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Adaptive optics with programmable Fourier-based wavefront sensors: a spatial light modulator approach to the LAM/ONERA on-sky pyramid sensor testbed

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Abstract. Wavefront sensors (WFSs) encode phase information of an incoming wavefront into an intensity pattern that can be measured on a camera. Several kinds of WFSs are used in astronomical adaptive optics. Among them, Fourier-based WFSs perform a filtering operation on the wavefront in the focal plane. The most well-known example of a WFS of this kind is the Zernike WFS. The pyramid WFS also belongs to this class. Based on this same principle, WFSs can be proposed, such as the n -faced pyramid (which ultimately becomes an axicon) or the flattened pyramid, depending on whether the image formation is incoherent or coherent. To test such concepts, the LAM/ONERA on-sky pyramid sensor (LOOPS) adaptive optics testbed hosted at the Laboratoire d'Astrophysique de Marseille has been upgraded by adding a spatial light modulator (SLM). This device, placed in a focal plane produces high-definition phase masks that mimic otherwise bulk optic devices. We first present the optical design and upgrades made to the experimental setup of the LOOPS bench. Then, we focus on the generation of the phase masks with the SLM and the implications of having such a device in a focal plane. Finally, we present the first closed-loop results in either static or dynamic mode with different WFS applied on the SLM. © 2019 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JATIS.5.3.039001]

Keywords: adaptive optics; optical bench; pyramid wavefront sensor; Fourier-based wavefront sensors; spatial light modulator.

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1 Introduction

Adaptive optics systems have been used in astronomy since the early 1990s^{1,2} to correct atmospheric turbulence, which degrades the quality of the observations from ground-based telescopes.³ These systems were first deployed with Shack–Hartmann wavefront sensors (SHWFSs). In the late 1990s, Ragazzoni proposed the pyramid wavefront sensor (PWFS),⁴ which promised better performance in terms of sensitivity, noise propagation,^{5,6} and aliasing.⁷

During the past years, PWFS has started being integrated on sky with promising results.⁸ There is still an effort to overcome the remaining challenges, such as handling the issue of optical gains^{9,10} or the nonlinear behavior of the sensor itself. To solve these issues, proposing and developing more robust wavefront sensing methods are necessary. Based on the focal plane filtering principle, the PWFS is part of a wavefront sensor (WFS) class called the Fourier-based WFS. We have recently proposed to push further the analytical description⁷ of this class of WFS, with the introduction of a general formalize to describe all Fourier-based WFS.¹¹

Along with the numerical and analytical studies, the Laboratoire d'Astrophysique de Marseille (LAM) and the Office National d'Études et de Recherches en Aérospatiales (ONERA) have developed an adaptive optics test bench for

investigating the PWFS.^{12,13} The LAM/ONERA on-sky pyramid sensor (LOOPS) optical bench is equipped with a four-faced glass pyramid, a SHWFS, a tip-tilt modulation mirror, and a 9×9 deformable mirror (DM). We present in this paper the upgrades that we have implemented on the LOOPS bench to provide a versatile tool for research on Fourier-based WFS. By adding a spatial light modulator (SLM) in a focal plane, we have equipped our bench with a reconfigurable phase mask capable of producing any kind of Fourier-based WFS, from the well-known four-faced pyramid to ideas such as the three-faced or the flattened¹⁴ pyramids. This device will allow the study and characterization of WFS in terms of robustness and performance, especially regarding their linearity, dynamic range, and sensitivity. The reconfiguration of the mask during closed-loop operation is also an advantage offered by this device and will be used to match the WFS mask to the turbulence parameters.

We present, in Sec. 2, the LOOPS upgraded optical design. The major components are detailed in the order following the light path. In Sec. 3, we focus on the operation of the SLM and the care we have taken in order to produce the best possible images. We tackle challenges that come with operating an SLM including polarization, diffraction, and phase wrapping effects, and propose a way to limit their impact on the WFS signal. Then, we present in Sec. 4 the first images acquired on the bench with different Fourier-based WFSs. We show as well the

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2 Experimental Setup: The LOOPS Bench

Figure 1 shows the optical scheme of the bench. The principal components are presented in the list below. A complete description of the parts I, II, and III (see Fig. 1) is available in a previous publication.¹³ The useful focal planes are pointed out with a black font value of the $f\#$ at their respective locations. The pupil planes are marked with red apertures and their corresponding diameter is given with a red font. The entrance pupil is defined by the DM, and the values correspond to the size of the reimaged pupil along the path. The cubes along the path are either cube beam splitters, half-mirrors, or flip-flop mirrors.

The bench is divided into four distinct blocks: (I) a common path (circled in blue in Fig. 1), (II) a metrology path (circled in red in Fig. 1), (III) a classic PWFS path (circled in green in

Fig. 1), and (IV) a Fourier-based WFS path (circled in purple in Fig. 1).

In (I) we have the following:

- A monochromatic light source [S] coming from a laser diode and going through an optical fiber. The wavelength is $\lambda = 635$ nm.
- A reflective phase screen (PS) reproducing ground layer turbulence. This mask is mounted on a rotating plate and emulates the effect of a turbulent atmosphere. The strength of the turbulence is given by $d/r_0 = 3.2$, where d is the actuator spacing and r_0 is the Fried parameter. This parameter is measured by fitting the mean variance of the first 100 Zernike coefficients measured at different locations on the PS.¹³ The outer scale factor is $d/L_0 = 0.32$ and the turbulence frequency is $v/r_0 = 25.6$ Hz, where v is the wind speed. These parameters are equivalent to $v = 8$ m/s for a 8-m telescope.
- A continuous-sheet DM from ALPAO® with 69 actuators. Nine actuators fit across the diameter of the pupil. The mirror has been calibrated to be used with either zonal control (i.e., actuator by actuator) or modal control (i.e., Zernike or Fourier modes).

Fig. 1 Schematic view of the LOOPS bench. Each pupil plane is marked with a red aperture, and its physical diameter is given. The $f\#$ at the two cameras, pyramid, and SLM positions are given as well.

- A PI[®] piezoelectric tip-tilt mirror (TTM) that produces modulation (beam wander) at the pyramid apex. The modulation unit is controlled in an open-loop mode (i.e., without feedback control on its position), in order to be operated at 500 Hz. A function generator produces the signal to control the mirror position and can generate an arbitrary waveform. When running at 500 Hz, the mirror can produce circular modulations with radii up to $10\lambda/D$. Operated at lower frequency, the TTM can produce arbitrary modulation paths.

In (II) we have the following:

- A SHWFS that samples the pupil diameter with 32 sub-apertures and provides reference wavefront measurements. The Shack–Hartmann has been used to calibrate the Zernike and Fourier modes on the DM and to measure the influence function of each of the actuators.
- A Hamamatsu[®] ORCA-Flash CMOS camera with 1024×1024 pixels serving as the scoring camera to provide PSF and Strehl ratio measurements to assess the performance of the adaptive optics system. The Strehl ratio is 74% for the best PSF and 3% for the image obtained with the turbulent PS.

In (III) we have the following:

- Monolithic four-sided glass pyramid.
- An OCAM² EM-CCD camera (P-WFS₁) with 240×240 pixels. The pupil is sampled by 62 pixels.
- A Thorlabs camera (T-CAM) for monitoring the modulation path delivered by the tip-tilt modulation mirror.

And finally in (IV), we have the following:

- A Hamamatsu SLM (LCOS-SLM X13138) with 1024×1280 pixels (with a $12.5 \mu\text{m}$ pitch) that produces arbitrary PSs in the focal plane. The use of this device, which has been initially proposed by Akondi et al.¹⁵ and applied on a real testbed more recently by Engler et al.,¹⁶ promises a reliable modular PS generator. The high $f\#$ at this focal plane is driven by the fact that we want as much pixel as possible in the PSF core in order to have more freedom of action regarding the creation of complex masks. There is also a minimal $f\#$ to respect in order not to superimpose diffraction patterns produced by the diffraction of the SLM. We go more into details on the SLM operation and control in Sec. 3. Note also that the SLM used on LOOPS is reflective.
- A second OCAM² EM-CCD camera (P-WFS₂), identical to the one used on the classic pyramid path. The pupil is sampled by 80 pixels.

The LOOPS bench is operated using the Object-Oriented MATLAB Adaptive Optics (OOMAO¹⁷) toolbox. The maximum closed-loop frequency is 300 Hz. In the spirit of versatility of the bench, we plan to replace the turbulent PS by a second SLM. This will allow us to generate turbulence PSs with configurable parameters, such as r_0 , L_0 , wind speed, or even with different power spectral densities. We could imagine the introduction of residual aberrations coming from a first

AO stage (e.g., from a SHWFS) and close the second stage of the loop using the PWFS. The SLM can be used as a high-definition DM as the pupil will be made of a few hundred of pixel.

3 Phase Masks Generation with a Spatial Light Modulator

The SLM uses liquid crystal technology and exploits the birefringence properties of the crystals to produce easily configurable phase masks. The crystals are oriented using an adjustable electric field that allows choosing the phase delay pixel by pixel, thus creating the desired phase map. Limitations are due to the discrete nature of a pixelated phase mask, as well as the fact that the light has to be linearly polarized to match the orientation of the crystals. WFS creation with an SLM has already been demonstrated in Engler et al.¹⁶ In this paper, authors have presented a method to produce Fourier-based WFS around the zeroth diffraction order (see below), which might, in some situations, interfere with the signal of interest. We describe, in this section, the operating method we have followed to produce the best possible images on (P-WFS₂) after the SLM.

3.1 Polarization

As stated previously, the polarization of the light incident on the SLM has to be linear and orientated in the direction of the crystals. Let us assume that the crystals are vertically oriented. The light after the polarizer will inevitably produce both a horizontal and a vertical component. This is because the polarizer is never perfectly aligned, and the extinction ratio between the vertical and horizontal components of a real polarizer is never exactly null. The horizontally polarized light not being affected by the SLM produces an unmodified pupil image at the exact same position in the pupil plane as if the SLM is a mirror, with a flux depending on the efficiency of the polarization. On the LOOPS bench, the polarizer has an extinction ratio of 700:1. It means there is at least 1/700 of the total flux going back into the zeroth diffraction order.

3.2 Filling Factor

Gaps between the pixels of the SLM are also present. The light reflecting on the SLM at these positions is, therefore, not affected by phase retardation. The fill factor of the SLM used on the LOOPS bench is 96%, meaning that 4% of the vertically polarized incoming flux is not affected by phase retardation. This contributes to the creation of pupil image replicas at each diffraction orders [see Eq. (1)] on the pupil plane. This means that even in the ideal scenario where we have a perfect polarizer, there will still be 4% of the incoming flux distributed between the diffraction orders. This contribution is vertically polarized and does not interfere with the contribution due to the extinction ratio or bad orientation of the polarizer, which is horizontal.

3.3 Diffraction

The SLM operates by diffracting the light, similar in principle to a computer-generated hologram (CGH^{18,19}) or diffraction grating.²⁰ One consequence is that the SLM produces multiple diffraction orders containing the same pupil image. Using geometric optics we can relate the positions of the diffraction patterns to the number of pixel of SLM n_p per diffraction element in the focal plane. This behavior can be seen in Fig. 2 (bottom

Fig. 2 Top: Bitmaps applied on the SLM to produce (a) a centered four-faced pyramid, (b) a shifted pupil, and (c) a shifted four-faced pyramid. The pixel values are set between 0 and 220, the value corresponding to 2π at the wavelength of operation. Bottom: corresponding pupil plane images obtained with these masks. The images have been intentionally shifted from the zeroth order of diffraction to show the diffraction effects. The zeroth order of diffraction is in the bottom right-hand part of the pictures. The white square represents the OCAM imprints.

image a) where the central pattern is repeated on the sides of the image in both x and y directions. Calling n_x and n_y the diffraction orders, their distance from the zeroth order in the pupil plane, denoted as $P(n_x, n_y)$ is given as

$$P(n_x, n_y) = \sqrt{(n_x^2 + n_y^2)} n_p D, \quad (1)$$

where D is the pupil diameter on the (P-WFS₂). The distribution of the diffraction orders will put constraints on the choice of n_p so that there is no superimposition of the signals. In addition, we also require avoidance of central diffraction order due to the imperfect polarization or the filling factor. This case can be seen in Fig. 2 (bottom image a), where the zeroth diffraction order degrades the signal from the pyramid. To correct this we add an additional tip-tilt to the phase map projected onto SLM in order to move the WFS pupil image away from the central order of diffraction. Let l_d be the size of the detector we put in the pupil plane (on LOOPS the detector is squared), we can express the minimal tip-tilt γ , given in rad/px, to apply so that the detector does not see the zeroth order of diffraction

$$\gamma_{\text{lim}} \geq 2\pi \frac{l_d/D + \sqrt{2}/2}{n_p}. \quad (2)$$

Figure 2 (bottom image b) shows the tilt at this limit applied on the SLM. The camera imprint is shown with the yellow square. We see that the bottom right-hand corner of the detector is touching the central order. The combination of γ and the phase to produce the pyramid is finally presented in Fig. 2(c), where

we see the pyramid signal being free of the central diffraction order. Owing to the nonunitary filling factor, there is a cardinal sine envelope modulating the intensity²⁰ on the images obtained after the SLM. It means that the greater the tip-tilt added to the phase of the SLM, the lower is the intensity of the tilted pyramid signal. By increasing the number of pixel per diffraction element in the focal plane, this effect is attenuated. In the limit conditions at γ_{lim} on the LOOPS bench, the intensity loss between the extremal points of a contiguous four-faced pyramid is around 4%.

Finally, for a given number N of faces on our pyramid, the minimal gradient to apply to each faces, in order to make sure that the pupil are not superimposed, is given as

$$\gamma_{\text{pyr}} \geq \frac{\pi}{2n_p \sin(\pi/N)}. \quad (3)$$

3.4 Phase Wrapping and Chromaticity

The optical path difference produced by the SLM has a limited range. It means that, at a given wavelength, the phase delay that one can obtain is between 0 and $2\pi + \delta_\Phi(\lambda)$, where $\delta_\Phi(\lambda)$ is a constant phase term depending on the wavelength of operation. At the wavelength of the laser on the LOOPS bench ($\lambda = 635\text{nm}$), the phase retardation can be set between 0 and 2.33π and the 0 to 2π range corresponds to 220 of the 256 discrete phase levels of the SLM. If not properly set, the setup wraps the phase between 0 and a value different from 2π . Figure 3(a) shows the effects of phase wrapping on the pupil plane. This image has been taken on a separated optical bench

Fig. 3 (a) Saturated image obtained on a separated optical bench with a four-faced PWFS in a phase wrap case with $\delta_\phi > 0$ and $f\# = 185$. (b) Simulation image corresponding to case (a) with $f\# = 185$. (c) Simulation image corresponding to case (a) with a $f\# = 92$.

with $f\# = 185$. Figure 3(b) presents the numerical simulation corresponding to case (a). Figure 3(c) shows the result of a simulation obtained in the same conditions but with $f\# = 92$. In this configuration, the signals from the four-faced PWFS and the replicas are overlapping. On the bench, the value used for 2π is the one given by the constructor. It removes the replicas showed in Fig. 3.

The use of the SLM with nonmonochromatic light source is, according to us, not considerable. It would produce pyramids with different angles for each wavelength, thus delivering blurred images in the pupil plane. The device might still be suitable when using narrow bandpass filters, but we have not led the experiment. Nevertheless, the use of this technology on-sky could still be considered for bright natural or laser guide star applications or even for optical telecommunications.^{21,22}

We have taken all of the above into consideration when we created the different Fourier-based WFS phase masks. Our polarizer has a 700:1 extinction ratio and our SLM has a 96% filling factor, which means that there is around 4% of the incoming light gathered on all the diffraction orders with a maximum at the zeroth diffraction order. We use an additional tilt slightly greater than γ_{lim} presented in Eq. (2). We chose to have $n_p \simeq 15$ in order to be able to produce subdiffraction variations on the phase mask. The pupil diameter on the detector is $D = 1.92$ mm (80 px) and the detector side is $l_d = 5.76$ mm (240 px). We present the results obtained on the LOOPS bench with this setup in Secs. 4 and 5.

4 Static Evaluation

Figure 4 presents the images acquired on the LOOP bench (top) along with their respective simulations (bottom) for the four-

Fig. 4 Top: Images taken on the LOOPS bench in the pupil plane after the SLM. Bottom: simulation images corresponding to the top cases. The focal masks applied on the SLM are, respectively: (a) a four-faced pyramid, (b) a three-faced pyramid, (c) an axicon, and (d) a four-faced flattened pyramid.

and three-faced pyramids (images a and b), the axicon (image c), and the flattened pyramid (image d). There is a good agreement between the images produced in simulation and the images obtained on the bench, which is promising in terms of quality in the phase measurement. The residuals that can be seen on the bench images are either residual phase on the wavefront (e.g., the recognizable waffle pattern coming from the DM) or phase aberrations in the focal plane, transforming into intensity variation in the pupil plane. To prevent this last point, we apply on the SLM the phase flatmap correction provided by Hamamatsu. Some fringes are present on the images as well. They come from interference between the WFS image and the ghosts coming from the multiple cube beam splitters. The contrast of these fringes is around 5%. These ghosts are too close to the PSF core to be filtered out optically. This pattern is static and disappears after the calibration stage. We added this effect to the simulated images in Fig. 4 by applying a fainter second source at the location of the brightest ghost we measured on the focal image at the SLM position. It could as well be numerically filtered afterward as it is way beyond the control frequency defined by the actuators pitch. Manufacturing errors such as rooftop defects, difference in face angles, or asymmetry in the masks can be produced by the SLM. The relatively high sampling of the focal plane insures that the mask can be considered as continuous. The impact of such defects on the performances of the different WFSs can then be assessed and classified as critical for the operation or not. The LOOPS bench thus offers the opportunity to test a large variety of configurations.

Figure 5 presents the images obtained with a modulation of $5\lambda/D$ on the bench (top) and in simulation (bottom). Here again the correspondence between simulation and bench

images is strong. An elongation of the subpupils can be perceived in Figs. 5(a) and 5(b) from the bench. The same behavior is present on the simulation image where the contours of the subpupils are oriented toward the center of the image. This effect is inherent to the mask that is used, as it divides the PSF into subpupils and thus diffracts light in directions given by the mask. The greater the modulation radius, the lower is the effect.

Finally, we calibrate the system by applying Zernike modes on the DM and measuring the resulting intensity distribution on the P-WFS₂. We present in Fig. 6 the results obtained when a primary spherical aberration is applied on the DM. The top images are the data acquired on the LOOPS bench and the bottom images are data from simulations. The bench data are the image when the DM is set to the given Zernike minus the reference frame when the DM is set to the flat commands. Animations corresponding to the full calibration process are available by following the links provided in the references given in the caption of Fig. 6.

As a first probe of wavefront reconstruction, we invert the calibration matrix acquired for the first 65 Zernike modes and retrieve the amplitude of one introduced mode (primary spherical aberration, referred to as mode #21 and presented earlier in Fig. 6) for three different modulation radii. The results are presented in Fig. 7, where the solid lines are the data acquired on the bench and the dashed lines are the data produced in simulations. As expected, the greater the modulation radius, the larger is the linearity range. This brings confidence that the bench is operating correctly and that we can reproduce the results accurately in simulation. This leads us to the next section where we present the closed-loop operation results.

Fig. 5 Top: Images taken on the LOOPS bench in the pupil plane after the SLM with a modulation of $5\lambda/D$. Bottom: simulation images corresponding to the top cases. The focal masks applied on the SLM are, respectively: (a) a four-faced pyramid, (b) a three-faced pyramid, and (c) an axicon.

Fig. 6 Top: Example of calibration images obtained on the LOOPS bench. Bottom: corresponding images obtained in simulation. There is no modulation in these images. In the presented case, we apply a primary spherical aberration on the DM and show the image taken from the camera minus a reference image taken when the DM is flat. (a) a four-faced pyramid,²³ (b) a three-faced pyramid,²⁴ (c) an axicon,²⁵ and (d) a flattened pyramid.²⁶ Videos showing the full calibration process are available by following the links given in the references section.

Fig. 7 Estimated wavefront error versus introduced wavefront error for different modulations using a four-faced pyramid. The introduced mode is a primary spherical aberration. The system is inverted with an unfiltered pseudoinverse of the command matrix obtained with 65 Zernike modes. Solid lines represent the measurements obtained on the bench, and dashed lines represent the simulation data.

5 Closed-Loop Results with Four-Pyramid Wavefront Sensor

We present, in this section, the results that we have obtained in closed loop with a four-faced pyramid applied on the SLM. The subpupils are separated by $1.25D$ (corner-to-corner distance of the square defined by the four pupil centers), as previously presented in Fig. 5. The DM is controlled using the first 65 Zernike modes. We use the classical slopes maps approach⁴ to handle the WFS signals. Before any operation, the static phase aberrations from optics present on the SLM path are minimized by calibrating the system with an unmodulated four-faced pyramid applied on the SLM and closing the loop on the reference mirror R_f1 while setting the reference slopes maps to zero. We ensure in that way to use a close to optimal PSF at the pyramid apex to avoid optical gain effects that may occur.^{9,10} We then acquire the calibration matrix with a $5\lambda/D$ modulation and invert it to build the command matrix. The condition number of the matrix is around 10 and we decide not to filter any modes. The loop gain is set to 0.5, in order to ensure the stability of the system. We measure the quality of the correction using the SHWFS.

We present in Fig. 8(a) a 10-s measurement of the residual wavefront error obtained on the bench and reproduced in simulation in open loop and closed loop. Hereafter, the term open loop is used to qualify the system when no AO correction is applied. The residuals when the loop is closed are ~ 150 nm RMS for both the bench and the simulation. To go more into details, we present in Fig. 8(b) the standard deviation of the wavefront error as a function of the Zernike index obtained on the bench and in simulation. The solid curves represent the open-loop scenario. The bench parameters (r_0 , L_0 , and D) are

Fig. 8 Open- and closed-loop results for a four-faced PWFS using slopes maps and modulated at $5\lambda/D$. (a) RMS wavefront error from 10 s open (solid line) and close (dashed line) loop on the bench (blue, triangles) and in simulation (red, squares). (b) standard deviation of the first 100 Zernike modes measured in open loop (solid line) and in closed loop (dashed line) on the bench (blue, triangles) and in simulation (red, squares). The yellow vertical line indicates the number of controlled modes. The hole visible in the bench data (around index 90) is due to the Shack–Hartmann software that did not estimate these modes.

used in simulation in order to reproduce the turbulent conditions. Dashed lines present the closed-loop results. We distinguish from modes 1 to 21 a decreasing standard deviation corresponding to the modulation radius (a $5\lambda/D$ spatial

frequency corresponds to Zernike modes with radial order close to 6^{27}). From modes 21 to 65, the standard deviation stays constant as expected for the PWFS beyond its modulation range.⁷ For mode index higher than 66, the system should not correct

Fig. 9 (a) Open-loop long-exposure image with the turbulent PS placed in the pupil plane (scale is $40 \times 40\lambda/D$). (b) Log-scale closed-loop long-exposure image with the turbulent PS placed in the pupil plane (scale is $10 \times 10\lambda/D$).

anymore as we only use the first 65 Zernike modes to control the DM. However, the Zernike modes produced on the DM are not perfectly exact and can contain higher frequencies. For example, when applying mode 65 on the DM and measuring the resultant wavefront with the SHWFS, we obtain a Zernike decomposition of the phase that is principally composed by mode 65 but that also presents higher-order modes contribution with small but not negligible amplitude. Therefore, there is no visible step at the location of the last controlled mode (65), but for higher frequencies, the corrected and uncorrected wavefronts superimpose again. We have taken this effect into account in our simulations by adding higher-order modes contributions (from measurements on the SHWFS), and we observed the same behavior in the cut-off frequency.

We can see a difference in the tip-tilt variance between the bench and the simulation in Fig. 8(a) (modes #1 and #2). The additional tip-tilt measured on the bench is believed to be directly inherent to the mask itself. We have accounted for this difference in Fig. 8(b) by subtracting the tip-tilt coming from this effect.

The long-exposure PSF are presented in Fig. 9(a) for the open-loop case and in Fig. 9(b) for the closed-loop case. The scales are different for each image and detailed in the caption. We clearly see in the closed-loop image the correction limits, spanning from $-4\lambda/D$ to $4\lambda/D$, corresponding to the spatial frequency of the actuators spacing in the pupil plane (eight interactor spaces comprised in the pupil). The closed-loop PSF is elongated at 45 deg. This is due to the noncommon path aberrations present between the SLM and the science optical paths because we chose to optimize the PSF at the SLM apex in order to minimize the optical gain effect.

6 Discussion and Conclusion

We have presented in this paper the latest upgrades made on the LOOPS bench at the Laboratoire d'Astrophysique de Marseille. We have presented in Sec. 2 the updated optical scheme of the bench. It now includes an SLM, which allows creating versatile focal phase mask and studying their behavior as WFSs. The bench is controlled with OOMAO and features as well as SHWFS, a four-faced glass PWFS, a 9×9 DM, and a Hamamatsu Orca Flash camera. It provides a solid basis for research and development on the Fourier-based WFSs. The comparison between the well-mastered SHWFS and the WFS such as the three-faced or flattened pyramids is made easy in this environment. In a future upgrade of the setup, another SLM will be added in the pupil plane to replace the rotating turbulent PS. It will allow the production of adaptable turbulent PSs with varying parameters (r_0 , L_0 , or even different power spectral densities), making the bench capable of reproducing a variety of atmospheric conditions.

We have shown in Sec. 3 the care we took during the integration of our SLM in a focal plane. Tackling the effects of polarization, diffraction, and phase wrapping, we are able to understand in detail the operation of the device, and confirm the results comparing the images obtained in simulation and on the bench. By shifting the signal out of the zeroth diffraction order, we enable the possibility of creating WFS with overlapping subpupils such as the flattened pyramid. As this experiment is a laboratory demonstration, we have chosen to use an SLM, but all the developments we made are applicable to other devices capable of producing reconfigurable phase mask. For use in polychromatic light, the mask could be produced with

high-resolution DMs, a technology yet to be available. However, the device could be used as is in the LGS case or in telecommunication application.

In Sec. 4, we have presented the first images obtained with different WFSs with and without modulation as well as phase estimation with an SLM-made four-faced PWFS. The data acquired from the bench fit well with the data we obtained by mean of numerical simulations. This ensures that the SLM is behaving as we want and can reproduce testbench data in simulations. We have presented the first calibration results at the end of Sec. 4 and are now investigating the performances of WFS.

Finally, we presented in Sec. 5 the closed-loop result that we obtained from an SLM-made four-faced PWFS. We measured the residual wavefront error in both open- and closed-loop situation and were able to reproduce with great accuracy these behaviors in simulation. The LOOPS bench was now ready to perform work on characterizing and developing WFS and wavefront-sensing techniques.

The work on characterizing WFS represents a significant step and is intended for the next coming papers. It will include linearity and sensitivity measurements as well as bootstrapping and closed-loop analysis for various Fourier-based WFSs. The points of peculiar interest are (1) the comparison between the four- and three-faced pyramids using a slopes map approach and (2) the comparison between the slopes map and full frame approaches on the four-faced pyramid. The reconfigurability of the focal phase mask during closed-loop operation will be closely investigated, especially testing the concept of the flattened PWFS,¹⁴ which has demonstrated in simulations an increase of sensitivity at tunable spatial frequencies. The bench will serve as a demonstrator for the optical gain compensation and will validate the results already obtained by mean of simulations.

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