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PAPYRUS: Design and integration of the Shack-Hartmann branch

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ABSTRACT

The PAPYRUS project is an adaptive optics bench installed on a 1.5 meter telescope at the Haute-Provence Observatory in south of France. Since the first light of the instrument in June 2022, it has now undergone one year of on-sky experiments. The purpose of PAPYRUS is to test new hardware components as well as new wavefront sensing and control strategies, and thus serve as a pathfinder to challenging AO systems for the upcoming Extremely Large Telescopes (ELTs). Especially, one of the main feature of PAPYRUS is its Pyramid Wavefront Sensor (PYWFS), that will be the type of wavefront sensor used by many first light instruments of the ELTs. In this framework, the desire to compare PYWFS and the classical Shack-Hartmann wavefront sensor (SHWFS) led us to install a new wavefront sensing branch with a SHWFS on PAPYRUS, in parallel of the already existing PYWFS branch. The technical solution chosen for the SHWFS detector part presents the originality of being a CMOS sensor in the visible with low readout noise ($2.5e^-$) : the Cblue One made by the First Light Imaging company. The real time computer used to control the AO loop is the same for the PYWFS branch and for the SHWFS branch and is made by the ALPAO company. This paper provides a description of the design and alignment phase, and present the results of the first on-sky tests of the PAPYRUS SHWFS branch.

Keywords: adaptive optics, wavefront sensor, Shack-Hartmann

1. INTRODUCTION

The PAPHYRUS bench is installed at the Haute Provence Observatory (OHP) in south of France, on a 1.5 meter telescope called the T152.

This observation site is located at an altitude of 650 m and present quite hard observing conditions as the weather is cloudy approximately 20 % of the nights and present a median seeing of 3 arcseconds [3][2].

The T152 has a total diameter of 1.52 m and a useful diameter of 1.5 meter. It possesses a Coudé focus with an f-number of 28.

The PAPHYRUS bench has 6 main parts, drawn on figure 1:

1. The telescope simulator unit: a laser and few optics that simulate the beam coming from the telescope for alignment purposes, in green.
2. The calibration unit: a laser at $\lambda = 635 \text{ nm}$ used to measure the interaction matrices of the bench, in yellow.
3. The common path: the optical path seen by both the light used for science and for wavefront measurement, in orange
4. The science path, with a visible scientific camera (The ORCA made by the Hamamatsu company), in purple.
5. The PYWFS branch that sees a modulation mirror made by the Physik Instrument company, a 4-sided glass Pyramid and an EMCCD camera, the OCAM 2K made by the First Light Imaging company, in blue.
6. The Shack-Hartmann branch, the subject of this article, in red.

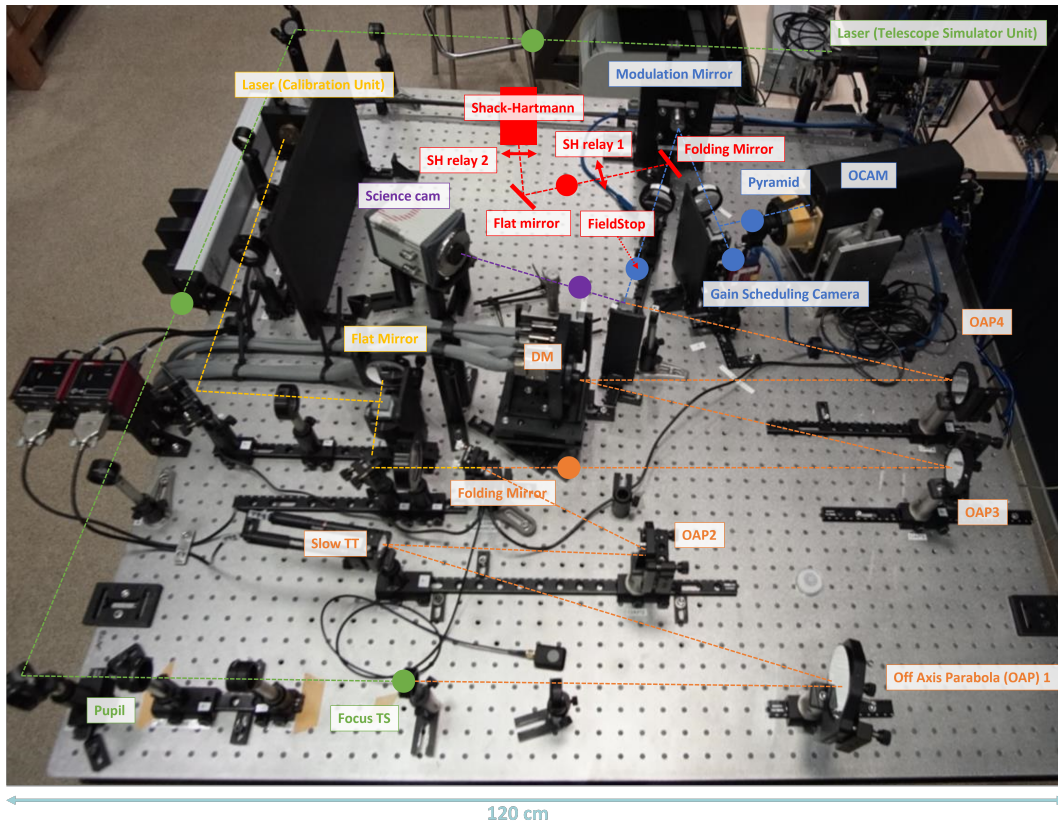


Figure 1. PAPHYRUS optical layout

2. SHACK HARTMANN BRANCH: OPTICAL DESIGN

This section present and explain the choices made for the Shack-Hartmann branch optical design.

2.1 Detector

The sensor used as our Shack-Hartmann detector is a CMOS visible camera: the Cblue One, made by the First Light Imaging Company. It has the following properties:

1. Resolution: 1024×1608
2. Pixel Pitch: $9 \mu m$
3. Read-out noise: $2.5e-$

2.2 Micro-lens array

The micro-lens array (MLA) has been designed, aligned and glued on the detector by the ALPAO company. It has the following properties:

1. Resolution: 64×64 . Only a 14×14 region is used in our context.
2. Focal length: $f = 7$ mm.

2.2.1 Photometry

A quick photometric study has been done taking into account the transmission of the atmosphere (90%), a rough estimation of the telescope transmission (50%), the measured transmission of the PAPHYRUS bench before the Shack-Hartmann (20%) and the average quantum efficiency of the Cblue (50%). Note that as there is no spectral filter, the spectral bandwidth is only limited by the quantum response of the camera. By considering all these effects, one can plot the number of photons per sub-pupil per frame in function of the magnitude of the observed star (see figure 2). The star is supposed to be at zenith, and the frequency of the loop is supposed to be 500 Hz. Our rule of thumb to determine the magnitude limit we should be able to observe with the Shack-Hartmann branch was to consider that at least 100 detected photons per frame per sub-pupils were needed. According to this principle, the limit magnitude appear to be between 4 and 5.

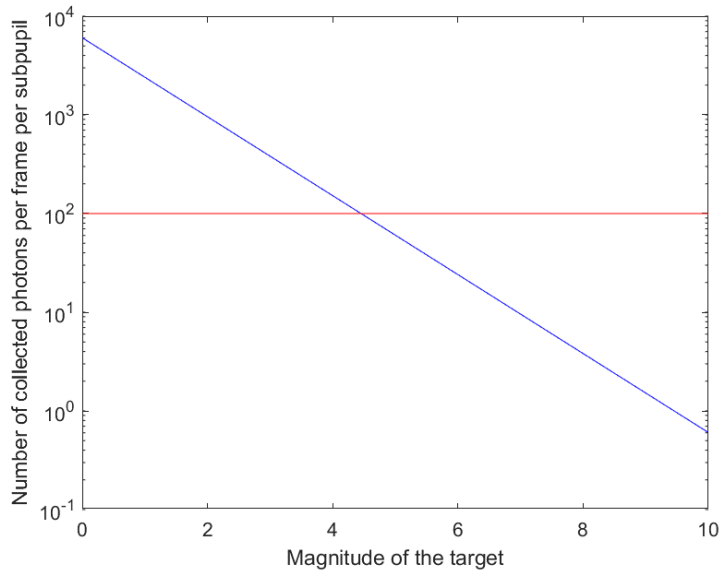


Figure 2. In blue: number of detected photons per sub-pupil and per frame, in function of the magnitude of the target observed at zenith, at 500 Hz. In red: the lower limit for this number, assumed to be 100 photons per sub-pupil per frame

2.3 Angle of arrival

From the characteristics of the telescope and of the MLA one can compute the on-sky angular size of one subpupil with the formula 1, where ϕ is the on-sky angular size of one lenslet in radian, N is the number of lenslet across the pupil diameter, d is the diameter of one lenslet in meter and D is the diameter of the telescope entrance pupil in meter as well. In our case we find $\phi = 5.63$ arcsec.

$$\phi = \frac{N \times d^2}{f \times D} \quad (1)$$

We need to ensure that the angle of arrival of the turbulent light will not exceed this value, otherwise the PSFs formed by the MLA will get out of the area designed for them on the detector (often called their boxes). The formula 2 provides the following expression to compute the variance of the angle of arrival over a given aperture in function of its diameter and the Fried parameter of the turbulence [1]. In our case we find $6\sigma = 5.4$ arcsec for a r_0 of half a subpupil, i.e 5 cm.

$$\sigma^2 = 0.17 \left(\frac{\lambda}{D} \right)^2 \left(\frac{D}{r_0} \right)^{\frac{5}{3}}. \quad (2)$$

In other words, for more than 99% of the cases, in open loop regime, for a r_0 of at least 5 cm, the PSFs formed by the MLA will not get out of their boxes.

Note that in order to be sure that our measure is not disturbed by an issue of this type nor by stray light we use a field stop in the Shack-Hartmann branch. See section 3.3.

3. SHACK-HARTMANN BRANCH OPTO-MECHANICAL DESIGN

3.1 Mount

The Shack-Hartmann Mount has been designed by Eric Stadler from IPAG. We used two off-the-shelf components already existing in our laboratory, the Thorlabs XYR1 Translation Stage with Rotating Platform and the Newport M36 tilt and rotation Platform.

This mount offered us the following degrees of freedom: tip and tilt, translation along x (horizontal) and z (optical axis), rotation along the optical axis (clock). The only missing degree of freedom is the height that we were able to adjust by placing thin spacers below the mount. The figures 3 and 4 show a 3D view of it.

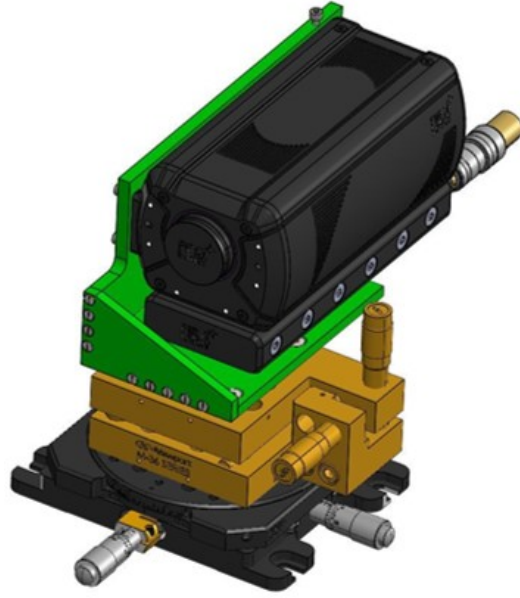


Figure 3. Shack-Hartmann mount holding the Cblue One camera



Figure 4. The tilt adjustment on the MLA plane is made possible by the two screws on the left

3.2 Optical solution to send the beam to the Shack-Hartmann branch

3.2.1 Relay

In order for the Shack-Hartmann to be in Fried configuration with the deformable mirror we needed to apply a magnification factor of 0.2 to the incoming collimated beam. Therefore, we used an afocal system made of two convergent lenses of focal length of respectively 150 mm and 30 mm. Its position on the bench can be seen on the figure 1.

3.3 Field stop

In order to avoid stray light on the Shack-Hartmann detector and to prevent the spots formed by the MLA to get out of their boxes we used a field stop of diameter equal to $500 \mu\text{m}$ in the position described by the figure 1, which correspond to an angular diameter on-sky of 4.3 arcsecond. The typical seeing at OHP is around 2 to 4 arcsec, so we assumed that the bootstrap of the AO loop can be done with such a field stop.

3.3.1 Flip mirror

In order to compare the PYWFS and SHWFS branches we need to be able to quickly switch from one branch to another. To address this need we used the MFF101 motorized flip mount made by the Thorlabs company, that allows us to change the optical path from one branch to the other in less than a second. Its position on the bench can be seen on the figure 1.

4. ON-SKY TEST

4.1 Observing conditions

Unfortunately, during this mission the weather was very cloudy. Because of that we only manage to close the loop four times and got only one exploitable run, from which are derived the results shown in section 4.2.

4.2 Results

The following results were obtained on Capella, a star of magnitude 0.08 in V band. The loop parameters were the following:

1. Loop Frequency: 500 Hz
2. Loop gain: 0.1
3. Number of controlled modes: 150 (Hadamard basis)

The flux estimated from the data is roughly 2500 photons per sub-pupil and per frame. The time between the open loop and the closed loop acquisitions is 6 minutes.

As the figures 5 and 6 show, we can see a clear improvement in the shape of the PSF when closing the loop. Also, the figure 7 show a partial tip/tilt correction by the AO loop. However, the correction is not effective enough to see a real Strehl Ratio improvement.

The first thing we could do in order to improve these results would be to raise the gain of the loop, in order to decrease the temporal error. Unfortunately we did not have the time to do it on this mission because of a cloudy weather.

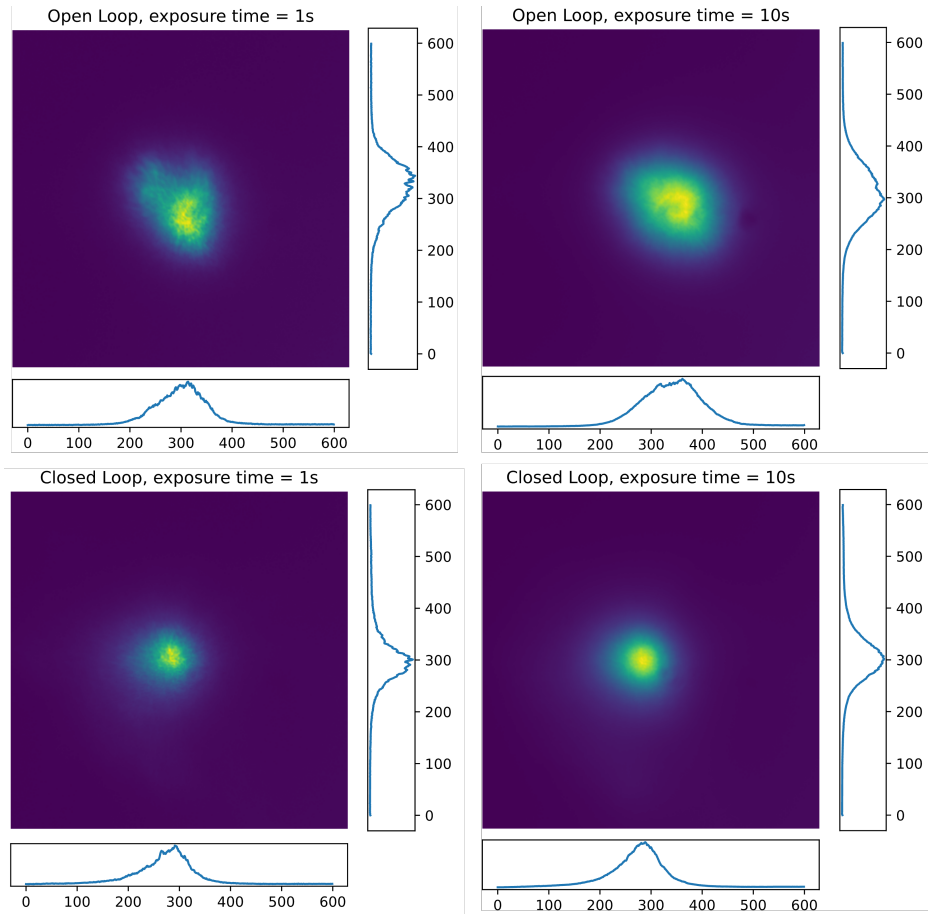


Figure 5. Open and closed loop short and long exposure

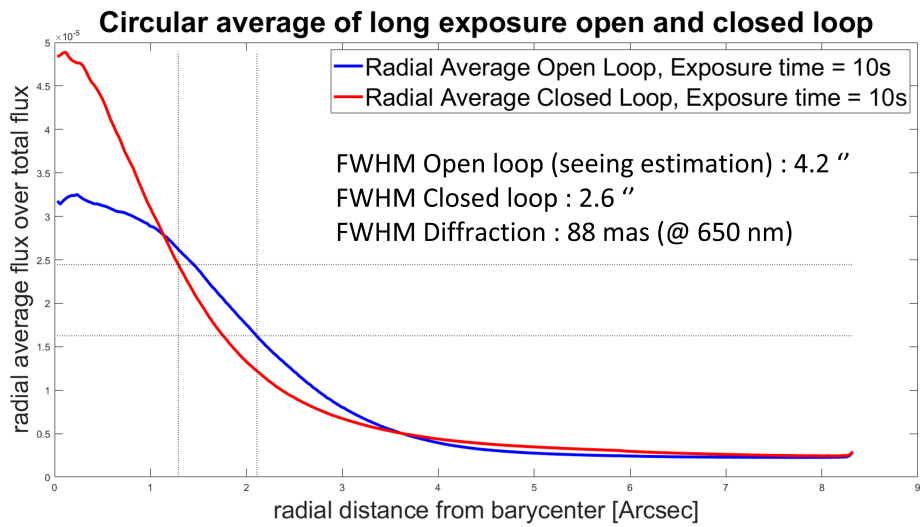


Figure 6. Circular average of the long exposure PSF in open and closed loop

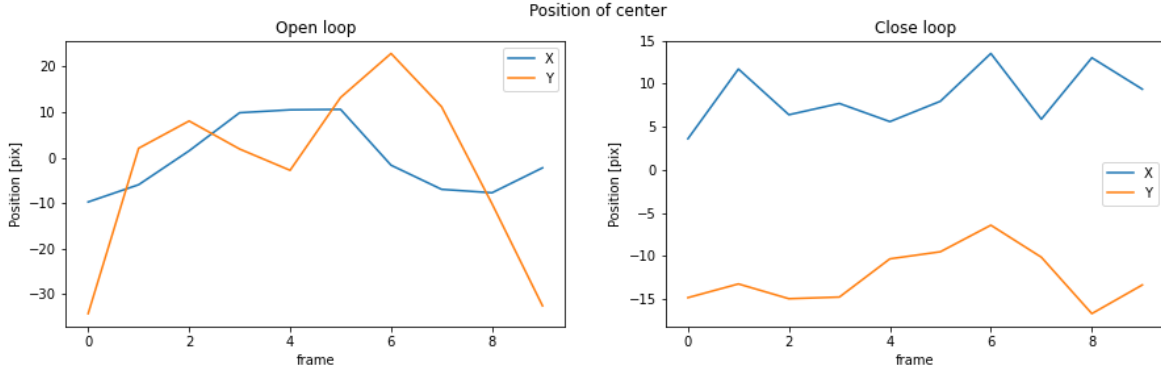


Figure 7. Evolution of the barycenter across time for closed and open loop

5. CONCLUSION

With this work we manage to design, build and align a new wavefront-sensing branch on the PAPHYRUS bench, based on a Shack-Hartmann wavefront sensor. We could test it on sky under quite tough conditions (very cloudy and with a strong seeing) and assess a good tip-tilt correction and an improvement of the shape of the PSF. Yet, we did not reach the expected level of performances, mostly because we did not have a large enough window of observation to adjust the loop parameters. In particular, we only tried to run the loop with a very low value for the integrator gain, and we expect to be able to show a significant Strehl ratio improvement by running the loop with higher values for this parameter.

Once we manage to fully validate its performances, the Shack-Hartmann branch on PAPHYRUS will be an opportunity to perform in-depth Pyramid and Shack-Hartmann comparison. We can also imagine using it as an observation wavefront sensor when closing the loop with the PYWFS branch in order to better understand the Pyramid behavior outside its linear regime.

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