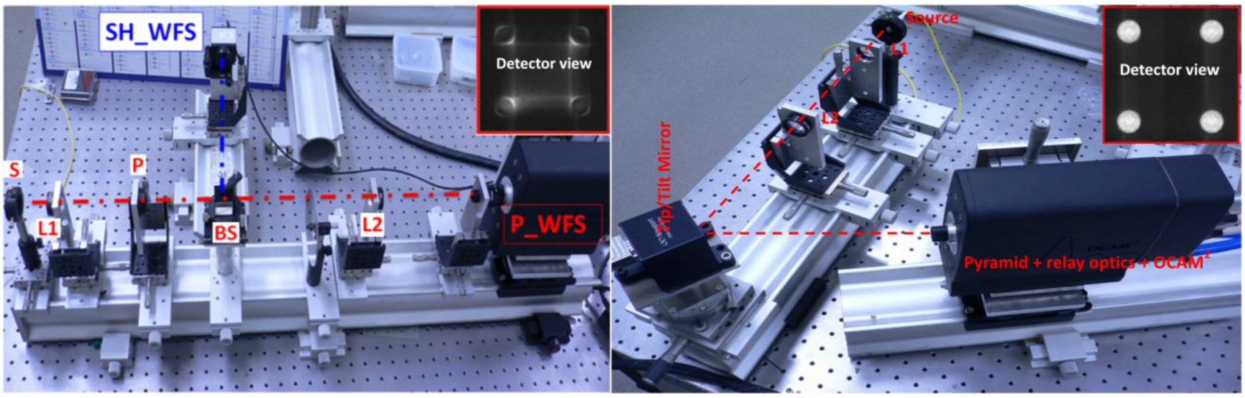


Figure 5. Pyramid experimental setups. [Left] Unmodulated version (S: source, P: pupil, BS: beam splitter, L1 and L2: optical lenses) with a Shack-Hartmann used for comparison. [Right] Modulated version using a TT mirror. In medallion: $OCAM^2$ detector views.

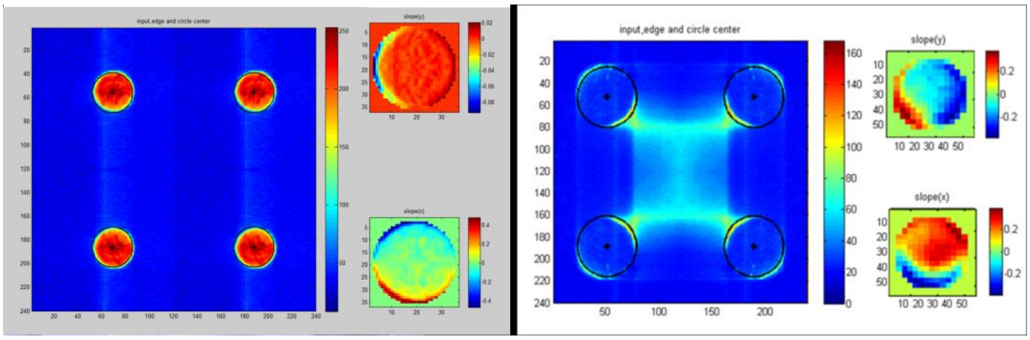


Figure 6. Pyramid signals (slopes) processed with Matlab algorithm for modulated (left) and unmodulated (right) modes.

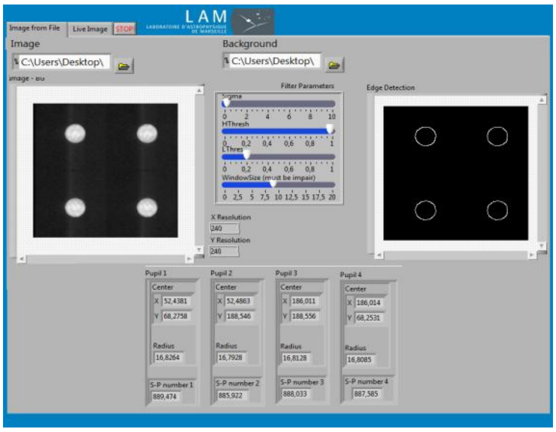


Figure 7. Labview user interface displaying all the parameters (modulated case).

3.4 First results and comparison with numerical models

- **Unmodulated mode**

We first used the pyramid sensor only in the unmodulated configuration to perform our experimental work. As shown in figure 8, the first results, obtained for tip/tilt aberrations for example, are in perfect accordance with simulations.

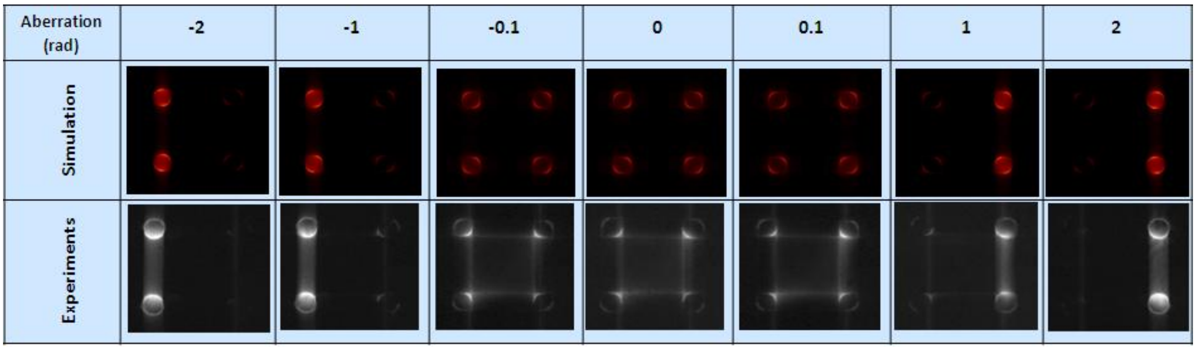
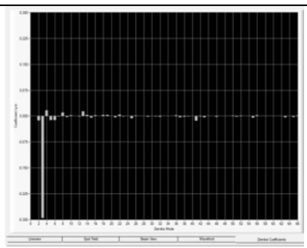
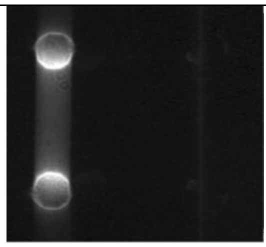
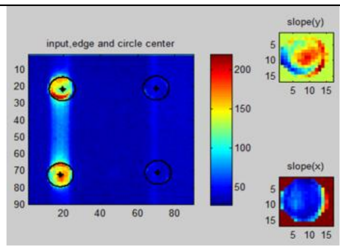
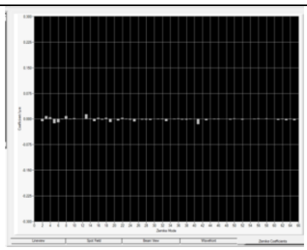
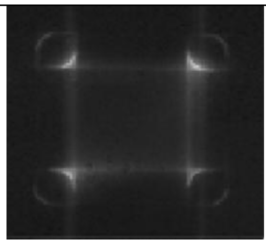
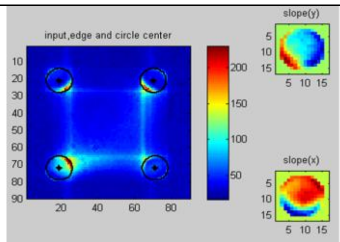
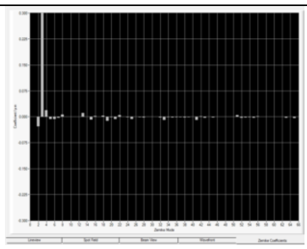
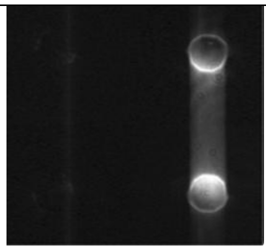
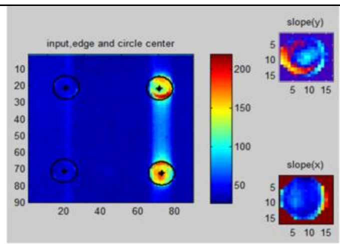


Figure 8. Comparison between simulation and experiments (unmodulated case) for different tip/tilt aberrations.

To test and validate our pyramid algorithm on simple cases (low order aberrations: TT and focus), the same aberration was simulated then applied, measured experimentally with the pyramid and compared with SH using the setup shown in figure 5 (left). The results are shown in table 2 and confirm the agreement with simulation and measurements from the SH sensor.

Table 2. Measurements from pyramid, processed and compared with SH (for negative, zero and positive aberration).

	SH_WFS	P_WFS	Processed (algorithm)
(-) aberration			
(0) aberration			
(+) aberration			

The measurements of wavefront slopes variation with TT aberration amplitude have shown also a perfect agreement with simulation as illustrated in figure 9.

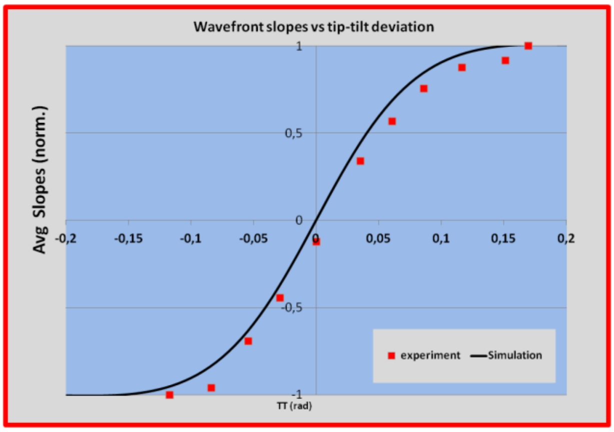


Figure 9. Variation of wavefront slopes with TT amplitude: comparison between measurements and simulation.

The same work has been done for focus also and similar results were obtained (figure 10) showing that (as expected) the pyramid becomes non-linear (reaching a saturation) when large aberration is introduced.

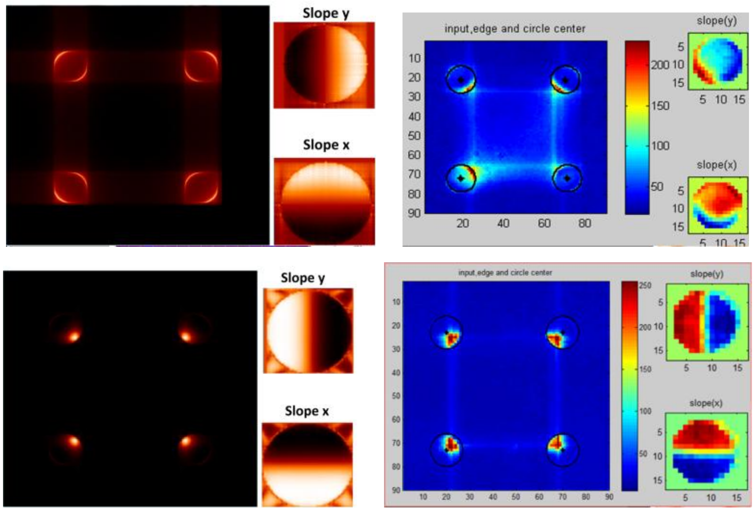


Figure 10. Simulation and measurement of a low (top) and strong (bottom) focus aberration (-2 radians). Data were analyzed using our pyramid algorithm.

- **Modulated mode.**

For the modulated mode, the idea was to perform the same tests and comparisons. However, this has been observed to be a little more complicated than planned. Indeed, with the OCAM2 camera running @1.5kHz, we have developed a specific electronic module to control finely the modulation: the TT mirror is then triggered from the camera for best synchronization. This work is undergoing for full tests and characterization. Once, the modulation is under control, then a suitable (the right) mirror has to be determined among those that we are testing with resonant frequencies up 5kHz (from Newport, PI, etc).

3.5 AO closed loop operation

For the reasons we mentioned previously, only the unmodulated mode is considered here. The control algorithm has been validated and transferred for a first "Lab RTC" (without real-time constraint) design. In the figure 11 are shown the AO loop setup using the pyramid with a 12x12 DM and the RTC interface (running @500Hz and still under optimization).

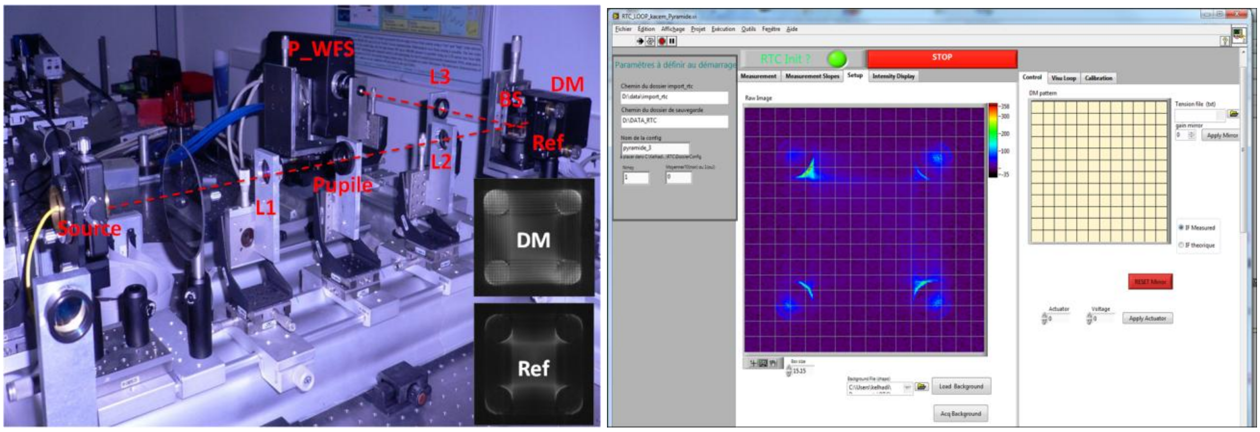


Figure 11. Pyramid experimental setup showing an AO loop with unmodulated pyramid version (Source, Pupil, BS: beam splitter, DM: deformable mirror, Ref: reference arm, L1, L2 and L3: optical lenses). In medallion: $OCAM^2$ detector views for both DM and Reference arms.

4. CONCLUSION AND PERSPECTIVES

In the E-ELT framework, particularly for the SCAO HARMONI system, the LAM-ONERA team is developing a performant pyramid wavefront sensor using the fast sensitive $OCAM^2$ (1.5 kHz and RON close de zero). Numerical models tools have been also developed for comparison and further pyramid behavior investigation. The final objective of our work, is to have a pyramid sensor implemented in an AO loop, fully functional, tested and validated in labs and on-sky both in modulated and unmodulated modes.

In this paper, we presented the "In labs" demonstration of a pyramid sensor with a closed AO loop operation using a12x12 DM. The first results obtained with the unmodulated version have shown good agreement with simulations models. The specific controls algorithms that we have developed for pyramid signal processing are functional. Then, a dedicated "Lab RTC" (without strong real-time constraint, now running @500 Hz) has been designed and developed. It has been used for a first AO loop operation coupling the pyramid sensor with a 12x12 DM. For the modulation mode, further investigation is needed in order to finely drive the TT mirror with synchronization with the OCAM2camera @1.5 kHz. Various TT mirrors are under test. Full modulated pyramid AO loop operation and validation is planned by the end of this year. The lessons learned will help us to move forward to design the "On-sky pyramid RTC"

On-sky tests, planned in 2015, using the ONERA test bench, will permit the pyramid validation

The access to an on-sky (and already fully characterized) test bench will represent a fundamental stone in the future optimisation of calibration, optimisation and operation processes of the pyramid WFS. This will permit also a real comparison with a Shack-Hartmann sensor (using the same $OCAM^2$) already used in the ODISSEE ONERA test bench at Observatory of Cote d'Azur (tests planned by 2015)

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