SAPHIR: a new concept of reflective pyramidal wavefront-sensor free from chromatic aberrations

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ABSTRACT

In the context of extremely large telescopes, the pyramid wavefront sensor is preferred to Shack-Hartmann sensor both because of its huge sensitivity advantage, and for the reduced number of pixels required in the analysis process. Meanwhile, in order to maximize the sky coverage and access the faintest guide stars, wavefront sensors need to cover a large spectral range. However, because pyramid acts as four adjacent prisms, it yields some chromatic dispersion on the pupil images. This chromatic blur is incompatible with the large number of pixels across the pupil.

In the context of the SCAO of MICADO (a first-light, wide-field near-IR imager instrument at the ELT), the specification on the tolerance on the pupil blur is of the order of a thousandth of the pupil diameter: chromatic effects of a single pyramid become unacceptable even with low-dispersion glasses. A common approach to overcome this issue is to use a double-pyramid with two components chosen for chromatic dispersion compensation.

Another way to get rid of chromatic effects is to replace all dioptric components by mirrors. Meanwhile, no reflective component is known to achieve the splitting function required in the pyramidal WFS. This is why we invented SAPHIR (Sensor Achromatic Pyramid HIgh-Resolution), a brand-new concept of pyramidal wavefront sensor where the splitting is done with an innovative pyramid, based on reflective surfaces only, making the design free of chromatic dispersion. The theoretical concept is described, especially its adaptability to diverse optical configurations and its compliance to ELT projects (in particular to MICADO SCAO module). Then a SAPHIR opto-mechanical prototype manufactured and tested on the SESAME AO test bench in Observatoire de Paris-Meudon is described. This new system is compared to a classical single pyramid prototype, also tested in parallel on the same bench.

Keywords: wavefront sensing, pyramidal wavefront sensor, achromatic wavefront sensing, MICADO

1. INTRODUCTION

In the context of ELT, the Pyramid Wavefront Sensor (PWFS)[1] is preferred to the Shack-Hartmann WFS both because of its huge sensitivity advantage and for the reduced number of pixels required in the analysis process. Meanwhile, in order to maximize the sky coverage and access the faintest guide stars, wavefront sensors need to cover a large spectral range. For MICADO, the adaptive optics first-light wide-field near-IR imager instrument at the ELT, the PWFS is designed to cover a spectral band as large as [589–960 nm]. In order to overcome the PWFS chromatic limit, we invented SAPHIR (Sensor Achromatic Pyramid HIgh-Resolution), a brand-new concept of PWFS where the splitting is done with an innovative pyramid, based on reflective surfaces only.

This paper is a progress report of ongoing prototyping of Reflective Pyramid Wavefront Sensor (RPWFS) from now on called SAPHIR, a process conducted at Observatoire de Paris (LESIA and GEPI), taking as a dimensioning basis the MICADO specifications. After reminding the limits of a classical PWFS, we describe the prototype conceived and manufactured. We detail the adaptive optics bench facilities with which the prototype has been tested, where a classical refractive PWFS and SAPHIR are mounted in parallel to be compared. The first results, showing their comparable performance in monochromatic light are finally shown.

2. CLASSICAL PYRAMID WFS: THE CHROMATIC LIMIT

The principle of the PWFS relies on the imaging of the telescope pupil through a 4-faces focal plane pyramid, generating 4 pupil images in the sensor plane, which fluxes are compared pixel-to-pixel in order to evaluate the aberrations of the PSF imaged at the pyramid summit[1]. Unfortunately, this refractive pyramid acts as four adjacent prisms and yields chromatic dispersion on the pupil images, which is incompatible with the large number of pixels across the pupil.

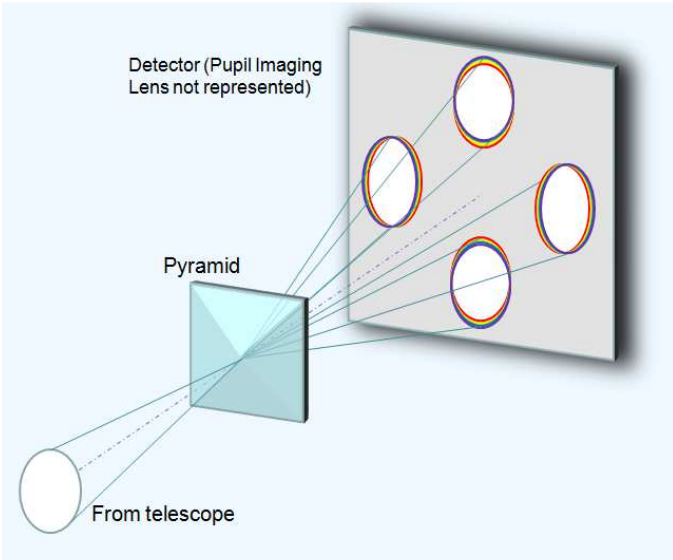


Figure 1. Chromatic dispersion effect due to the use of a refractive pyramid to generate the 4 pupil-like images

A common approach to overcome this issue is to use a double-pyramid with two components which combined indexes and Abbe numbers are chosen for chromatic dispersion compensation. The figure below shows the baseline double pyramid for MICADO PWFS, made with the association of two single refractive pyramids, one in S-LAH51, and one in N-KZFS5.

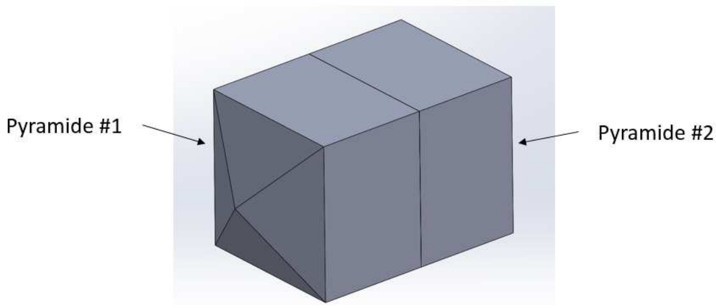


Figure 2. MICADO double pyramid used to compensate chromatic aberrations with glasses S-LAH51 for pyramid #1 and N-KZFS5 for pyramid #2.

Meanwhile, this leads to manufacture and alignment issues, and the achromatisation remains imperfect. Only a reflective component would lead to a perfect built-in achromatisation, but no known optical combination exists to ensure the splitting function in the focal plane.

3. SAPHIR: FROM THE OPTO-MECHANICAL CONCEPT TO THE MANUFACTURED PROTOTYPE

3.1 Optomechanical concept

The pyramid component function is to split, in the focal plane, the beam into four new beams. In the SAPHIR concept, exactly like in the refractive pyramid approach, light from the telescope is focused on the entrance of a sharp reflective double-pyramid with four faces, and directed towards four independent flat mirrors. Then light is directed to the output of the SAPHIR where a last reflection occurs. After this, light goes towards the pupil imaging lenses and the detector, exactly like in the classical refractive pyramid approach. One can notice that, compared to a refractive pyramid, a pupil axial symmetry occurs in one direction. This is taken into account in the phase reconstruction processs.

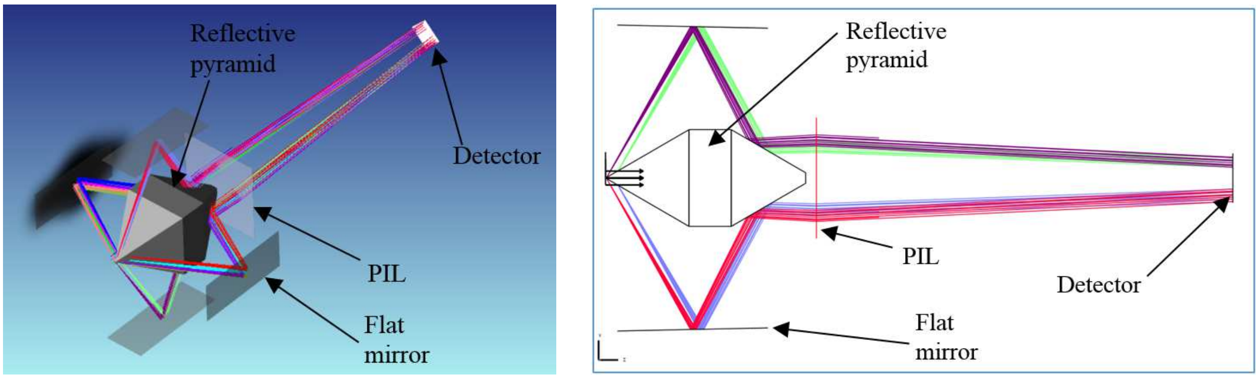


Figure 3. 3D view (left) and 2D view (right) of a SAPHIR reflective pyramid. The Pupil Imaging Lens (PIL) is represented as a paraxial lens for the sake of representation simplicity.

A dedicated mechanics is designed to mount the SAPHIR. Movements of the whole system is necessary in order to position the sharp entrance of the prism at the telescope focus: a rail allows the translation of the assembly to roughly position the pyramid summit in the focal plane. A precise displacement in focus and height can also be performed to finalize the alignment. The mount also permits the rotation of the pyramid around the optical axis to adjust the average positioning of the pupils on the CCD. Eight independent tip-tilt movements permit the orientation of the four flat mirrors in order to precisely position the pupils on the detector.

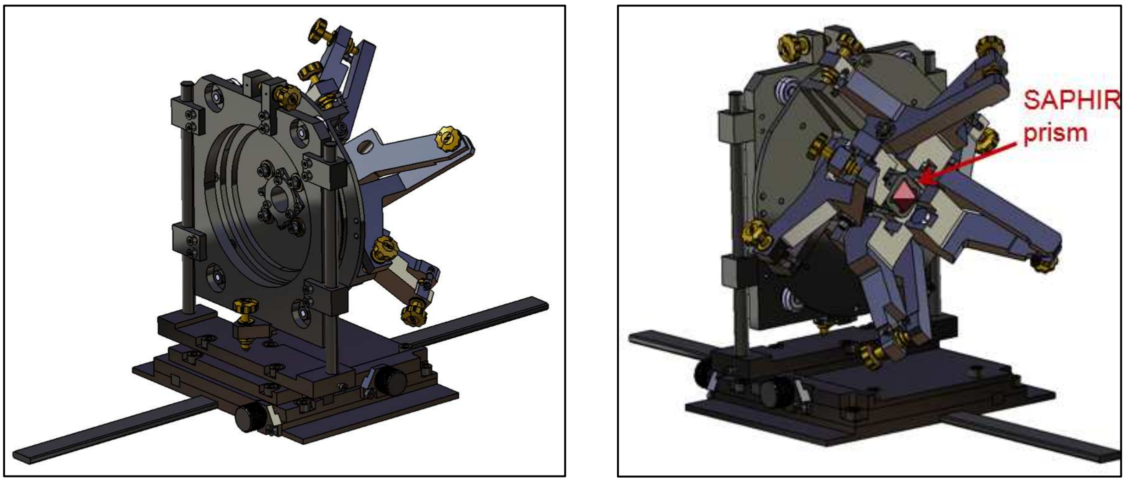


Figure 4. Front view (left) and back view (right) of SAPHIR's mechanical mount. The pyramid (visible on the right-side image) is held at the center of the mount.

3.2 Prototyping

Following the design study, an opto-mechanical prototype has been manufactured.

The manufacturing of the prism, despite its unusual shape, is not an issue. Its polishing is easier than for the classical refractive design pyramid: the potential errors on the angles of the faces are easily compensated using the flat mirrors adjustments. From the manufacturer point of view, an acute angle such as that required by SAPHIR is easier to make than a nearly flat pyramid as it is required in the refractive design.

Meanwhile, because the intention was the validation of a concept rather than the integration in an instrument, and in order to minimize the costs, the specification on the pyramid summit sharpness has been relaxed to 50 µm.

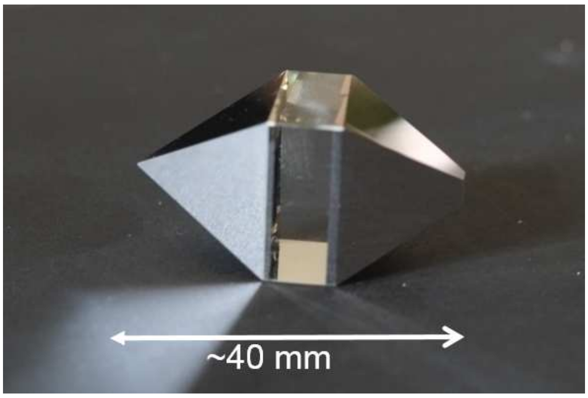


Figure 5. SAPHIR pyramid manufactured in borosilicate and coated with a MgF_2 protected aluminization optimized for visible.

The design and manufacturing of the mount have been done at GEPI department, along with a separated dedicated mount for the PIL that can also be translated on the same rail. Because this prototype goal was to validate the concept on a test bench, no particular care has been given to the volume of the mount, the main consideration being the achievement of the angle precisions on the flat mirrors: an accuracy of 5 µrad and a stability of 1 µrad was required to reach a positioning of the pupil smaller than $1/10^{th}$ of a pixel. Meanwhile, thanks to phase reconstruction algorithms for PWFS recent progress, the precise positioning of the four pupils is now far less critical than before[3]. Future versions of the mechanics could be a lot simpler, without accurate adjustment of the flat mirrors (this may be replaced by shimming to keep the pupil onto the detector). Indeed, the specification is relaxed by a factor 30 to 40, the only constraint being, from now on, to keep the pupil in its quadrant without approaching the edges by more than 2 pixels.

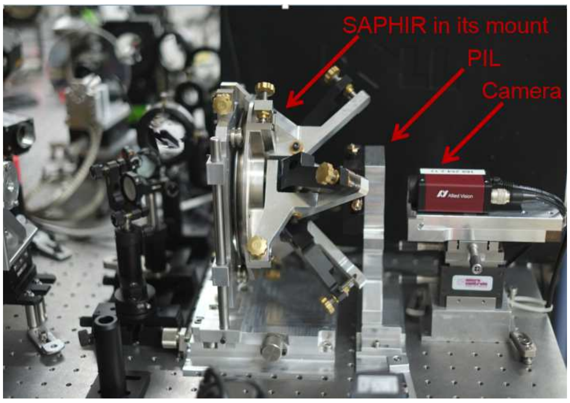


Figure 6. SAPHIR mounted on the SESAME adaptive optics bench (Observatoire de Meudon). Right after the SAPHIR, is implemented a pupil imaging lens (PIL) that forms the four pupil images on the camera.

4. TEST BENCH

We characterize this new PWFS on SESAME bench, already existing with several AO facilities, and in particular: an SLM (Spatial Light Modulator) and a tip-tilt mirror. This bench is currently used to characterize a classical refractive PWFS (named PYRCADO[2]). In its original version, SESAME delivers an F/15 beam. Meanwhile, because PYRCADO - and now SAPHIR - work with a slower beam entrance (F/50), an adjustable zoom system is implemented at SESAME's output in order to adapt the aperture of the bench (available aperture range from F/55 to F/25).

The test of a PWFS on SESAME thus consists in generating a known phase with the SLM, and measuring it with the PWFS. This phase measurement can be used to close the adaptive optics loop (on the SLM itself). SAPHIR is used with a modulation ranging from 0 to 20 λ/D, provided by a dedicated mirror inserted in a pupil plane in the optical path.

In order to be able to compare the two types of PWFS measurements, just before focusing the F/50 beam on the pyramid (@ λ=633 nm), we add an exchangeable fold mirror to redirect the beam either towards SAPHIR, or towards PYRCADO. The modulation path, the beam geometry, and the phase are identical for both PWFS, making the comparison accurate.

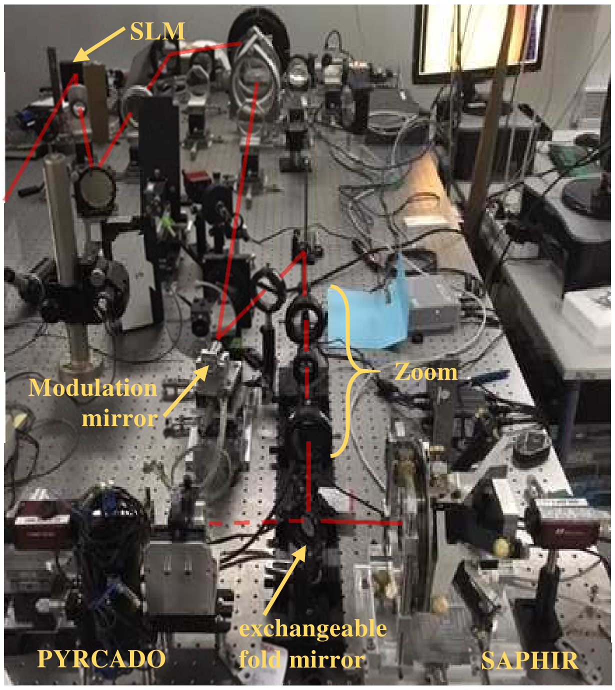


Figure 7. View of SESAME adaptive optics bench. It delivers a beam that hits an exchangeable mirror, mounted on a kinematic mount. The beam can be directed either towards PYRCADO (a classical PWFS) or towards SAPHIR (the reflective PWFS).

Table 1. SESAME bench parameters for the test PYRCADO of SAPHIR (N.B: The tests are done in monochromatic light. Indeed, the fact that mirrors do not introduce any chromatism does not need to be demonstrated)

	PYRCADO	SAPHIR
Pyramid edge	20 µm	~50 µm
Number of pupil formed	4	
Number of pixels per pupil diameter	65	60
Number of slopes (full pixel method)	13656	11392
# of actuators (SLM)	1131	
λ	633 nm	

5. RESULTS

First, the RAW images of SAPHIR and PYRCADO are compared without introducing any aberration with the SLM. Flat and dark correction are performed. One can see that the images are comparable for the two systems.

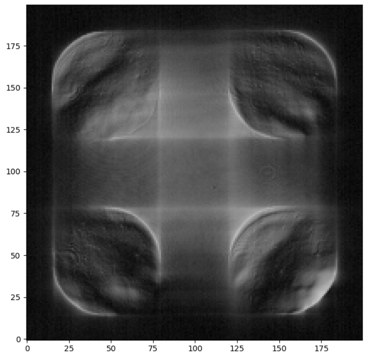
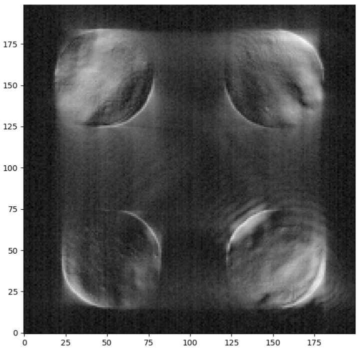
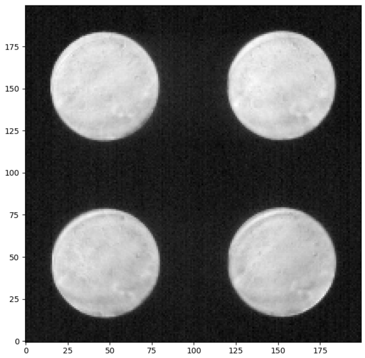
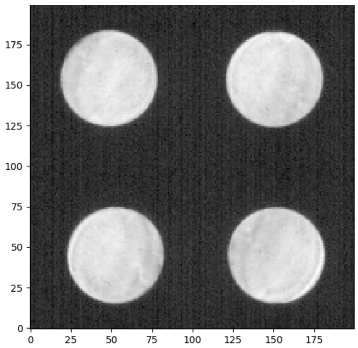
	PYRCADO	SAPHIR
No aberration + No modulation		
No aberration + 20 λ/D modulation radius.		

Figure 8. Example of RAW images (after flat and dark correction) of the 4 pupils for the case with no aberration, compared for the two WFS (images displayed in log scale).

Then a phase is applied with the SLM, in open loop, for low (mode #12), medium (mode #200) and high (mode #1000) spatial frequencies deformable mirror modes. The figures below show the simulated phase generated by the SLM on the left, and the corresponding raw images on both WFS on the right (modulation is 20λ/D for all RAW images).

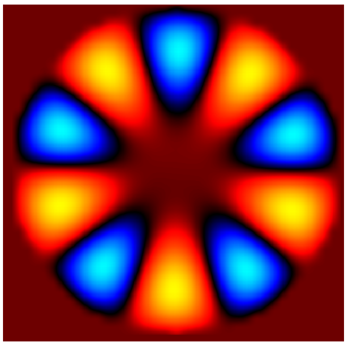
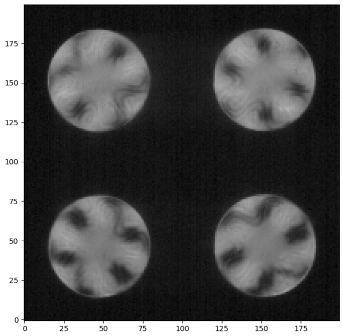
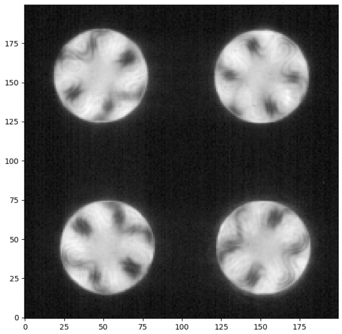
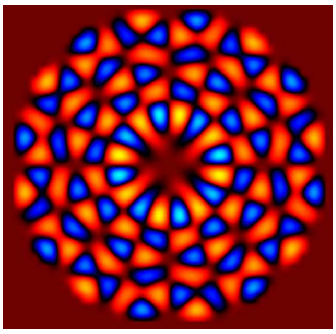
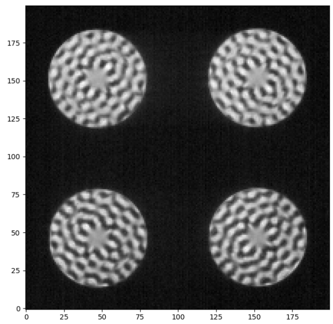
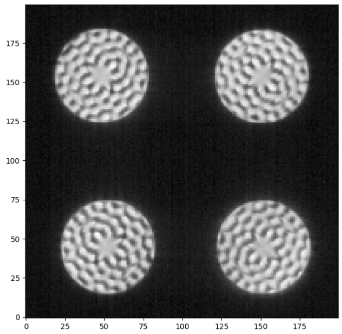
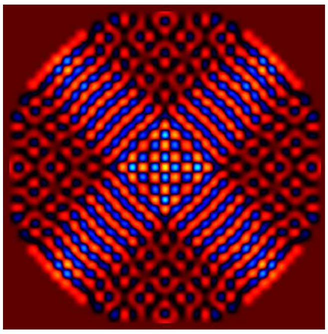
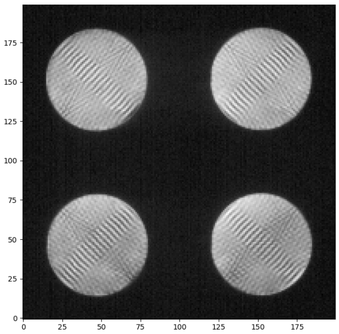
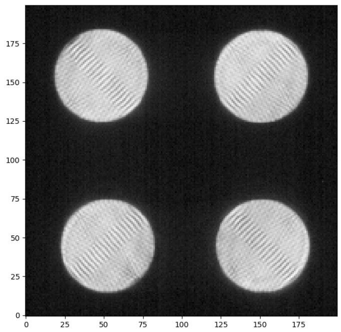
	Simulated Phase using SLM	PYRCADO	SAPHIR
500nm rms of mode #12			
200nm rms of mode #200			
50nm rms of mode #1000			

Figure 9. Example of RAW images for both WFSs (PYRCADO and SAPHIR) on low (mode#12), medium (#200) and high (#1000) spatial frequencies deformable mirror modes

Last, we used SAPHIR to close the loop on a 20cm r_0 seeing and measured the PSF during the adaptive optics correction. The figures below show the PSF obtained on the scientific camera at 633 nm in open loop, and a compensated PSF with the loop closed using SAPHIR after 100 iterations.

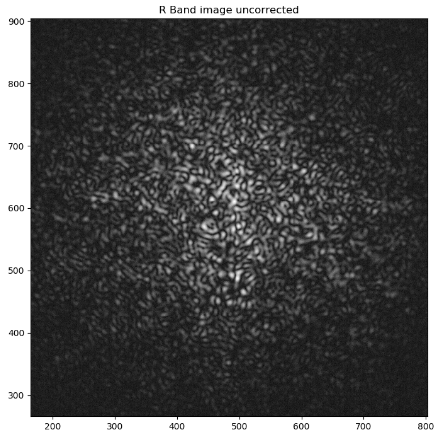
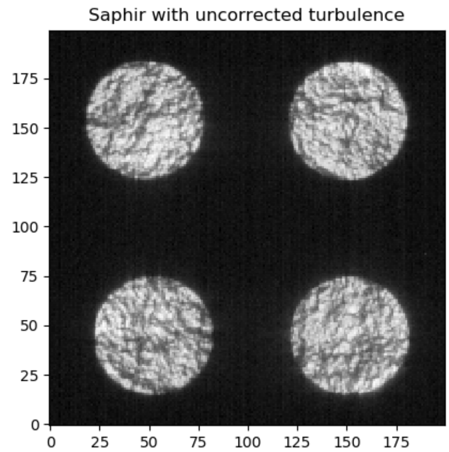
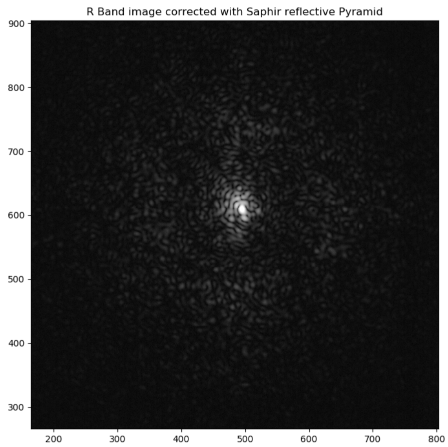
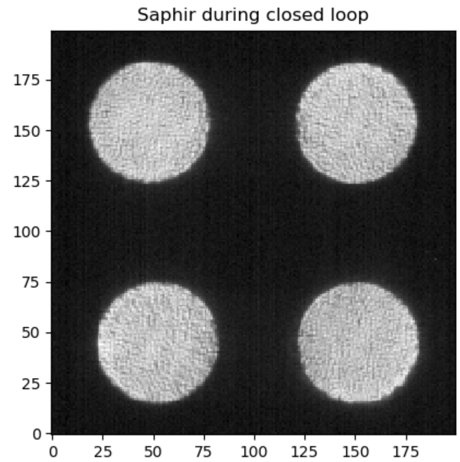
	PSF at 633 nm (≈R band)	SAPHIR Pupil plane
Open loop (r0=20cm)		
Loop closed with SAPHIR after 100 iterations		

Figure 10. Left: PSF obtained on the scientific camera at 633 nm (≈ R Band) in open loop and closed loop. Right: corresponding pupil-like images on SAPHIR.

6. CONCLUSION AND PERSPECTIVES

We have demonstrated SAPHIR's ability to provide wavefront measurements that are equivalent to the ones delivered by a refractive PWFS. These measurements allowed us to work in closed loop in order to compensate a blurred PSF.

An important effort has been done on the mechanical design for this first prototype version, especially because a sub-pixel positioning (typically 1/10th of a pixel) was required. This positioning, relying on the angles of the four flat mirrors, needed very precise mechanisms. This additional complexity, compared to a classical PWFS, could make SAPHIR less competitive. Meanwhile, recent work on phase reconstruction algorithms (full pixel method[3]) has permitted to get rid of this constraining specification, and to relax the positioning precision to 3 to 4 pixels. A new simplified mechanical design is currently in progress, with a reduced volume and no degree of freedom on the flat mirrors. This opens perspectives to make SAPHIR compliant with telescope instruments environment constraints.

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