Integration, tests and laboratory performance of SAXO, the VLT-SPHERE extreme AO system.

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Abstract. Direct detection and spectral characterization of extra-solar planets is one of the most exciting but also one of the most 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 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 a status of SAXO assembly integration and testing. The main AO system characteristics are recalled, then each sub system is individually presented and characterized. In the end, SAXO shall meet its challenging requirements (more than 90% of SR in H band with a residual jitter lower than 3 milli-arcseconds for average observation conditions on the VLT). Assessment of the performance shall be performed in a near future, but we propose first results of the AO system in its current status.

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 AO system (XAO). Still, the very high expectations of SPHERE not

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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, integration of SAXO has been defined as a two step process. During a first step (current one), the AO main components (active mirrors, Vis-WFS, IR-WFS, RTC, spatial filter) are integrated and tested in a dedicated AO bench, located in Observatoire de Meudon. This bench allows a functional validation of each component and more globally of the AO functionalities, though it is not designed to assess the final performance of the AO. In a second step, the AO components will be removed from this bench and shipped to Grenoble to be integrated in the final system (Common Path Infrastructure). AO will be then tested for final performance assessment and used to provide SPHERE instruments with incomparable coronagraphic images. This article proposes a status of SAXO integration in Meudon. After a short summary of SAXO requirements and design (Sect. 2), we propose an overview of the AIT of SAXO (Sect. 3). We propose a status of its main components (Sect. 4) and a description of the first validations and performance results.

2. SAXO requirements and design

SAXO high level requirements are described in [3]. 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, 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
- SR (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 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.

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

- Main AO loop (1.2 kHz): correct for atmospheric, telescope and common path defects.
- The DTT loop for fine centring on coronagraph mask (correction of differential tip-tilt between VIS and IR channel).

- The PTT loop for pupil shift correction (telescope and instrument).
- NCPA pre-compensation which will lead to the reduction of persistent speckle

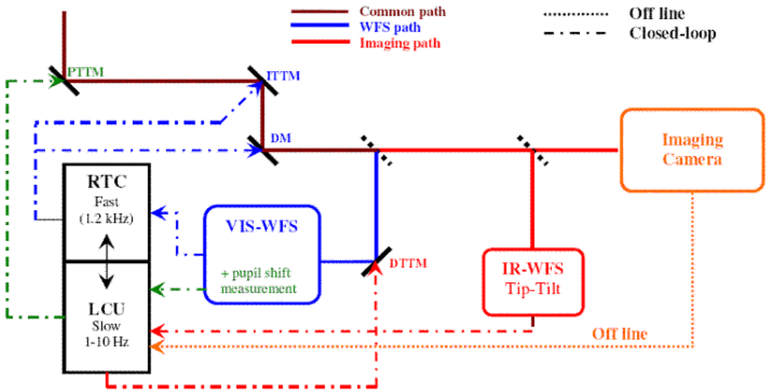

Fig. 1. overview of SAXO functional and control diagram

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) [4]]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 tip-tilt 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.

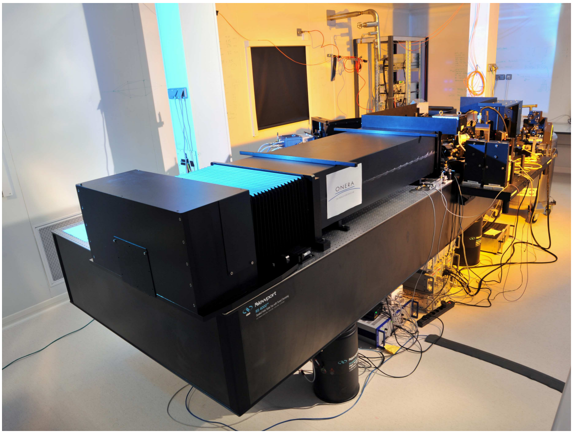

Fig. 2. picture of SAXO test bench in Meudon clean room

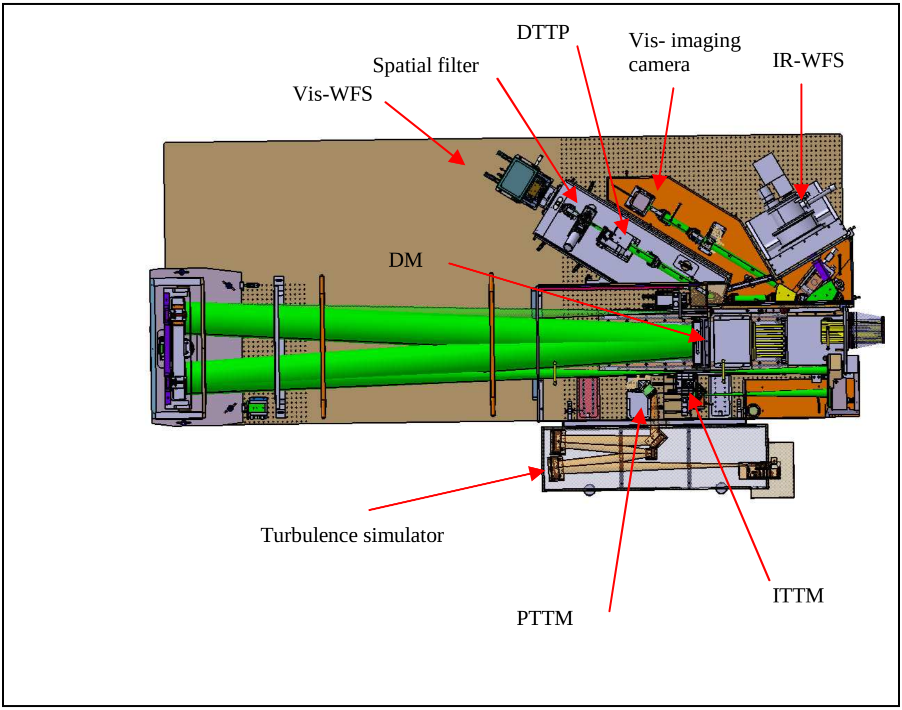

Fig. 3. overview of SAXO test bench in Meudon, with the SAXO components.

3. Bench global status

SAXO components as described in previous section are currently installed in Meudon Observatory, Paris, in clean room, in a fully dedicated AO bench as can be seen in Fig. 2. This bench has been taylor-made for SAXO components that will 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 Fig. 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’’.

Table 1 summarizes SAXO main components status. Details of status and tests of each component are described in next section.

Table 1. Summary of SAXO component status, with their supplier.

Component	Component Status + functionality status
High Order Deformable Mirror (CILAS) 41x41 piezo stack DM	Model #1, limitations: flatness, 4 dead actuators, and high frequency behavior
Image Tip Tilt Mirror, high speed tip-tilt (LESIA)	OK, functional up to 125Hz because of Vis-WFS
Differential Tip Tilt Plate, to correct the tip-tilt between wavefront sensor (WFS) beam and NIR beam (LESIA)	OK, differential TT loop OK at nominal speed (between 1 and 10 Hz)
Pupil Tip Tilt Mirror, to keep the pupil location stable in SPHERE (PI)	OK, pupil loop OK at nominal speed
40x40 Shack-Hartmann WFS (ESO)	Prototype, limited to 125 Hz
Spatial filter (variable square pinhole) (IPAG)	OK, spatial filtering functionality OK
NIR Differential Tip-Tilt Sensor (ESO)	OK, differential TT loop OK
Real Time Controller : SPARTA platform, (ESO).	Software version 5, all loops OK to max. speed, control laws OK, some high level functionalities

4. SAXO detailed status

We now focus on the status of the main components of SAXO. A particular feature of SAXO in its current implementation is the use of a prototype camera in place of the final Vis-WFS. This prototype, based on an OCAM camera, is however not compliant with the current RTC plateform (SPARTA) leading to a reduced sampling frequency of 125Hz compared to the nominal 1200Hz. This is of course temporary.

4.1. High Order Deformable Mirror

The DM has been extensively characterized in terms of spatial properties. It proves to be far beyond specifications, with a very high static deformation of 7.3µm surface error PV, dominated by astigmatism and defocus (Fig. 4). Due to the fast evolution of aberrations at DM edges, correction of DM own aberrations leads to the use of the full dynamic of the DM. Origin of this flaw is still under investigation, but this clearly affects the performance. Correction of DM aberrations (astigmatism and defocus) using a cylindrical lens located in a pupil plane on the bench has been considered. The residual aberrations after compensation is lower than 2 µm surface error PV, allowing a nominal use of DM. Correction of DM own defects on final SPHERE bench is under investigation. Dynamic validation shall be performed at full speed (1.2 kHz).

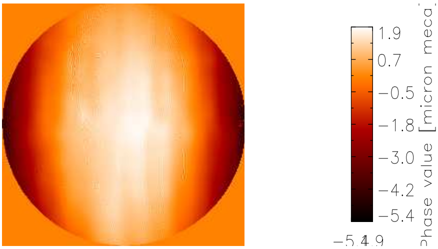

Fig. 4. flat shape of HODM at rest, values in µm surface error

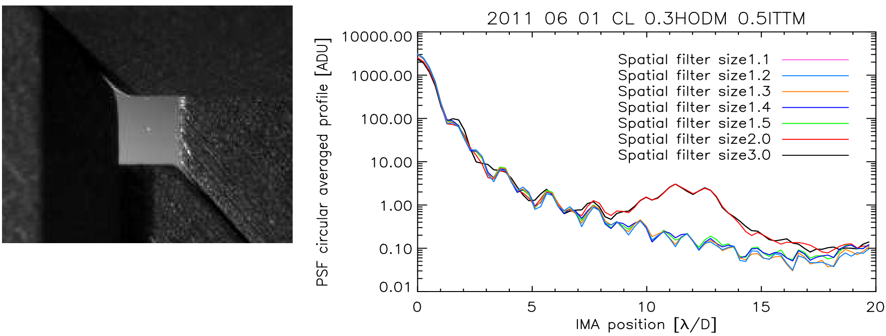

Fig. 5. The spatial filter of the AO system. [Left] picture of spatial filter and guide star in the middle. [Right] shows how the spatial filter cut's off the aliases created by higher frequency components (size of spatial filter in λ/d).

4.2. Spatial filter

A spatial filter is used to reduce aliasing and increase AO performance. The use of the spatial filter has been verified in an unexpected way: one of the AO test bench optics is diamond turned and produces multiple images of the guide star by diffraction. When the spatial filter is opened too much, these images create aliases on the Shack-Hartmann sensor and degrade the image quality. See Fig. 5. Reduction of the filter size leads to complete suppression of these aliased components and image quality improvement.

4.3. Non Common Path Aberration measurement and correction

The correction of the non-common path aberrations (NCPA) has also been demonstrated. The NCPA are one of the main limitations of any AO system. The method implemented to compensate for these NCPA is to measure them in the imaging focal plane (here the IR DTTS) and to modify the reference slopes of the AO system to perform the compensation [5]. **Fig. 6** shows the result of the pre-compensation method implemented at SAXO-MEUDON, which is fully compliant with the expected performance. A Strehl Ratio (SR) higher than 97% at 1.6µm has been obtained (internal SR, no turbulence). This procedure has also been validated in the coronagraphic focal plane.

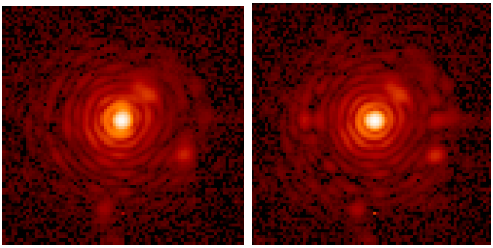

Fig. 6. Closed loop PSF on DTTS IR sensor. The source is at bench entrance. No turbulence but the local one. [Left] before NCPA compensation. [Right] after NCPA compensation. 220 Zernike modes have been compensated. The compensation effect is clearly visible up to the 5th Airy rings. Three ghosts are clearly visible, due to parasite reflections.

4.4. Control laws

The various control loops have all been tested functionally and all loops have been closed at nominal speed except the main AO loop (DM and ITTM) due to VIS-WFS limitation at 125Hz. All loops prove to be compliant with specifications, with a 2 frame delay for the main loop, and slightly over 1 frame for the others. DM is controlled through optimized modal gain integrator. ITTM is controlled through LQG control (a.k.a Kalman filter) to correct for both turbulence and vibrations [6]. While in the future this control law and its matrices will be automatically computed and updated through fine analysis of input turbulence and vibrations, it is so far constructed based on off-line codes. The gain brought by this control solution and filtering of vibrations has been validated by introduction of turbulence with a 0.62'' seeing, and additional vibration directly injected onto the ITTM as additional disturbance (unknown by the control law). A 40 Hz vibration is used. Turbulent TT is 62 mas rms, while total input TT is 72 mas rms with vibration. Use of LQG leads to a residual TT of 0.87 mas rms, while a simple integrator provides a residual of 12.8 mas rms due to vibration amplification (see Fig. 7). With no vibration, integrator performance is 0.91 mas rms, LQG is 0.45 mas rms. These results prove the ability of LQG to handle both vibrations and turbulence. Automatic procedure for update of the control law shall be validated in the future.

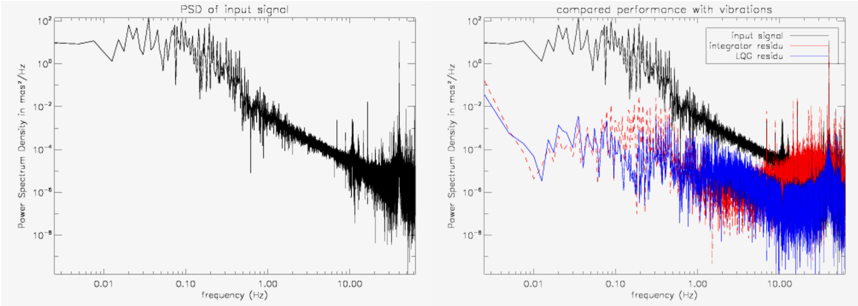

Fig. 7. [left] temporal power spectrum density (PSD) of input Tilt with 40 Hz vibration, [right] PSD of residual after integrator (red) or LQG correction (blue). Clear dampening of vibration is visible with LQG.

5. Conclusion

We have proposed a short overview of SAXO AIT status. AIT of such a high order performance system is a challenge in itself. We have now a functional system but reaching the desired performance and interoperability with subsystems still represents a considerable amount of work, before integration in SPHERE system planned early 2012, for first light in Paranal end of 2012.

6. References

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