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DEVELOPMENT OF THE ADAPTIVE OPTICS TESTBED LOOPS FOR FOURIER-BASED WAVEFRONT SENSORS DEMONSTRATION AND ANALYSIS

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Abstract. We present in this paper the latest news about the adaptive optics facility bench LOOPS at LAM. A review of the scheme of the bench is first given, going through the optical path module after module. The first results obtained with a spatial light modulator, used to produce high-definition reprogrammable focal phase mask, are then presented.

Keywords: Adaptive optics, pyramid wavefront sensor, phase measurement, spatial light modulator

1 Introduction

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 Fauvarque et al. (2016), 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 is now in progress at Laboratoire d'Astrophysique de Marseille (LAM) on the pre-existing AO bench entitled LAM-ONERA On-sky Pyramid Sensor (LOOPS, Bond et al. 2017). 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 ($\sim$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 as well as adjustable faces angles, opening the way to innovative and hopefully more powerful WFS designs. The complete setup of the LOOPS bench is tackled in Section 2. The Section 3 then presents the first results obtained with the SLM on a dedicated test bench. We finally conclude with the work in perspective in Section 4.

2 The LAM/ONERA On-sky Pyramid Sensor bench

The LAM/ONERA On-sky Pyramid Sensor bench (LOOPS) is an adaptive optics facility hosted at LAM. It features a versatile environment to test concepts related to the Pyramid Wavefront Sensor (P-WFS). Figure 1 shows the schematic diagram of the optical bench. We describe it component by component (except for lenses):

1. a laser source (S) producing a monochromatic light at $\lambda = 660$nm,
2. a neutral density (ND) to control the light flux,

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3. a pupil diaphragm (P)
4. a cube beam splitter (not repeated for the next ones),
5. a flat mirror serving as a reference flat path for the light (R_f1),
6. a phase plate (PS), mimicking an atmospheric turbulence phase screen at $0.4'$,
7. a second reference mirror (R_f2),
8. a 12×12 actuators Deformable Mirror (DM) from Boston Micromachine,
9. a piezoelectric tip-tilt mirror (TTM) in order to modulate the P-WFS,
10. a Shack-Hartman Wavefront Sensor (SH-WFS) with 32 lenslet across the pupil serving as an absolute phase measurement,
11. an Hamamatsu science camera (lower-left CAM) to measure the PSF of the system,
12. a classical Pyramid-Wavefront Sensor (P-WFS$_1$), based on a glass-pyramid phase mask (in red on the figure) and an OCAM^2 camera,
13. a Thorlabs alignment camera to measure the modulation path created by the TTM,
14. a Spatial Light Modulator (SLM) allow the creation of arbitrary focal phase masks that will be detailed in Sec. 3,
15. the second OCAM^2 re-imaging the pupil plane after the SLM in order to compute the P-WFS$_2$ signals.

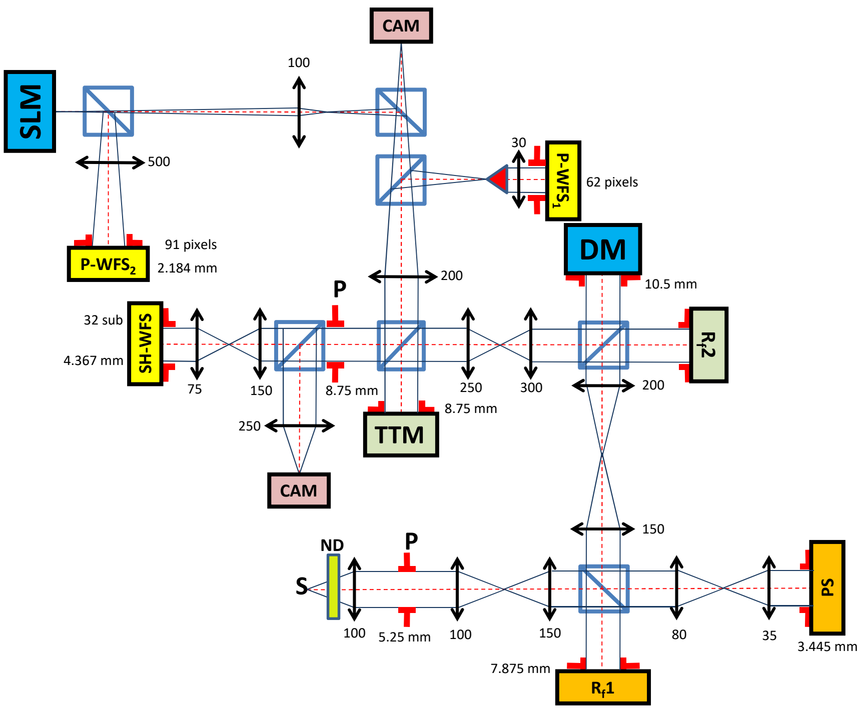

Fig. 1. Scheme of the adaptive optics testbed LOOPS. The acronyms are translated as follow: Source (S), Neutral Density (ND), Pupil (P), Phase Plate (PS), Reference Mirrors (R$_f$), Deformable Mirror (DM), Tip-Tilt Mirror (TTM), Camera (CAM), Pyramid-Wavefront Sensors Cameras (P-WFS) and Spatial Light Modulator (SLM). The position of each pupil plan is reported by the red apertures. Their corresponding diameters are labelled as well.

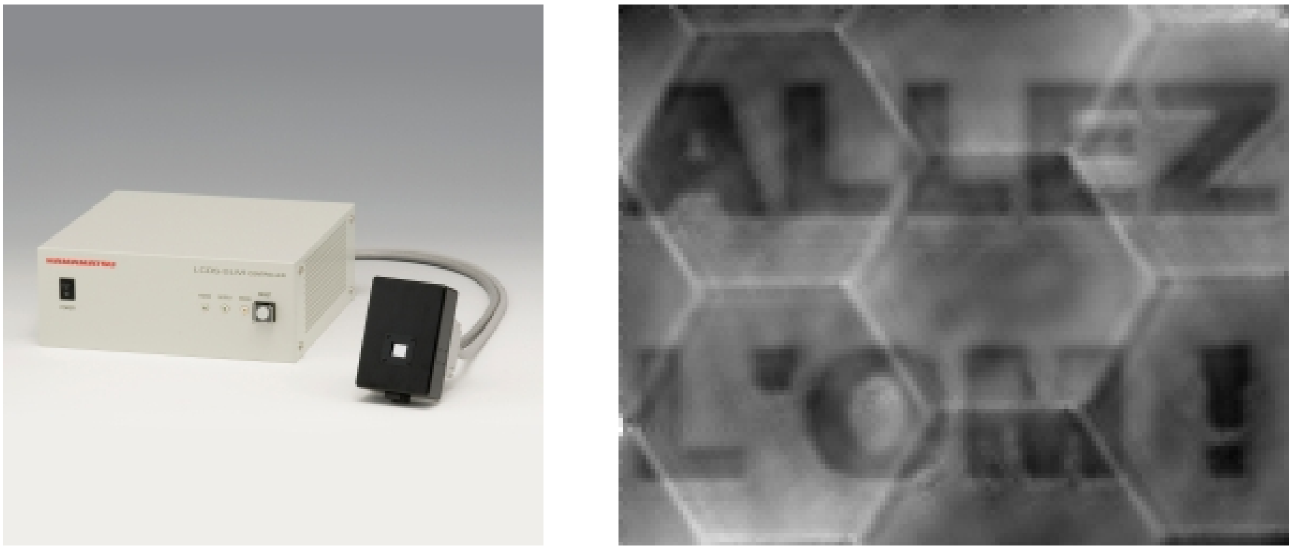

Fig. 2. Left: Picture of a SLM along with its electronic control station (credits: Hamamatsu). **Right:** SID-4 measurement of the phase coming from the evenly illuminated SLM. With its 1280x1024 pixels, the SLM offers a high definition control of the phase. On the image, a reproduction of an hexagonal segmented mirror incremented with a typical tagline from Marseille.

3 Results

Preliminary results have been obtained on a separated test bench with only the SLM and the imaging camera. We first tested the response of the SLM in term of phase modulation. Figure 2 shows a picture of the SLM itself (left) and a phase measurement obtained with a SID-4 wavefront analyser showing a reproduction of an hexagonal segmented mirror incremented with a typical tagline from Marseille. The SLM allows to produce high definition phase mask. It works only with rectilinear polarization and therefore, a polariser is placed upstream of it.

We produced in the same way various flavours of pyramid-based wavefront sensors. Figure 3 shows four configurations where the number of faces of the pyramids varies. The angle of these faces can be adjusted as well, allowing to test some new configurations, especially the so-called flattened pyramid, were the sub-pupil images in the pupil plane start to superimpose (see Fauvarque et al. 2015). We generated other kinds of focal mask as the Four Quadrant Phase Mask (FQPM, Rouan et al. 2000) coronagraph or the ZELDA wavefront sensor (Dohlen et al. 2013).

The SLM is based on a liquid crystal pixelized matrix which means it produces odd diffraction patterns, similar to what can be observed in the diffraction by a grating. Figure 4 (left and center) presents the images measured on the pupil plane after a 4-faces pyramid is applied on the SLM for two different f-ratio (i.e. size of the PSF on the SLM). We can see the grating effect in the sense that the images are periodically repeated. We

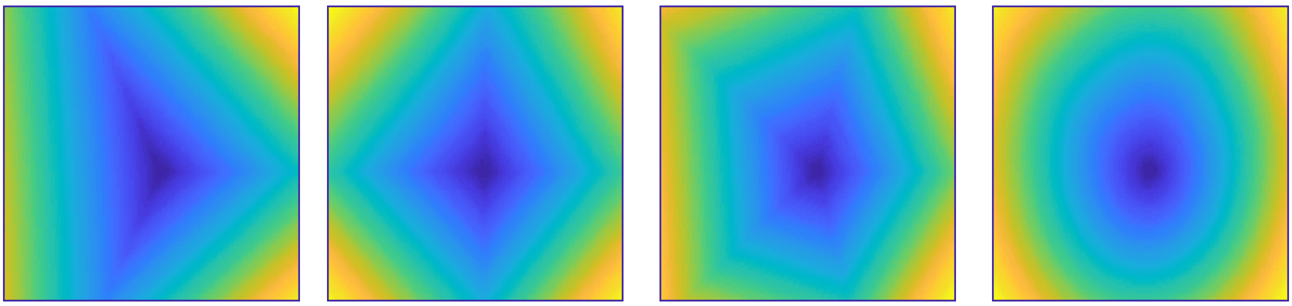

Fig. 3. From left to right: SID-4 measurement of the phase for 3-, 4-, 5-sided pyramids and an axicone created on a spatial light modulator.

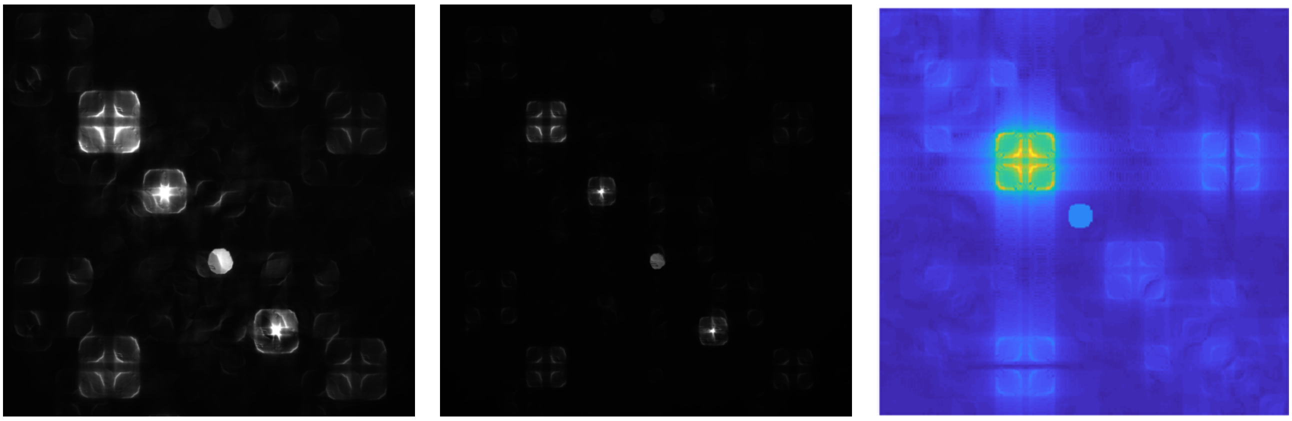

Fig. 4. Left and center: Pupil plane images obtained after a SLM showing a 4-faces pyramid. The f-ratio are respectively ∼150 and ∼200. **Right:** Pupil plane image issued from a numerical simulation of the physical processes at play when propagating through the SLM.

also see the unmodulated part of the light at the center of the image where we see a round pupil unaffected by the SLM. This is due either to badly polarized light of to the inherent filling factor of the SLM (close to 96% in our case). On Fig.4 (right), the results from a numerical simulation of the physical phenomenons at play during the propagation of light in the SLM is presented. We were able to reproduce the artefacts coming from the grating as well as the effects due to polarisation considerations.

4 Conclusion

We developed in this paper the actuality of the LOOPS bench. In Sec. 2, we describe the optical scheme of the LOOPS bench, including its new optical path that is now being integrated in order to characterise and test innovative focal masks for adaptive optics corrections. We presented in Sec. 3 the first results obtained with the SLM on a dedicated test bench. We were able to produce and control different kind of masks. We also faced some effects related to the grating geometry inherent to the SLM. We were able to design the new arm of the LOOPS bench in order not to be affected by these phenomenons. We validated these assumptions by mean of numerical simulations that were able to reproduce really well what we observed on bench.

Finally, the SLM path is now integrated on the LOOPS bench. The first interaction matrix have been measured as well as sensitivity and linear range measurement for various kind of focal mask.

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