# The SPHERE XAO system SAXO: integration, test and laboratory performance.

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## ABSTRACT

Direct detection and spectral characterization of extra-solar planets is one of the most exciting and challenging areas in modern astronomy due to the very large contrast between the host star and the planet at very small angular separations. SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research in Europe) is a second-generation instrument for the ESO VLT dedicated to this scientific objective. It combines an extreme adaptive optics system, various coronagraphic devices and a suite of focal instruments providing imaging, integral field spectroscopy and polarimetry capabilities in the visible and near-infrared spectral ranges.

The extreme Adaptive Optics (AO) system, SAXO, is the heart of the SPHERE system, providing to the scientific instruments a flat wavefront corrected from all the atmospheric turbulence and internal defects. We present an updated analysis of SAXO assembly, integration and performance. This integration has been defined in a two step process. While first step is now over and second one is ongoing, we propose a global overview of integration results. The main requirements and system characteristics are briefly recalled, then each sub system is presented and characterized. Finally the full AO loop first performance is assessed. First results demonstrate that SAXO shall meet its challenging requirements.

**Keywords:** Adaptive Optics

## 1. INTRODUCTION

The SPHERE system [1] aims at detecting extremely faint sources (giant extra-solar planets) in the vicinity of bright stars. Such a challenging goal requires the use of a high-order performance Adaptive Optics system (XAO). Still, the very high expectations of SPHERE not only require the use and the optimization of such an AO system, but they also require an extreme control of the system internal defects [2] such as Non Common Path Aberrations (NCPAs), optical axis decentering, vibrations, coronagraph and imaging system imperfections and so on, leading to additional devices in the AO concept to reach the ultimate detection limit. Consequently, demanding requirements have been defined for the SPHERE AO system SAXO. To validate such a complex AO system, Acceptance, Integration and Test (AIT) of SAXO has been defined as a two step process. During a first step, the AO main components (active mirrors, visible WaveFront Sensor (WFS), infrared WFS, Real Time Computer (RTC), spatial filter) have been integrated and tested in a dedicated AO bench, located in Observatoire de Meudon. This bench allowed a functional validation of each component [3,4] and more globally of the AO functionalities, though it was not designed to assess the final performance of AO. A first Acceptance and Readiness Review (ARR) was still carried out. In a second step, the AO components have been removed from this bench and shipped to Grenoble to be integrated in the final system (Common Path Infrastructure). This is the present status of the system. AO is currently being tested for final performance assessment and used to provide SPHERE

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instruments with coronagraphic images. This article proposes a status of SAXO at ARR after first integration and optimisation in Meudon, and current status after re-integration in common path of SPHERE system at Grenoble.

After a short summary of SAXO requirements and design (Sect. 2), we propose an overview of the AIT of SAXO in Meudon and work arounds used to validate the AO functionalities in spite of the bench limitations (Sect. 3). We then propose a status of its main components and first performance assessment at ARR (Sect. 4). Finally we propose a description of the current validations and performance results in SPHERE system.

## 2. SAXO REQUIREMENTS AND DESIGN

SAXO high level requirements are described in [2]. We summarize hereafter the main requirements that drove the SAXO design:

- Residual Tip-Tilt (TT), in normal conditions (seeing = 0.85 arcsec, average wind speed = 12.5 m/s, L0 = 25 m, Guide Star (GS) magnitude < 9 (in V, GO star)) is 3 mas rms.
- Turbulent residual wavefront variance on corrected modes in normal conditions is 60 nm rms
- Strehl Ratio (SR) (at 1.6 µm) is higher than 15% in poor (seeing = 1.1”, wind speed = 28 m/s GS magnitude < 8) or faint (normal conditions with GS magnitude < 12) conditions
- System pupil shall stabilized in translation below 0.2% of pupil diameter
- Stability of image position (hence compensation of image movements due to differential atmospheric dispersion between Vis and Near Infra-Red (NIR) bands for instance) shall be better than 0.5 mas
- The residual non common path aberrations shall be lower than 0.8 nm per mode.
- AO system shall pre-compensate for 50 nm rms of non common path defocus and 40 nm rms of the 55 first Zernike modes.

These requirements lead to a drastic optimization of the AO loop to fulfil the tight error budget associated.

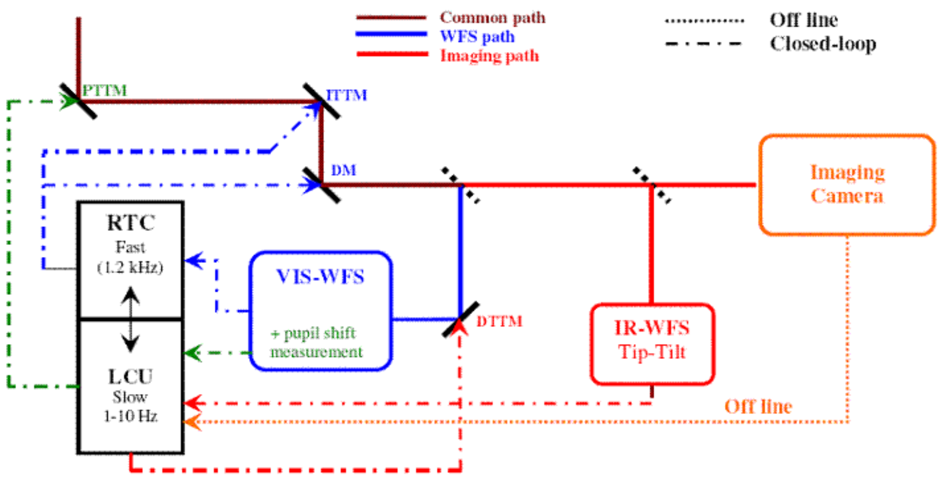



Figure 1. Overview of SAXO functional and control diagram

The SAXO system is then composed by 3 loops plus one off line calibration (Figure 1):

- Main AO loop (1.2 kHz): correct for atmospheric, telescope and common path defects.
- The Differential TT (DTT) loop for fine centring on coronagraph mask (correction of differential tip-tilt between VIS and IR channel).
- The Pupil TT (PTT) loop for pupil shift correction (telescope and instrument).
- Non Common Path Aberrations (NCPA) pre-compensation which will lead to the reduction of persistent speckle

SAXO thus gathers the following elements:

- A high spatial (41x41 actuators) and temporal frequencies Deformable Mirror (DM) provided by CILAS to correct for phase perturbations but the tip-tilt.
- A fast (bandwidth at -3db larger than 800 Hz) Image TTM (ITTM) for image motion correction.
- A 40x40 visible Spatially filtered Shack-Hartmann (VIS-WFS) [5] with EMCCD 240x240 pixels working at 1200 Hz and a read out noise smaller than 1 e- . A spatial filter device is added in front of the WFS to reduce the aliasing effects.
- A Real Time Computer (RTC): the overall AO loop delay (defined between the first pixel read on the detector to the last voltage sent to the DM) shall be equal to 1 ms. A mixed control law shall be implemented in RTC to handle separately ITTM and DM control [3]: Optimal modal gain integrator for the DM mode and Kalman filter based control law for the tip-tilt mode (Linear Quadratic Gaussian (LQG) control). This Kalman filter control law shall correct for 10 vibration patterns located around the AO system bandwidth
- A phase diversity algorithm which will measure and optimize the non common path aberrations (NCPA) at the level of the coronagraph.
- A slow Pupil TTM (PTTM) close to the entrance focal plane to correct for pupil shifts

A slow infra-red Differential TT Sensor (DTTS) on the scientific channel measuring the differential tip-tilt between the common and imaging paths. Differential TT is corrected by use of a Differential TT Plate (DTTP) located in the main AO loop.

## 3. SAXO COMPONENTS TEST BENCH AT OBSERVATOIRE DE MEUDON

As a first step of integration, SAXO components, as described in previous section, have been installed in Meudon Observatory, Paris, in clean room, in a fully dedicated AO bench as can be seen in Figure 2. This bench has been taylor-made for SAXO components that would then be shipped for re-integration in SPHERE system after validation. An overview of the bench with identification of the SAXO components is proposed in Figure 3. A turbulence simulator is used to reproduce realistic turbulence conditions. It is based on 2 rotating phase screens, inducing turbulence with Von Karman statistics, with variable speed, conjugated to the system pupil, and providing seeing conditions of respectively 0.62'' and 0.84''.

This bench allows testing the AO components with respect to their specifications and the overall AO functioning with the RTC. First integration results and components characterization were presented recently [4]. Still, as underlined in [4], some limitations, either in the early version of components or in the bench design limited the integration and tests procedure. Components limitations mainly affected the HODM and the Visible WFS, leading respectively to high static residual wavefront error due to HODM poor flatness (7.3µm surface error PV at rest) and limited sampling frequency (125Hz). Since them, these problems have been solved. A cylindrical lens has been introduced in the bench to compensate the HODM defects down to a residual 2µm wavefront error PV. The visible WFS has been updated allowing a full speed use of system at 1.2 kHz.

Additional functionalities could not be fully tested due to bench limitations. In particular low flux testing could not be performed. DTT loop and PTT loop could only be tested functionally. In the end, this bench allows to perform some first performance assessment, though, due to these limitations, comprehensive performance tests are limited and have been postponed to integration in SPHERE final system at Grenoble.

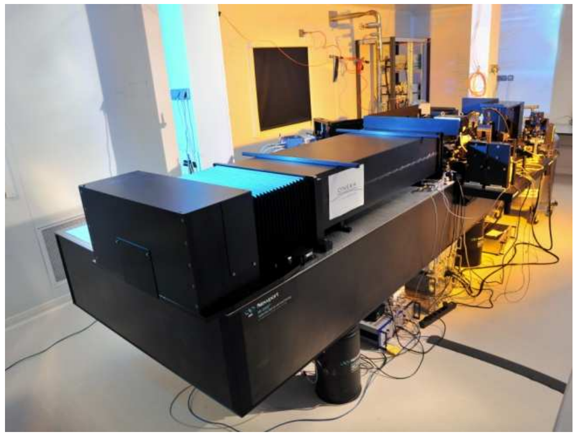


Figure 2. Picture of SAXO test bench in Meudon clean room

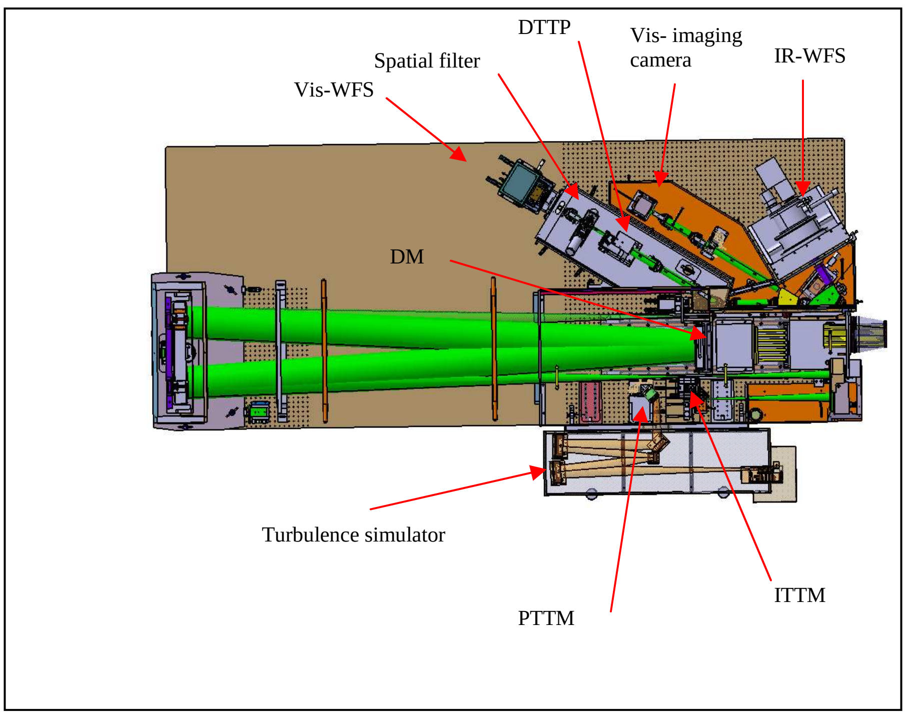



Figure 3. Overview of SAXO test bench in Meudon, with the SAXO components.

An Acceptance and Readiness Review (ARR) of the AO has been performed in these conditions, prior to the shipping of the AO components to Grenoble and their re-integration of the SPHERE system. Description of the various components status at ARR is proposed in table 1.

Table 1. Summary of SAXO components status at ARR.

| Component | Component Status + functionality status at ARR |
|---|---|
| High Order Deformable Mirror (CILAS) 41x41 piezo stack DM | Model #1, limitations: flatness see [4], 4 dead actuators, and high frequency behaviour defects |
| Image Tip Tilt Mirror, high speed tip-tilt (LESIA) | Within specifications. Fully functional up to 1200Hz. |
| Differential Tip Tilt Plate, to correct the tip-tilt between wavefront sensor (WFS) beam and NIR beam (LESIA) | Within specification. differential TT loop functional at nominal speed (between 1 and 10 Hz) though performance assessment limited by bench design. |
| Pupil Tip Tilt Mirror, to keep the pupil location stable in SPHERE (PI) | Within specifications. Pupil loop functional at nominal speed (0.033Hz) though performance assessment limited by bench design. |
| 40x40 Shack-Hartmann WFS (ESO) | Partially within specification. Functional at nominal speed (1200Hz), but gain limited up to 100. |
| Spatial filter (variable square pinhole) (IPAG) | Partially within specifications. Spatial filtering functional though must be re shaped to have a proper square (see [4]). |
| NIR Differential Tip-Tilt Sensor (ESO) | Within specifications. Fully functional at nominal speed. |
| Real Time Controller : SPARTA platform, (ESO). | Almost within specifications. Fully functional at full speed on all loops. Wavefront sensing and control laws validated, part of high level functionalities available and validated |

# 4. FUNCTIONAL VALIDATION AND FIRST PERFORMANCE ASSESSMENT

All the critical components of SAXO (ITTM, PTTM, DTTP, DM, RTC, Visible and IR WFS, spatial filter) have been successfully tested. It has been demonstrated that most of them are (or will be in a very near future) completely within the specifications. Some defects have been identified (especially concerning the current version of the DM) and some solutions have been provided to overcome the induced limitations.
The coupling of all the components in a single, coherent and efficient AO system has been performed. More than 90 % of the SAXO functionalities have been successfully implemented and tested for ARR (at least from a functional point of view).
A preliminary coupling of SAXO (mainly its RTC SPARTA) with the INstrument Software (INS) has also been performed. From a performance point of view several tests and measurements have been conducted.
This performance tests can be separated in two main items:

- The optimization of SAXO internal performance thanks to the NCPA correction
- The optimization of SAXO loop parameters and the measurement of final performance obtained using the turbulence simulator and both a Visible test camera and the DTTS sensor (in its wide field mode)

## 4.1 Main components and functionalities testing

We propose hereafter some comments on the testing of SAXO key features. First of all, we focus on High Order DM and its control law. Apart from its static defects discussed before, the DM has been extensively tested with respect to its dynamic performance. Over 1377 actuators, 4 are optically or electronically dead, and about 6 ones present some high temporal frequency defects induced by high impedance, leading to oscillatory behavior at high gain. This behavior is however strongly dampened through modal control. Indeed, as described in [3], DM control is defined on a particular Karhunen-Loeve basis and ensured by Optimized Modal Gain Integrator.

Figure 4 shows the correct behavior of DM and its control law for various gains and provide a first estimate of global delay of the system, estimated to 2.14 frames, within specifications (nominal: 2.2, goal: 2). Control through OMGI, with online optimization of gain has been also validated. This control law being prone to wind-up effect, an anti-wind-up procedure, associated to garbage collection (for filtered mode stabilization) has been implemented and validated. This leads to improved robustness in stability and performance has shown in [8].

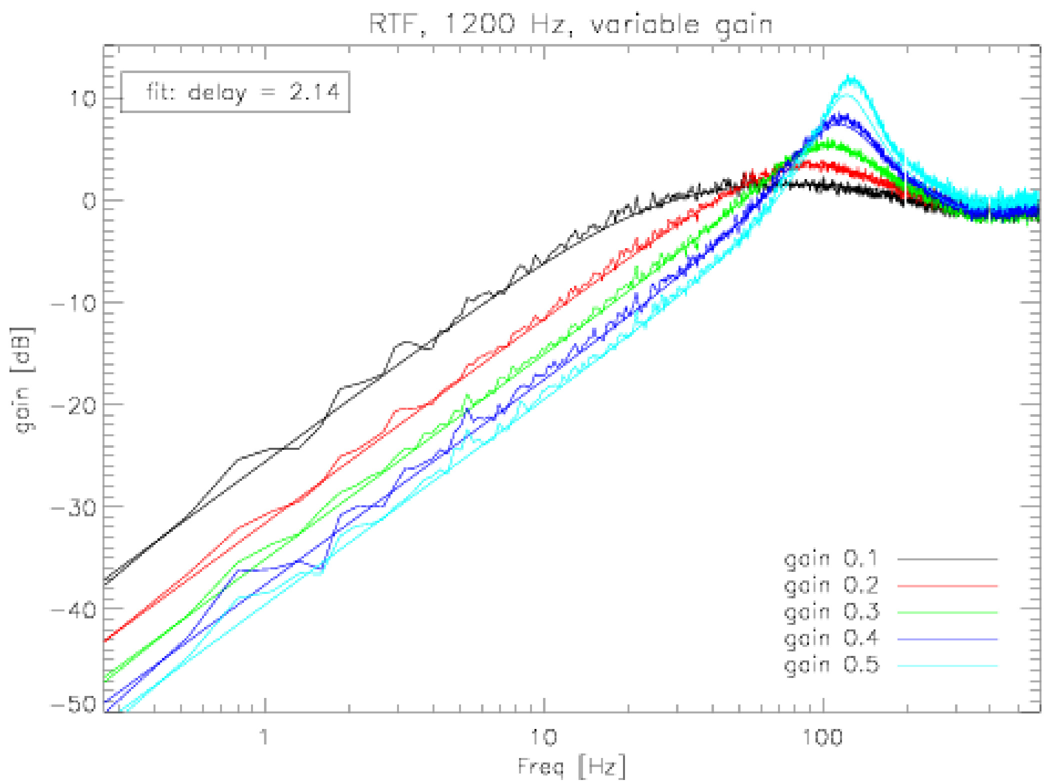



Figure 4. Experimental Rejection Transfer Function (RTF) of the HODM integrator based control loop for various gains, compared to theory. As a scalar gain is set on all modes RTF are averaged over all valid actuators.

Another particular feature of SAXO control scheme is the decoupling of ITTM and DM controls, as ITTM control is ensured through Linear Quadratic Gaussian control (a.k.a. Kalman filter). This control law has been chosen both for its optimal rejection of turbulence and vibrations. Decoupling between ITTM and DM was tested and proved that contribution of DM to ITTM closed-loop correction, in variance, corresponds to a ratio lower than 5e-6 [8]. ITTM control through LQG works fine ensuring vibration filtering (see [8]). Final performance is still to be assessed with automatic identification procedure of turbulence and vibration parameters.

Visible WFS has undergone its major upgrades allowing a full speed control of the system (1.2kHz) and use of the electronic gain amplification up to a gain of 100. Associated to it, a spatial filter is used to filter out high spatial frequency components and reduce aliasing. This component already proved its efficiency [4].

Finally, 95% of RTC functionalities have been validated. SPARTA platform proves to be well within specification, from all point of views, ensuring the 4 real-time AO loops (DM, ITTM, PTTM, and DTTP) control, and all the online optimizations (parameters, modal gains optimization, anti wind-up, garbage collection, first data processing and storage). In the following, we address NCPA compensation and first performance assessment in Meudon.

### 4.2 Optimization of SAXO internal performance

Optimisation of SAXO internal performance (meaning without turbulence simulator, using AO entrance focal plane) relies on NCPA estimation and compensation. To reach the specification of 4nm RMS on all pupil of residual NCPA a specific NCPA compensation iterative procedure has been designed [9]. It shall also optimize the NCPA compensation at the coronagraph level to reduce persistent speckles. During tests in Meudon, the NCPA compensation procedure has been optimized, without coronagraph. This optimization had however to account for bench limitations. First, object source proved not to be an unresolved point like source due either to some source defect or ghost. Second, in addition to central obscuration, pupil illumination proved to be non uniform. These two phenomena require particular handling in NCPA estimation and SR computation.

In the following, performance is given either in rough SR or corrected SR. Rough SR is direct computation of SR accounting only for background and pixel response but without accounting for object profile and pupil illumination non uniformity. This SR estimation is then corrected to provide refined estimation of performance.

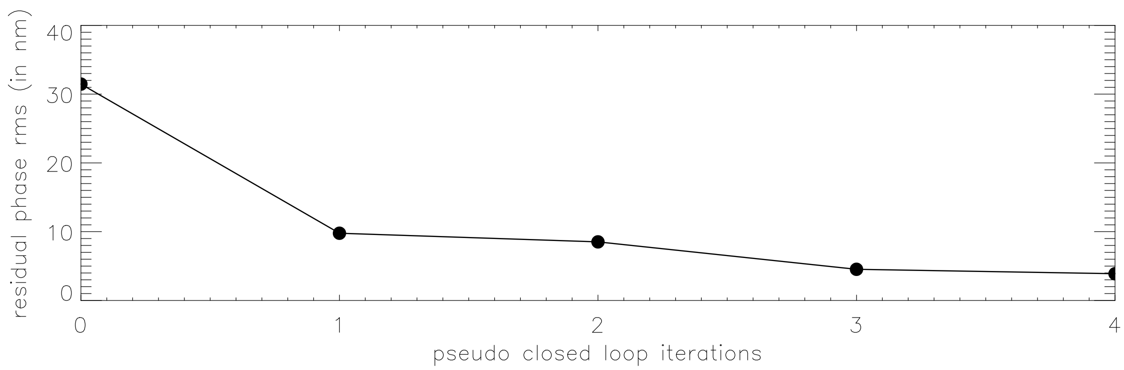



Figure 5. RMSs value (in nm) of the residual phase along NCPA compensation iterations. The very first point is the NCPA value before any compensation.

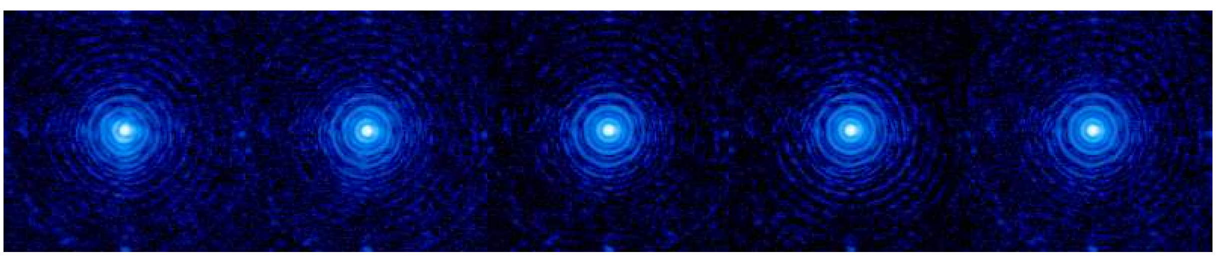
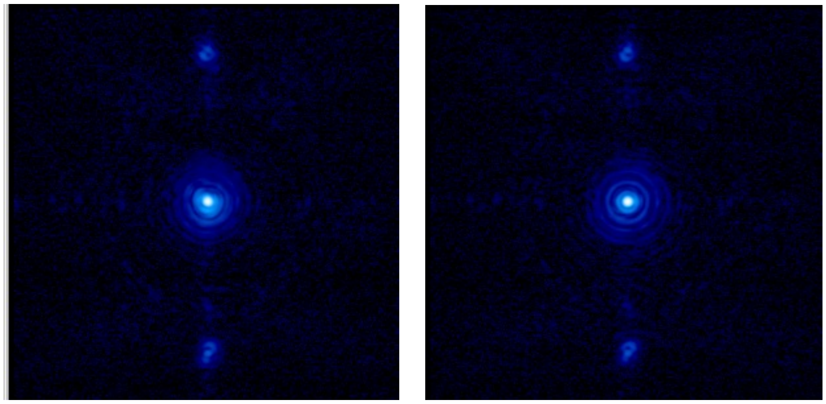


Figure 6. Experimental PSF obtained at each iteration step.

NCPA iterative procedure is extensively described in [10]. We only remind that aberrations are estimated through phase diversity and correction is applied by conversion of the estimated phase into reference slopes on visible WFS modification. The procedure is repeated iteratively to ensure convergence (pseudo-closed loop scheme). Result of the procedure is described in Figure 5 and Figure 6. A quick and efficient convergence below 4nm rms of estimated residual aberrations is obtained in 4 iterations, with a significant improvement of the PSF. This test has been performed in the visible (635nm), using a Hamamatsu CDD imaging camera. Same procedure and convergence has been obtained in IR on the DTTS used as imager. It is important to underline that corrected SR are in very good agreement with performance estimated from NCPA residual aberrations estimation (at convergence 3.8 nm rms that is 99.8% SR to be compared to 99% corrected SR). As a conclusion even if computation of SR is a tricky job and 100%confidence in SR estimation cannot be ensured, results proposed are coherent with phase estimation.



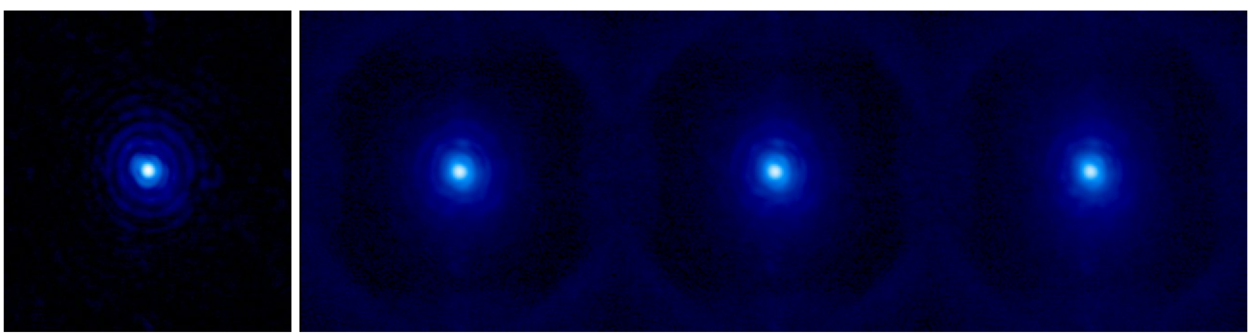
Rough SR/corrected SR 64.4 % / 78% 80.8 %/ 99%

Figure 7: Visible images at 365 nm. [left] without and [right] with NCPA compensation. Top and bottom secondary peaks are due to high frequency defects of one parabola of the bench. Use of spatial filter allows avoiding aliasing (see [4]), rough and corrected SR are given below.

A 80.8% rough SR is obtained after NCPA compensation, corresponding to 99% corrected SR. Interaction between spatial filter size and NCPA estimation and compensation procedure has also been investigated showing that NCPA correction shall be optimized for the nominal spatial filter size.

### 4.3 SAXO performance

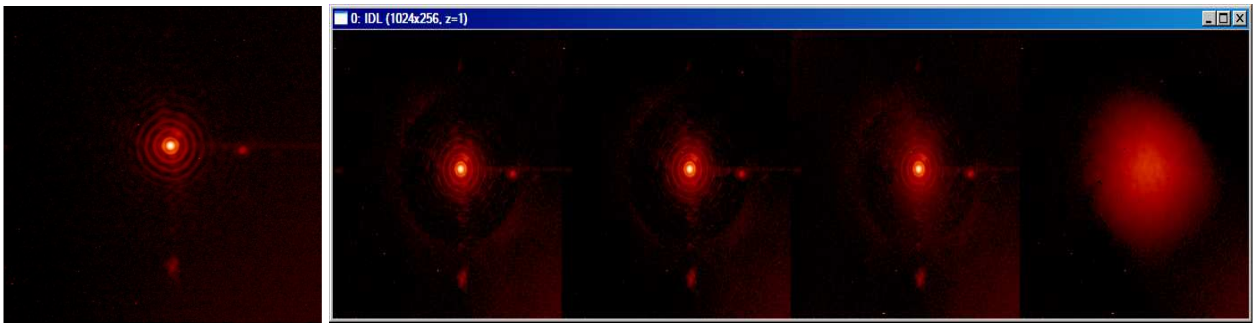
We now consider performance assessment in presence of turbulence simulator. Source is placed at entrance focal plane of the simulator. Turbulence is generated with one phase screen for a 0.87 arcsec seeing and various wind speeds.



a b c d

Rough/relative SR 67%/100% 42%/ 62% 41%/ 61% 37%/55%

Figure 8: Turbulent visible images (635 nm). a: reference PSF with NCPA compensation, closed loop on dummy phase screen, b, c, d: closed loop on 0.87 arcsec seeing turbulence, with wind speed 2, 5, 10m/s.Rough/corrected Strehl Ratio in visible are indicated.




a b c d

Rough SR/relative SR 88%/100% 84%/ 95% 84%/ 95% 83%/ 94%

Figure 9: Turbulent IR images (1.6µm). a: reference PSF with NCPA compensation, closed loop on dummy phase screen, b, c, d: closed loop on 0.87 arcsec seeing turbulence, with wind speed 2, 5, 10m/s.Rough/relative Strehl Ratio in IR are indicated. Ghosts are visible at bottom and right side.

Using the turbulence simulator and without the turbulence the rough SR drops from 80.8% down to 67%. This is due to the impact of pupil illumination non uniformity, which is far greater using the turbulence simulator, and a resolved source (bigger fiber size). As it becomes tedious to correct SR from these two problems when turbulence is injected and corrected, we compute a relative SR, defined as the ratio of measured rough SR by rough SR obtained at turbulence simulator focal plane but without turbulence. Results in term of PSF and SR are proposed in Figure 8 for visible (635 nm) and IR (1.6µm).

IR and visible performance are fully in agreement. Relative SR indicates a performance larger than 90% SR for a 10m/s wind speed and 0.87 arcsec seeing in the IR which is compliant with FDR simulations.

# 5. SAXO IN SPHERE COMMON PATH (GRENOBLE)

Following the success of SAXO ARR in Meudon observatory, the SAXO components have been dismounted and shipped to Grenoble for re-integration in SPHERE common path. All components have undergone a systematic control and functional validation. As SAXO is in the heart of the global SPHERE system, the basic strategy was first to ensure performance after re integration were at the level of those obtained at ARR. Then second goal was to allow quickly integration and testing of all components in the presence and eventually in full cooperation with AO. As a consequence the global AO loop functionalities have been validated and various components have been updated (Visible wavefront sensor and RTC software upgrades). Then a regular and user-friendly use of AO has been ensured. We first propose an overview of this re-integration and its specific issues. We then discuss first results obtained in common path with IRDIS.

## 5.1 SAXO components re-integration and upgrades

While most components have been re-integrated without major issue, re-integration of HODM was troublesome. Indeed, while a cylindrical lenslet could be used to compensate for the HODM own optical static defects (14.6µm wavefront error PV at rest) on the Meudon bench, this solution could not be applied in SPHERE system in the absence of an intermediate pupil plane. To circumvent this limitation one of the SPHERE bench toric mirror has been put under mechanical constraint to introduce astigmatism and compensate for most of the HODM own defects. Up to a 10µm wavefront error PV is generated on one toric mirror leading to a residual 5 µm wavefront error PV. It has been checked that the use of this constrained toric mirror placed out of a pupil plane generates less than 0.2% of anamorphosis (ellipticity of pupil), fully within specifications.

Previous limitations spotted during first phase of integration in Meudon have been also corrected. The spatial filter now exhibits a perfect square shape with a size and positioning accuracy lower than 5 µm, and visible WFS limitations (gain amplification mostly) have been solved allowing up to a x1000 gain.

Finally, RTC, also known as SPARTA platform, developed by ESO, has undergone its last upgrades, hence benefiting from all its high level functionalities.

Figure 10 shows the SPHERE optical bench with SAXO components integrated, when the optical bench was still on the ground for fine alignment. In particular, the HODM is visible at the front bottom. The optical bench has been then transferred to its final position on the damping system and within its enclosure, at some 2.5m high (Figure 11).

Figure 10: SPHERE optical bench, on the ground for SAXO components integration and alignment. Bottom front: HODM is visible, on the left, black box is IFS.

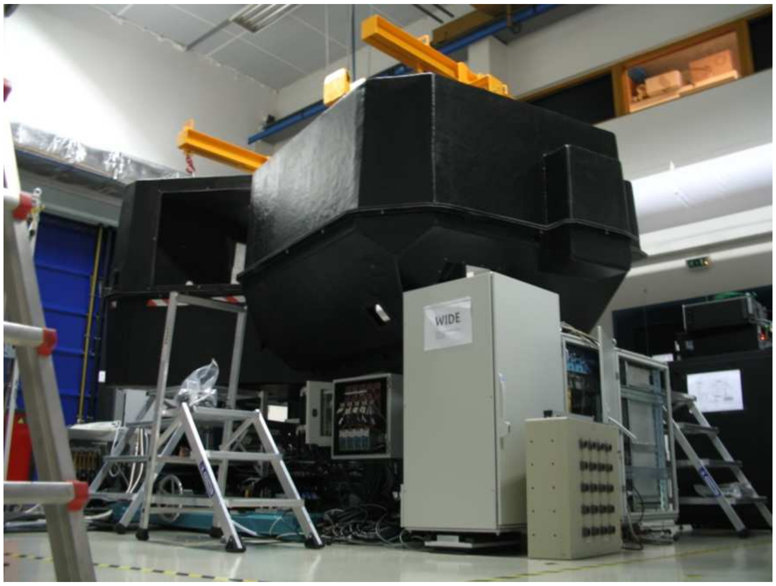



Figure 11: SPHERE system. Optical bench is mounted on its damping system and within its black enclosure.

### 5.2 First performance in common path

While AO loops are already functional, turbulence simulator is not available. Performance assessment has been focused on optimization of internal performance through NCPA compensation, down to IR dual imager IRDIS, in the prospect of optimization of performance at coronagraph level.

More details on NCPA estimation and compensation in SPHERE system can be found in [10]. We only gather here final results. It is shown that once again, object profile and pupil illumination homogeneity are critical, in addition to flat fielding of the camera. All these elements being accounted for, phase diversity allows to estimate NCPA and compensate them through the reference slopes modification in the iterative process.

We propose in Figure 12 a comparison between experimental PSF as obtained on IRDIS IR imager using SAXO closed-loop and numerical PSF as reconstructed by phase diversity. Matching is very good and allows compensating aberrations (see Figure 13).

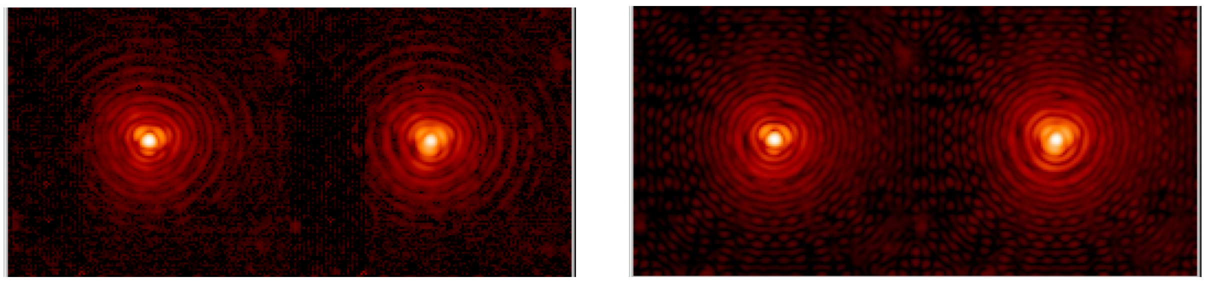


Figure 12: [left] experimental PSF focus and defocused obtained with AO loop ON, no turbulence (internal performance estimation) on IRDIS imager. Defocus value is 0.75 radians RMS. No NCPA are compensated here. [right] Numerical images (focused and defocused), reconstructed from Phase Diversity aberrations and object measurements. A good matching with experimental data is visible.

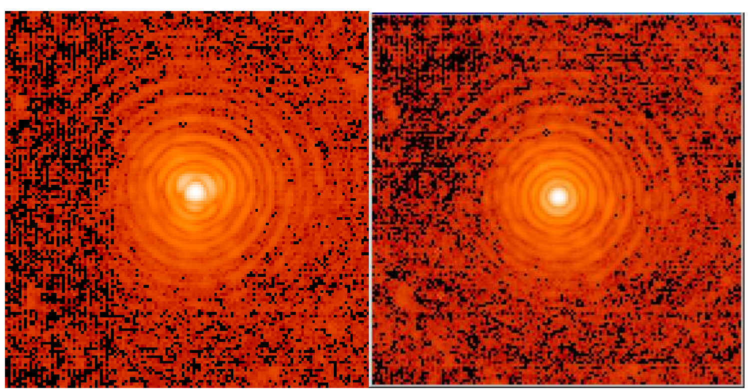


Figure 13: Focal plane PSF. Without NCPA compensation, and after 2 iteration NCPA compensation. Image is thresholded and saturated to enlighten the PSF quality.

The NCPA procedure that aims at estimating and compensating for the NCPA in the SPHERE system has thus been validated. Improvement of PSF quality are spectacular, corrected Strehl Ratio increases from 90 to more than 99.6% at 1.589µm, thus demonstrating the NCPA compensation scheme. Residual aberrations estimated are less than 15nm RMS, which is 99.6% Strehl ratio, and fully compatible with Strehl Ratio estimated in the images. There is still room for performance improvement as the current images suffers from limited signal to noise ratio, which shall be improved by dithering. Moreover, additional defects such as flat field, glitches in images etc can be taken into account to improve NCPA estimation.

## 6. CONCLUSION

While SAXO AIT are still on going within the SPHERE system, tests performed so far have proved that all components were within specifications, except high order DM for which workarounds have been found and validated. The system is now fully operational, with 95% of its functionalities available and validated. First performance assessment has been performed, showing that NCPA compensation down to 4 nm rms of residual aberrations can be reached. Spatial filter is operational and provide efficient aliasing reduction. Main control laws have been validated. First correction of turbulence, compliant with FDR, has been shown, with SR up to 90% in IR with 0.87 arcsec seeing and 10 m/s wind speed. Still, performance needs to be assessed further, in particular within SPHERE system and in interaction with instruments, and fine optimization shall be performed. This last phase of AIT is currently on going.

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