DEVELOPMENT OF A PYRAMID WAVEFRONT SENSOR

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Abstract. Within the framework of the E-ELT studies, several laboratories are involved on some instruments: HARMONI with its ATLAS adaptive optics [AO] system, EAGLE or EPICS. Most of the AO systems will probably integrate one or several pyramidal wavefront sensors, PWFS (R. Ragazzoni [1-2]). The coupling in an AO loop and the control in laboratory (then on sky) of this type of sensor is fundamental for the continuation of the projects related to OA systems on the E-ELT.
LAM (Laboratory of Astrophysics of Marseille) is involved in particular in the VLT-SPHERE, ATLAS, EPICS projects. For the last few years, our laboratory has been carrying out different R&D activities in AO instrumentation for ELTs. An experimental AO bench is designed and being developed to allow the validation of new wave-front sensing and control concepts [3]. One the objectives of this bench, is the experimental validation of a pyramid WFS. Theoretical investigations on its behavior have been already made.
The world's fastest and most sensitive camera system (OCAM2) has been recently developed at LAM (J.L Gach [4], First Light Imaging). Conjugating this advantage with the pyramid concept, we plan to demonstrate a home made Pyramid sensor for Adaptive Optics whose the speed and the precision are the key points.
As a joint collaboration with ONERA and Shaktiware, our work aims at the optimization (measurement process, calibration and operation) in laboratory then on the sky of a pyramid sensor dedicated to the first generation instruments for ELTs. The sensor will be implemented on the ONERA ODISSEE AO bench combining thus a pyramid and a Shack-Hartmann wavefront sensors. What would give the possibility to compare strictly these two WFS types and make this bench unique in France and even in Europe.

1. Introduction

Laboratory of astrophysics of Marseille (LAM) is one of leading players in France and in Europe involved in the preparation of the E-ELT [5-7]. From both the technical point of view (studies for the manufacturing of the segments of M1 for example [8]) or scientist (PI of two studies of phase A for the ELT instrumentation), the LAM's engineers and researchers are strongly involved in this major project of the ground astronomical instrumentation.

In the last few years, our R&D optics instrumentation team (LOOM) has been carrying out diverse activities around the application of Adaptive Optics techniques (OA) within the framework of the E-ELT. An AO bench, designed to allow the validation of new instrumental concepts is under development.

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One of the objectives of this bench, is the experimental validation of a pyramid wavefront sensor (PWFS). Theoretical studies and simulations on its behavior were led and have shown that the PWFS is competitive in comparison with the classical Shack-Hartman one. Using an $OCAM^2$ camera (First Light Imaging), a state of the art in terms of detectors, the idea is to develop at LAM a unique sensor which will be one of angular stones of the future developments of the AO instrumentation for the ELT.

In this paper, we present the status of the pyramid wavefront sensor development at LAM. It will be implemented in a multi-purpose AO bench, designed to demonstrate different AO solutions for ELT instrumentation.

2. Presentation of LAM AO bench

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 (fig.1) makes several AO studies possible (Multi stage AO, Large Degrees of Freedom systems, woofer-tweeter solution, fast AO system with up to 1.5 kHz, Local ETKF [9]). It is based on the use of:

- Low order (LO) and high order (HO) correctors, respectively, MEMS DM and high density spatial light modulator (SLM) mirror.

- LO and HO wavefront sensors, respectively, Shack-Hartmann and Pyramid types

- Versatile Real Time Controller, based on ORCA concept, whose development (by SHAKTIWARE), was partially funded in the frame of FP7-OPTICON program.

- State of the art detector with OCAM2 (and other new large CCD development undergoing).

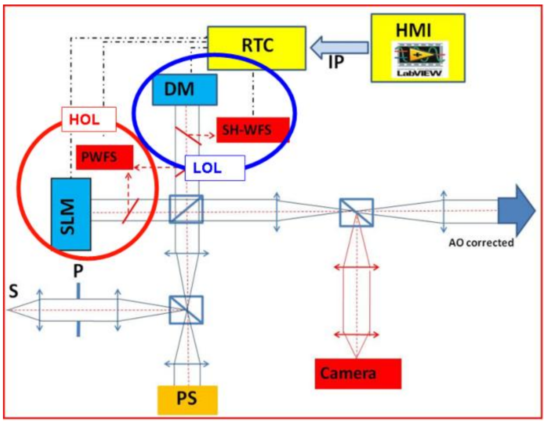

Fig. 1. Schematic representation of LAM AO bench : S (source), P (pupil), PS (phase screen), DM (deformable mirror), SH-WFS (Shack-Hartman wavefront sensor), SLM (spatial light modulator), PWFS (pyramid wavefront sensor), HOL (high order loop), LOL (low order loop), RTC (real time controller), IP (internet protocol address), and HMI (Human Machine Interface).

3. Pyramid wavefront sensor development

3.1. Optical and opto-mechanical design design.

First, we worked on the optical design and optimization of the pyramid parameters (material, angle, thickness, back face angle, edge width, faces orthogonality, etc.) as well as the entrance and relay optics. Illustration of the concept and the effect of the relay optics are shown in fig.2. Parameters of the pyramid as well as its characterization under microscope are presented in fig.3.

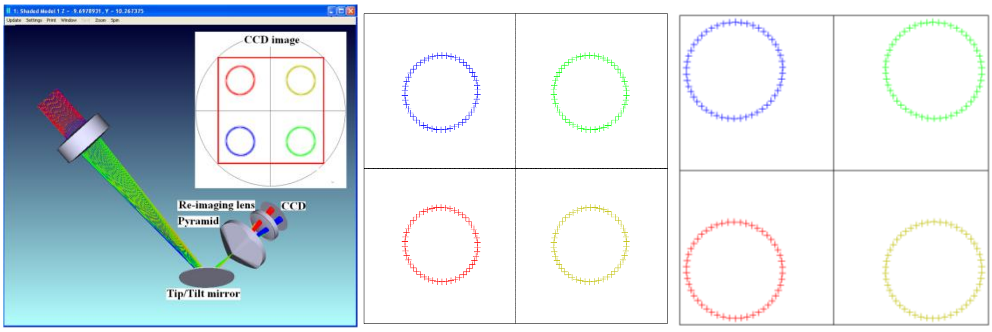

Fig.2 . [Left] Pyramid concept under zemax . [Center and right] Two different cases of relay optics effect showing the size of pupils on the OCAM detector.

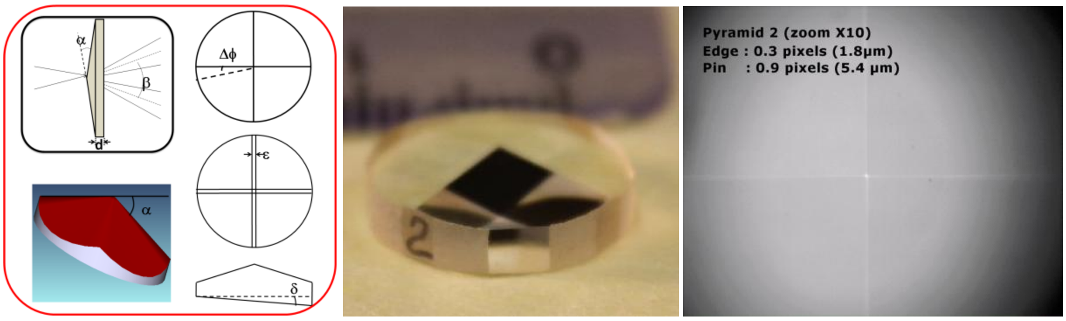

Fig.3. [Left] Pyramid parameters (α: angle, d : thickness, β: beam divergence, Δϕ:faces orthogonality, ε: edge width, δ: back face angle). [Center] Pyramid view. [Right] Pyramid observation under microscopy.

In parallel to this work, we also worked on an opto-mechanical concept with the aim of its integration on our AO bench (fig. 4).

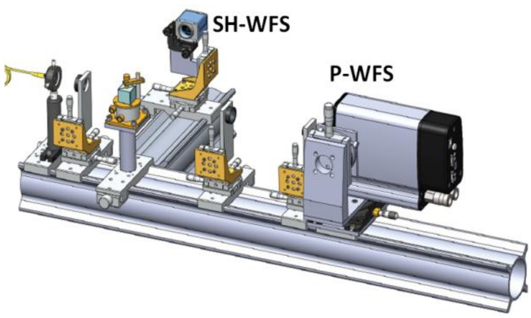

Fig.4. : Opto-mechanical concep showing the pyramid sensor (P-WFS) based on OCAM2 camera with a Shack-Hartmann (SH-WFS) for performance comparison.

3.2. Assembly and test.

Secondly, once the OCAM camera and Tip/Tilt mirror were interfaced with the RTC, we began to assemble and to test the pyramid sensor. Both fixed and modulated versions experimental setups are shown in fig.5.

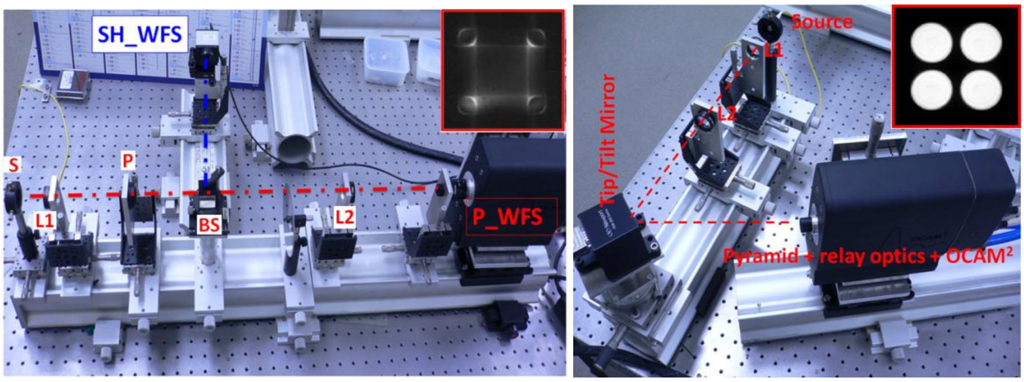

Fig. 5. Pyramid experimental setups. [Left] fixed version (S: source, P: pupil, BS: beam splitter, L1 and L2: optics).[Right] Modulated Version. In medalilon: OCAM pictures.

3.3. Pyramid control algorithm development

Naturally and for the following stage, it was necessary to develop control algorithms associated to the pyramid. From the "pyramid" images obtained on the camera, we settled two objectives:

- Matlab program to determine all the parameters of wards(pupils) (centers, beams(shelves), intensities, location(localization), etc.) and to calculate the by-products of the phases (slopes) to consider the forehead(front) of wave following formulae given onto the face(figure) 7 (center).

- Labview interface (fig.7) for the control and the display of the pupils parameters ignoring at this stage real time aspects.

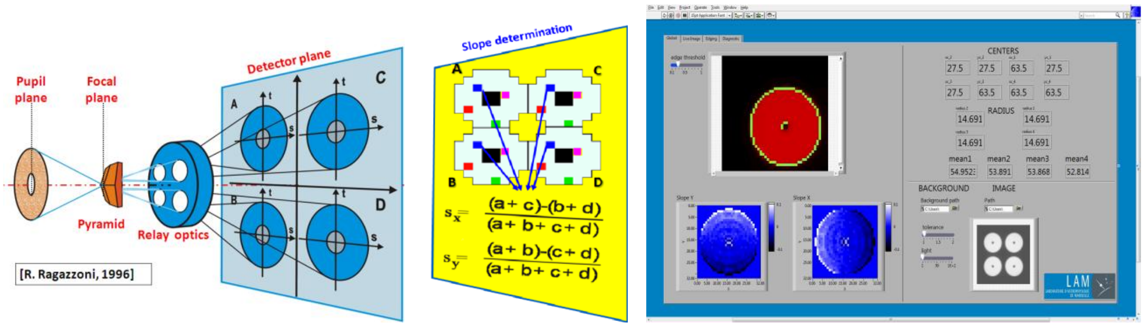

Fig.6. [Left] Pyramid concept. [Center] Slopes calculation method from pixels (intensity) associated with each sub-pupil. [Right] Labview interface.

3.4. First results

For the moment, we used the pyramid sensor only in the fixed configuration (no modulation) to perform our experimental work. As shown in fig.7, the first results, obtained for tip/tilt aberrations for example, are in perfect accordance with the simulations.

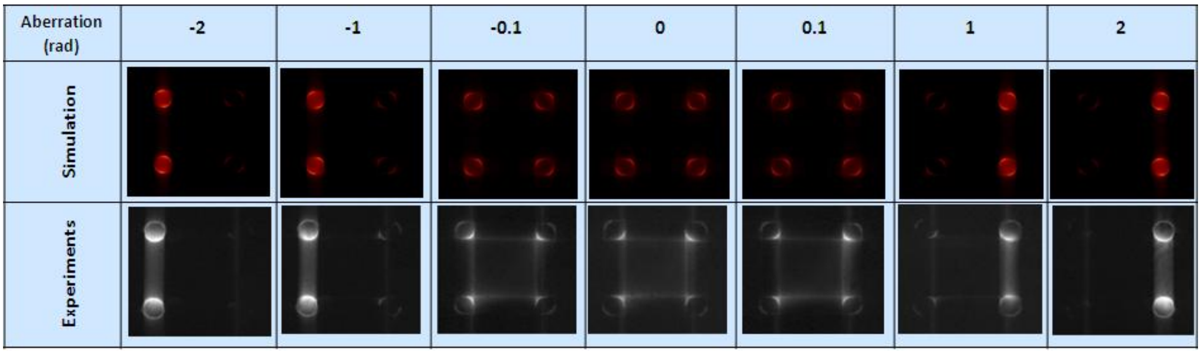

Fig.8. Comparison between simulation and experiments (fixed pyramid) for different tip/tilt aberrations.

To test and validate our pyramid algorithm on simple cases, the same aberration (focus for example) was simulated then applied and measured experimentaly. As presented in fig.9, the results have shown a perfect correspondence. In this case of strong aberration, the pyramidal sensor becomes non-linear reaching a saturation (slopes).

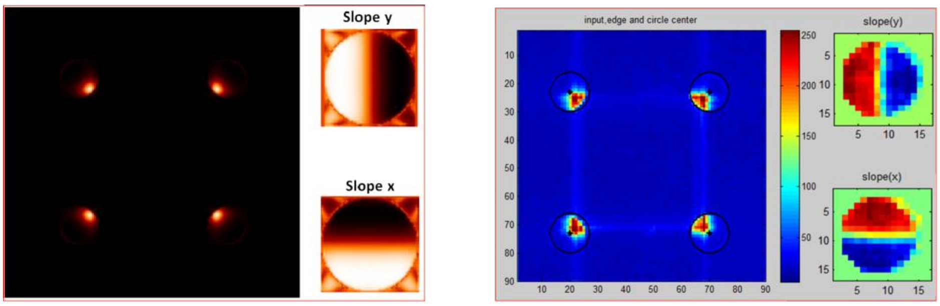

Fig.9. [Left] Simulation of a strong focus aberration (-2 radians). [Right] Measurement and data analysis using our pyramid algorithm.

4. 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 AO concepts for wavefront sensing and control solutions. As joint equipment, a laboratory versatile AO bench (LAM) and an On-Sky test bench (at ONERA, Observatory of Cote d'Azur) are available. With the main AO components [high and low order correctors (MEMS and SLM mirrors) and sensors (Shack-Hartmann and Pyramid)], and a versatile Real Time Controller, tested and validated both in laboratory and On-Sky, several AO configurations studies are then possible.

In this paper, we presented the work undergoing on our homemade pyramid wavefront sensor based on the use of an $OCAM^2$ camera (1.5 kHz). The first results, obtained in fixed pyramid configuration, have shown a perfect correspondence with simulations. On the other hand, we developed associated algorithms for the sensor control which have shown encouraging results.

A "laboratory real time controller", specific to the pyramid sensor, is under construction. Tests in modulated configuration will be performed in the next days. The implementation and integration on our AO bench planned by the end of 2013. Naturally, after these laboratory demonstrations, On-Sky tests (ODISSEE ONERA bench) and validation of our pyramid sensor will take place in 2014.

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