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PAPYRUS : Second stage adaptive optics with a vector Zernike wavefront sensor

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ABSTRACT

The Provence Adaptive optics PYramid Run System (PAPYRUS) is a pyramid-based Adaptive Optics (AO) system installed at the Coudé focus of the $1.52m$ telescope (T152) at the Observatoire de Haute Provence (OHP). PAPYRUS is a young researcher project that aims to strengthen our knowledge in AO. This bench is an education tool and technological platform to test and better understand Fourier Filtering Wave-Front sensors operating on sky.

In the coming months, we will be improving the AO bench and implementing a second stage of correction with a vector Zernike wavefront sensor (vZWFS). This 2^{nd} stage aims to significantly improve the AO correction of the 1^{st} stage by reducing the temporal error, which is the main limitation of the PAPYRUS bench. To do so, the 2^{nd} stage will work in the NIR and with a low-order Deformable Mirror (DM) with fast control frequency.

We present the optical setup of this 2^{nd} stage based on a vZWFS. We also present the first simulation results regarding the 2^{nd} stage obtained with OOPAO.

Keywords: Adaptive optics, high angular resolution, wavefront sensor

1. INTRODUCTION

The Provence Adaptive optics PYramid Run System (PAPYRUS) [9] is an AO bench installed at the Coudé focus of the T152 at Observatoire de Haute Provence (OHP). The goal of this AO bench is to test state-of-the-art AO systems starting with the pyramid wavefront sensor (PWFS) [11]. Indeed, this bench is a demonstrator of the

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feasibility on sky to use new kinds of wavefront sensor for the next generation of telescopes like the European Extremely Large Telescope (ELT).
The first images of PAPYRUS were obtained in June 2022. The bench was also used by students in the FOCUS autumn and summer schools in November 2022 and May 2023.
PAPYRUS is a young researchers project using components available at LAM and ONERA but it is also open to collaboration in order to test new wavefront sensors (WFS) technology. In this context, PAPYRUS will host an echelle spectrometer Virtually Images Phased Array (VIPA) [2] in the next few months. PAPYRUS will also host a vector Zernike WFS [6]. The vZWFS will be the WFS of the 2^{nd} stage of the PAPYRUS AO system. The first goal of this 2^{nd} stage is to test and characterise this new phase mask; the vZWFS. This 2^{nd} stage will also help us to improve the performances of the 1^{st} stage by reducing the temporal error of the AO loop. In this paper, we will first present the performance of the PAPYRUS bench. We will then present the optical design and the performances of the 2^{nd} stage with the vZWFS.

2. PAPYRUS PERFORMANCES

PAPYRUS [9] optical design and performances are described in [7]. We will remind the main characteristic of the bench. The optical design is drawn in Figure 1. PAPYRUS is a pyramid-based AO bench working in the visible around the central wavelength $\lambda = 635nm$. We can close the AO loop at 500 Hz on natural sources up to magnitude 5. The PAPYRUS bench has a 17×17 actuators ALPAO DM. The wavefront sensing camera is an OCAM2k EMCCD running up to $1.5kHz$. It is equipped with a Tip/Tilt modulation mirror allowing to modulate the Point Spread Function (PSF) at a typical radius of $5\lambda/D$ up to $7\lambda/D$. The bench can work with two different Real-Time Computers (RTC) the PAPYRUS homemade RTC and the ALPAO **ref** so the AO loop can run between $500Hz$ up to $1.5kHz$. With the data extracted from the observations, we can have a proper estimation of the environment, the seeing condition and the jitter for example (see [7]). The typical performances of the bench are described in Figure 2. We can reach Strehl Ratio of 10% up to 30% in the visible when observing a bright star.

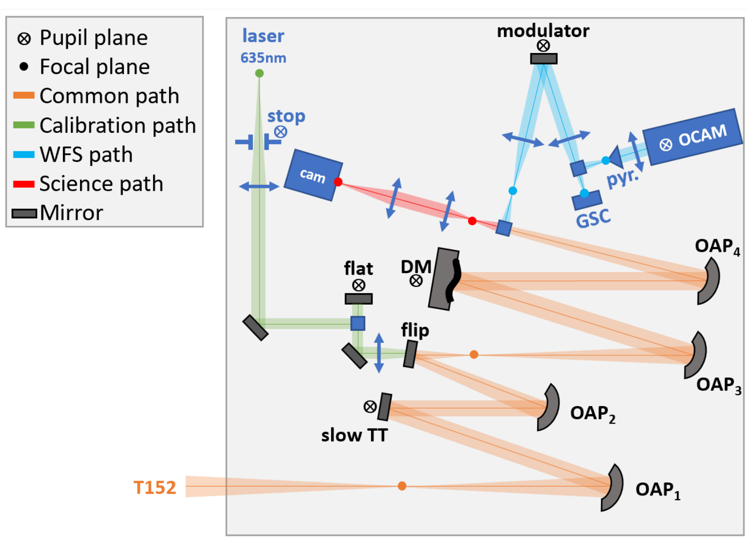


Figure 1: Optical drawing of the PAPYRUS bench

3. PAPYRUS SECOND STAGE AO: OPTICAL DESIGN AND PERFORMANCES

PAPYRUS is an AO test bench that allows us to test different WFS. It started with the PWFS to have a better understanding of the behaviour of this sensor on sky. The next step on the PWFS branch will be to implement

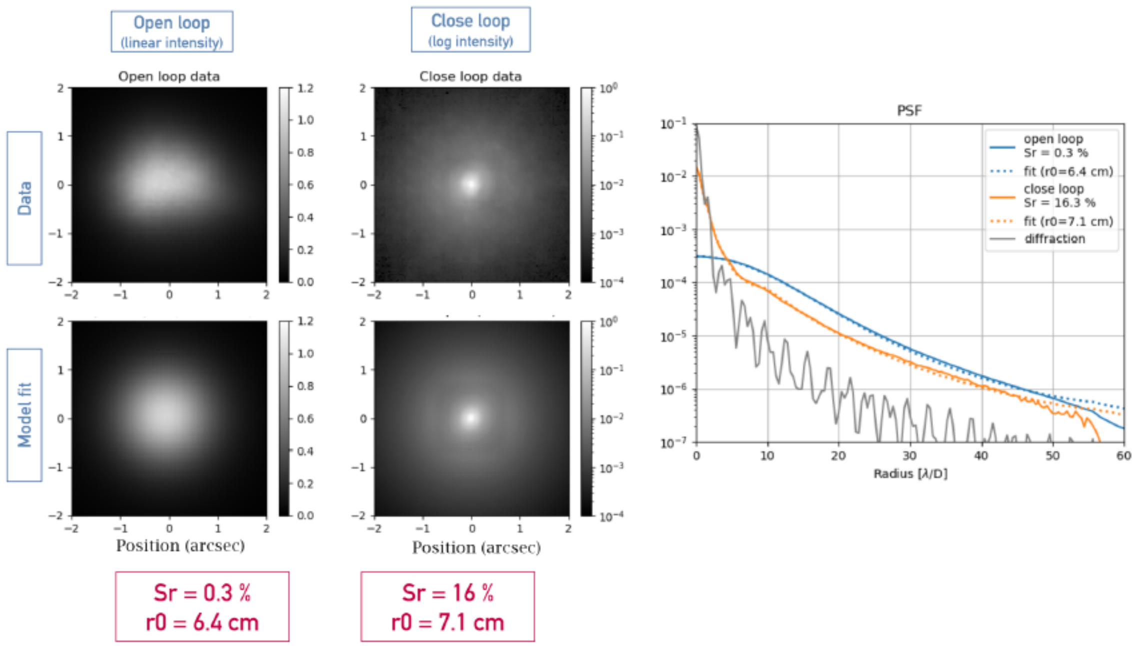


Figure 2: Performance of PAPYRUS on Vega

the optical gain compensation (see [12]), in order to increase the performances of the AO correction. We will also upgrade the current AO system to reduce the temporal error with a two-stage AO system composed of :

- 9×9 ALPAO DM
- vector Zernike wavefront sensor (vZWFS) with a dot of $23\mu m$ diameter optimised for K-band
- CRED2 camera
- RTC running up to 1.5kHz
- Central wavelength $\lambda = 1.65\mu m$

The originality of the 2^{nd} stage is in the use of a vector Zernike (vZWFS). The phase mask was developed by [13], it is made on metasurface [1]. The special feature of this vZWFS is that it produces two different phase shifts. Indeed, two different polarizations will see two different phase shifts. One polarization will see a phase-shift of $\pi/2$ while the orthogonal polarization will see a $3\pi/2$ phase-shift. After the phase mask, the light go through a birefringent prism to split the 2 polarizations. We have two images of the pupil on the detector that we can use to estimate the wavefront. By doing this we can measure both the phase and the amplitude of the wavefront [6]. But most importantly we double the dynamic of the classical ZWFS [5]. With this vZWFS we will be able to sense bigger phase aberration which is why we could use it as a 2^{nd} stage WFS to correct phase residuals after the correction provided by the PWFS.

3.1 Dynamic and sensitivity of the vZWFS

The vZWFS is a Fourier Filtering WaveFront Sensor. The intensity can be expressed as in equation 1 [10]. By doing linear combinations of the intensities I_L and I_R we have access to the sine and the cosine so the phase can be estimated on a 2π range (cf 3.1). Therefore, the vZWFS allows to increase the dynamic of the classical ZWFS. However, it comes at the cost of a decrease in sensitivity compared to the ZWFS. The sensitivity curves were plotted following the method developed by [3]. Indeed, if we consider the Read-Out Noise (RON) sensitivity while

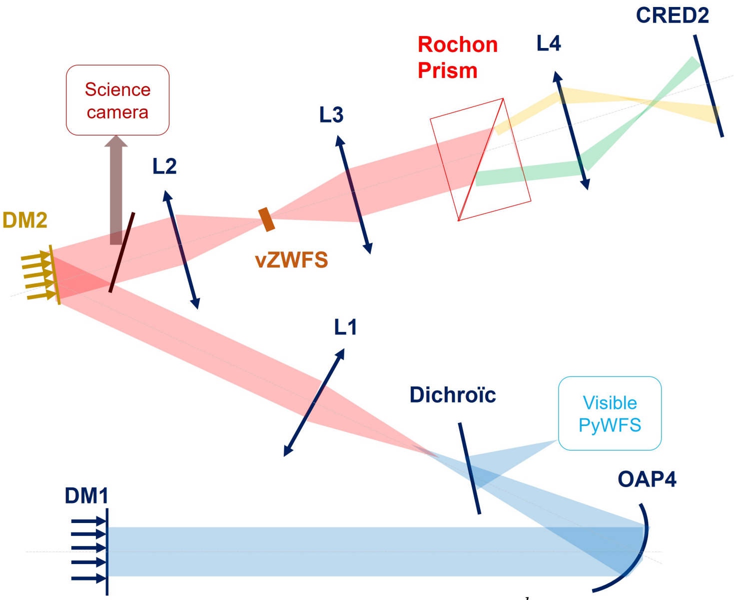


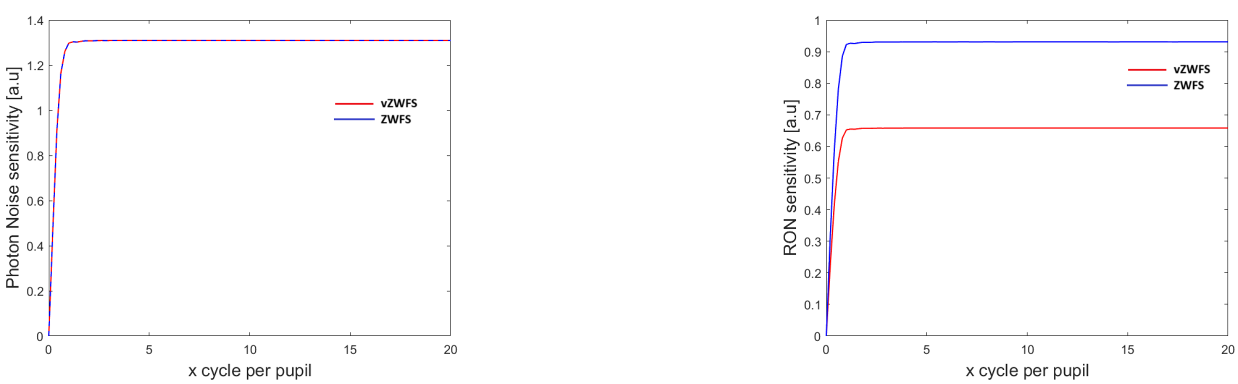
Figure 3: Optical setup of the 2^{nd} stage

using a vZWFS we will double the number of useful pixels therefore, reducing the sensitivity by a factor $\sqrt{2}$ see Figure 4b. However one needs to notice that the vZWFS is still more sensitive than the non-modulated PWFS[4].

$$\begin{aligned} I_L(\phi) &= \mathbb{I}_p^2 + \frac{1}{2} + \mathbb{I}_p(\sin(\phi) - \cos(\phi)) \\ I_R(\phi) &= \mathbb{I}_p^2 + \frac{1}{2} - \mathbb{I}_p(\sin(\phi) + \cos(\phi)) \end{aligned} \tag{1}$$

Where $\mathbb{I}_p$ is the pupil function and ϕ the phase to be measured.

$$\left.\begin{array}{l} I_L + I_R \rightarrow cos(\phi) \\ I_L - I_R \rightarrow sin(\phi) \end{array}\right\} \phi_{estimated} \in [-\pi; \pi]$$



(a) Photon Noise sensitivity

(b) Read-Out Noise sensitivity

Figure 4: Comparison of the sensitivity of the vZWFS and the ZWFS

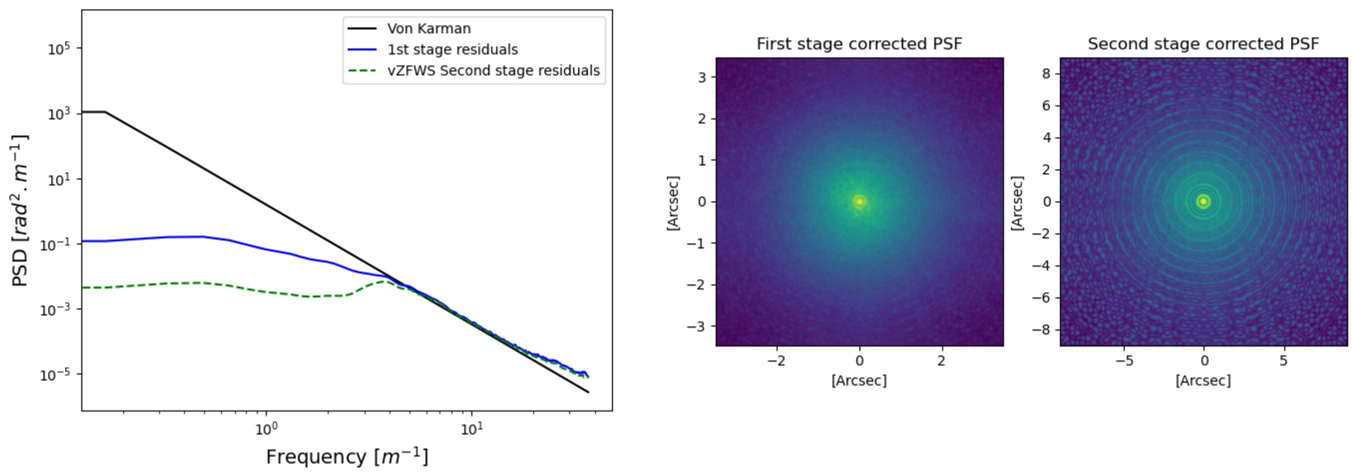


Figure 5: Left: PSD of the phase residuals after the 1^{st} stage in blue and after the the 2^{nd} stage in green. Right: PSF in K-band after the 1^{st} and the 2^{nd} stage.

3.2 First simulation of the PAPYRUS two stages AO system with a PWFS and a vZWFS

We build a simulation on OOPAO [8], an end-to-end python AO simulator, of our two-stage AO system. The parameters of the simulation are given in Table 1. The first stage describes the current PAPYRUS bench with a modulated PWFS at $7\lambda/D$ running at $500Hz$ (typical speed of the PAPY RTC). The 17×17 DM of the first stage will correct 228 Karhunen-Loève (KL) modes. The simulations are done without any noise. In this configuration, the expected Strehl ratio of the first stage would be 13% in the visible so 74% in the K-band. The performances of the first stage are consistent with the current performances of PAPYRUS.
The second stage is composed of a vZWFS of diameter λ/D with a 9×9 DM running at $1.5kHz$ correcting 70 KL modes. We plotted the Power Spectral Density (PSD) of the phase residual after the first and the second stages in Figure 5. We note in the plot that the 2^{nd} stage improves the correction of the 1^{st} one for the low-order aberration. This results from having a low-order DM running three times faster than the first DM. By improving the correction of the low-order aberrations we note an increase of the Strehl ratio in K-band from 74% to 89% after the 2^{nd} stage. Thanks to its increased dynamics, the vZWFS is more robust and could be used outside the linear range of the simple ZWFS.

Table 1: Simulation parameters

Telescope	1.52m
Resolution	80 pixels
$DM1$	17×17 actuators
$DM2$	9×9 actuators
λ_1	$640nm$
λ_2	$1665nm$
r_{mod}	$7\lambda/D$
$F1$	$500Hz$
$F2$	$1500Hz$
r_0	8cm
wind speed	$5m.s^{-1}$
gain	0.5 (both stages)

4. CONCLUSION

PAPYRUS is an essential development tool for understanding future adaptive optics systems, of which the wavefront sensors will be a pyramid. This AO bench has shown good performances with Strehl ratio up to 30% in the visible.

In the coming month, we will implement the optical gain compensation with the gain-sensing camera, allowing to improve the performances of the PWFS branch. The corrected beam will then be injected into the VIPA spectrometer. These next steps will turn papyrus into a complete AO bench with a sensing and a scientific branch. With the vector Zernike phase mask, PAPYRUS will host a two-stage AO system composed of a visible PWFS and a NIR vZWFS. Initial simulation results are encouraging. Indeed, this new version of the AO system will improve the performances of the current bench by reducing the temporal error and improving the Strehl ratio in the NIR. With this state-of-the-art phase mask, PAPYRUS will help to characterise and test this technology on sky.

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