An analytical approach to model the second-stage Adaptive Optics correction for SPHERE

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ABSTRACT

SAXO+ is the name of the proposed second-stage adaptive optics module to increase the performance of the SPHERE[1] instrument at the Very Large Telescope (Chile). This upgrade aims at improving the raw contrast (up to 10^{-5}, goal 10^{-6}) close to the optical axis (at a separation of 0.2 arcseconds, with a goal of 0.1), enabling the observation of fainter and redder targets. SAXO+ will be implemented on a mezzanine above the main bench and it will be fed by an exchange mechanism deploying a pick-off mirror in order to preserve all the functionalities of the original instrument. The wavefront sensing will be based on pyramid wavefront sensor in the near-infrared. In order to define the main requirements for the second-stage module design, a few trade-offs need to be carried out. We present in this paper an analytical approach, based on spatial PSD analysis, to study some error terms affecting the SAXO+ system and to directly compute the AO residual phase screens. For this purpose, a second-stage correction filter in the spatial frequency domain has been implemented in PAOLA, a software tool for the analytical modeling of Adaptive Optics systems.

Keywords: Extreme adaptive optics, SPHERE, VLT, PSD, Simulations

1. INTRODUCTION

In order to improve the raw contrast close to the optical axis of the SPHERE instrument, a second stage qdaptive optics (AO) correction system has been recently proposed[2]. The additional loop will work at an higher frequency with respect to the main SAXO loop (up to 3 kHz, to be confirmed [7, 10]) in order to reduce the temporal error contribution and will be based on pyramid wavefront sensing in the near-infrared, in order to also minimise the wavefront sensor measurement error term, estimating that these two terms are the main contributors to the SAXO loop wavefront residual affecting the contrast close to the optical axis. The PSD-based system analysis is based on the construction of an analytical model for the long exposure AO-corrected phase spatial power spectrum density (s-PSD). AO correction is seen as a spatial filter applied on the turbulent phase s-PSD. This approach assumes that the PSDs of the different error terms directly sum. This kind of analysis permits to produce an error budget and to study different error components separately. It permits also to estimate performance in a broad parameter space avoiding a huge number of numerical simulation, much more demanding in terms of computation. On the other hand, this approach is based on simple assumptions that could be not valid in some case, in particular when the expected performance are low. Complementary numerical simulations are indeed necessary to confirm and complete the system analysis. A nice and reliable tool widely diffused for s-PSD AO system analysis is the PAOLA software[5]. However, this software does not include in its configuration neither the P pyramid wavefront sensor model, nor the possibility to add different correction loop in sequence. We present in this paper the main modifications we have implemented in the PAOLA code in order to be used to study the SAXO+ system. We also show some example of validation case study computed with both end-to-end simulation with the COMPASS software[4] and s-PSD analysis with the modified PAOLA code, hereafter referred to as 'PAOLA+'.

2. PSD-BASED SYSTEM ANALYSIS

In this section we present the PAOLA tool and we describe the assumptions and the functionalities we have implemented in order to use it for the SAXO+ system.

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2.1 The PAOLA tool

PAOLA is a set of functions and procedures written in the IDL language for modeling the performances of an astronomical adaptive optics (AO) system. The starting point version we adopted is the 7.6.3. The error terms are described as spatial filters applied on the turbulent phase PSD. The main error terms computed in PAOLA are listed below:

- Fitting error or high order wavefront error: this term is related to the maximum spatial frequency that the wavefront sensor can measure and/or the deformable mirror (DM) can correct;
- Wavefront sensor aliasing: this term is related to the uncorrected high spatial frequency phase seen by the wavefront sensor as a low spatial frequency;
- Servo lag: this term is related to the temporal fluctuation of the phase occurring during the wavefront sensor integration time and the AO cycle delay (camera readout, commands computation, commands application etc. . .);
- Wavefront sensor noise: this term is related to the wavefront measurement error by the wavefront sensor due to readout noise and photon noise.

Another important source of error that is not listed above is due to anisoplanatism that occurs when the position of the guide star(s) for the phase measurement does not coincide with the position of the science object. This is not applicable in the case of SAXO, where the guide star coincides with the science object. The PAOLA software implements the wavefront error noise model and the Aliasing error of the Shack-Hartmann wavefront sensor. On the other hand it implements a few DM spatial transfer function models, based on laboratory measurements of real DM influence functions.

2.2 Added functionalities

Figure 1 shows a conceptual scheme of the PAOLA+ functioning with two correction stages. The first stage (grey rectangle) corrects for the incoming turbulent phase, producing a residual phase that enters a faster second stage. The residual phase at the output of this second stage is used to compute the output s-PSDs and PSF. Since the SAXO+ stage is faster than the first one, the temporal error is computed considering the second stage turbulence sampling and the contribution of the residual of the first stage temporal error[3].

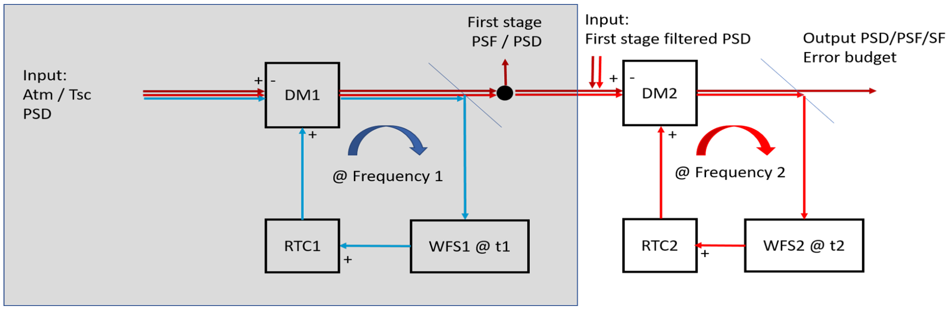

Figure 1. SAXO and SAXO+ interaction conceptual scheme

In order to properly simulate the double correction SAXO/SAXO+ system, a few functionalities have been added.

- Pyramid Wavefront sensor model: starting from the pyramid wavefront sensor model of the propagated phase error power spectrum in one dimension illustrated in the paper of Verinaud 2004[9], equation n.22, we have generalised it in 2 dimensions following the implementation of the Shack-Harmann wavefront sensor noise s-PSD in PAOLA (equation n.58 in [5]).

$$\sigma_{\varphi}^{2}=\left|\Xi_{PY}\left(\boldsymbol{f}\right)\operatorname{sinc}(df_{x})\operatorname{sinc}(df_{y})\right|^{-2}\sigma_{n}^{2}\,, \tag{1}$$

where σ_{φ}^{2} is the 2D s-PSD of the propagated phase error due to wavefront sensor measurement noise, Ξ_{PY} is the 2D generalisation of the sensitivity function defined in [9], equation n.15 and σ_{n}^{2} is the pyramid wavefront sensor noise measurement error. For the pyramid measurement error we have adopted the formulas in [6].

- Aliasing error: the high order wavefront error is seen by the wavefront sensor as a low spatial frequency error and reconstructed as such, therefore the AO system is compensating an error which actually is non-existant. PAOLA computes the aliasing error of the Shack-Hartmann wavefront sensor, but to properly simulate the SAXO system, an aliasing s-PSD that takes into account for the spatial filter has been included. The aliasing error of the pyramid wavefront sensor has been considered negligible.

3. VALIDATION AND PRELIMINARY RESULTS

In this paper we present the results obtained by simulating the SAXO/SAXO+ system with PAOLA+ in two key science cases for the SAXO+ application. The first case, named as 'Bright 1 case', is characterised by a bright guide star of spectral type AF, G magnitude 5.5 and H magnitude 5.1. The gain in contrast in this case is mainly due to a reduction of the temporal error thanks to the second stage higher correction frequency. The second case, named as 'red 1 case', is characterised by a redder and fainter star, spectral type earlyM, 11.9 magnitude G, 7.9 magnitude H. In this case, the gain in contrast is also due to the higher sensitivity of the pyramid wavefront sensor in the near infrared. The first stage correction due to the SAXO system has been simulated using the classical PAOLA software with a custom DM spatial transfer function built starting from the first stage 41×41 high order DM (HODM) influence functions. The first stage wavefront sensor is a 40×40 Shack-Harmann wavefront sensor coupled with a focal plane spatial filter to reduce aliasing. The temporal frequencies characterising the first stage are consistent with the SAXO science templates currently implemented in the SPHERE instrument control software (1380, 600 or 300 Hz, depending on the guide star magnitude). The second stage frequencies used in this paper are optimised.

For the SAXO+ second stage AO correction loop, three different DM pitch sizes have been considered, allowing a 21×21, 25×25 (baseline) and 31×32 sampling of the telescope pupil. The pyramid wavefront sensor samples the pupil image with 50×50 pixels in a wavelength interval of 0.95-1.2 μm[8]. In all the considered simulations, we have used the ESO 35 layers CN^2 profile with a coherence time of 3 ms and a seeing of 0.5". The comparison between end-to-end simulations and s-PSD analysis of the Bright 1 case is shown in Figure 2. The used merit function is the average contrast for the end-to-end simulation computation and the PSD for the PAOLA+ simulation, considering that the PSD, properly normalised, nicely approximate the PSF intensity profile after the application of a perfect chronograph. The values of the Strehl Ratio (SR) are also reported. The considered frequencies of the first and second correction stage in the Bright 1 case are respectively 1380 and 2760 Hz. Figure 3 shows the three DM cases in the Red 1 case. The obtained SR are respectively 0.5 for the SAXO loop and 0.82/0.83/0.85 respectively for the SAXO+ loop considering the three different DM samplings. The gain in contrast going from the single stage correction to the double stage combination is not negligible (factor ≈ 4 at 300 mas).

4. CONCLUSIONS

We have shown in this paper an analytic approach to evaluate the performance of the SAXO+, a second stage correction system for the SPHERE instrument that will increase the raw contrast close to the optical axis. The PAOLA code has been adapted to our case by implementing new functionalities. We validated the analytical tool based on PAOLA with end-to-end simulation through the analysis of one bright case. Through the preliminary analysis of two emblematic science cases, we confirm the gain on raw contrast thanks to the implementation of SAXO+. Further analysis and system trade-offs need to be carried out in the next future.

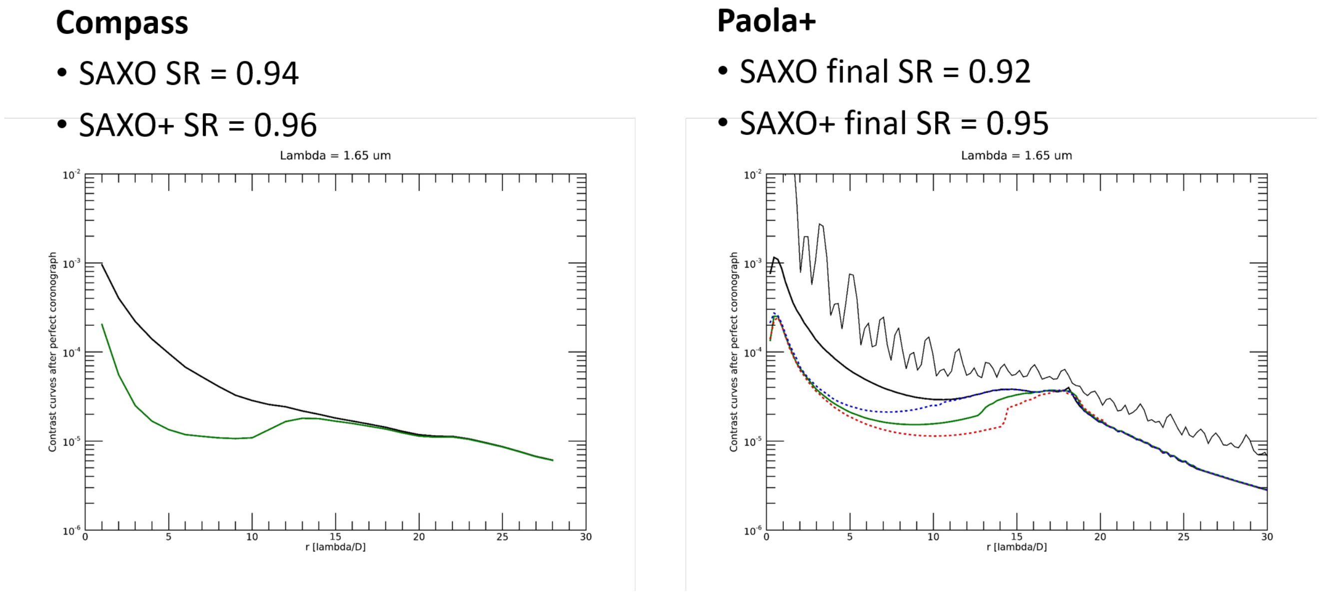

Figure 2. Bright 1 cases: Compass vs PAOLA+ performance estimation. Left panel: Simulated contrast curves for SAXO (black curve) and adding the SAXO+ second stage correction (green curve). In this simulation, the deformable mirror (DM) for the second stage correction has 28 actuators across the diameter (baseline TBC). Right panel: Theoretical average contrast curves computed by PAOLA+ for SAXO (black curve) and adding the SAXO+ second stage correction (green curve). The result in case of 22 (dotted blue) and 32 (dotted red) useful actuators across the diameters are also presented. The final choice of the DM will depends on the results of trade-off studies.

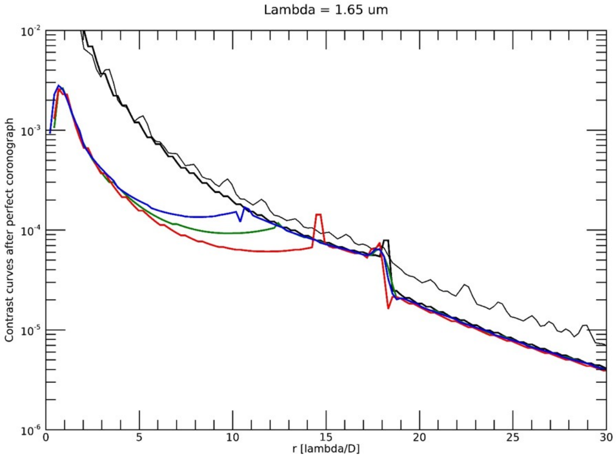

Figure 3. Red 1 cases performance estimation with PAOLA+

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