Optimizing Wavefront Sensing for eXtreme AO

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ABSTRACT

Extreme adaptive optics (XAO) systems are highly specialized systems to achieve very high Strehl numbers on comparatively small fields of view, e.g. for high-contrast applications like planet finding. We present a study of an XAO system using a pyramid wavefront sensor on telescopes of 8 m aperture diameter and above. We used standard (CAOS) and custom numerical simulation tools to examine the influence of the number of basis functions in a modal correction model, the control loop frequency of the XAO system, and atmospheric conditions.

Keywords: AO: extreme AO, wavefront sensing, control loop; Exo-Planets: search, direct imaging

1. INTRODUCTION

Extreme AO (XAO) systems are designed to reach very high Strehl ratios and therefore a high contrast, with the aim to detect and obtain images of faint objects (brown dwarfs or planets) close to relatively bright stars. In 2002, a preliminary proposal was made to ESO in response to a call for a second generation VLT instrument called "Planet Finder". The instrument was to be optimized to image faint companions next to bright stars, "ideally down to planets".[1] The instrument described by this proposal became the CHEOPS project – **CH**aracterization of **E**xo-planets by **O**pto-infrared **P**olarimetry and **S**pectroscopy.

The basic idea was to combine an eXtreme AO system (XAO) with two differential imagers. One – called ZIMPOL[2] – will be using the polarization of the exo-planet's reflected light in I-band to detect the planetary signal against the bright central star's halo. The other one will be a low-resolution integral-field spectrograph (IFS)[3] working in the very near infrared (J and H-band). It will discriminate between stellar and planetary light by using the methane bands of the exo-planetary atmosphere.

The XAO system will comprise a deformable mirror (DM) of very high order ($\sim$ 1600 actuators) and run at high loop frequencies ($\sim$ 2 kHz). It will make use of a pyramid wavefront sensor placing 40 gradient sensing elements across the VLT's 8 m aperture. It also has one special element that combines a Lyot-type coronograph[4] with the beam-splitter between the AO's wavefront sensor (WFS) and the science beam. A fully reflective mirror in the focal plane with a pin-hole in the centre will transmit most of the light of the bright central star to the WFS while sending the field containing the faint companions to the science cameras. This principle has many advantages: In closed-loop, operating at the envisioned Strehl numbers of $\sim$0.7 at 800 nm, basically all of the central star's photons are sent to the WFS, while ZIMPOL – working at the same wavelength as the WFS – still receives all photons from the field. To a more limited extent, the same is true for the IFS. At the same time, a Lyot-type coronograph is introduced into the system "for free".

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Our study how the performance of the coronograph influences the performance of the WFS is described elsewhere in these proceedings,[5] in this contribution we analyse if and how the Strehl ratio necessary for the operation can be achieved. We present the results of numerical simulations to examine the influence of various parameters.

2. SIMULATIONS

2.1. Model of the Atmosphere

The screens representing the phase of the incoming wave fronts that were used throughout the simulations for this work were created with a simplified version of the TurbuLenZ code[6]. The simplifications consist mostly in a skipping of the propagation between atmospheric layers, i.e. a single-layer model is created. This way no scintillation effects and no anisoplanacy could be simulated, but these are of no concern here. The basic parameters of the atmospheres used for the simulations presented in this work are shown in Tab. 1. The parameters quoted are valid for the simulation wavelength of $0.5\,\mu$m, for WFS operation simulations at $0.8\,\mu$m, the screens were scaled accordingly.

λ	$0.5\,\mu$m	$0.5\,\mu$m	$0.5\,\mu$m
Seeing	0.6”	0.85”	1.0”
r_0	0.17 m	0.12 m	0.10 m
τ_0	3 ms	3 ms	3 ms
L_0^a	25 m	25 m	25 m
v_{wind}	18 m/s	12 m/s	11 m/s
ν^b	4 kHz	4 kHz	4 kHz

[a] Outer scale
[b] Frame simulation frequency

Table 1. Atmosphere Parameters

2.2. Model of the Telescope and AO System

We used the CAOS software system[7] (Version 4.0) with some custom modifications. This software allows to create a simulation by arranging various modules in a graphical application builder. Most of the modules represent the parts and subsystems of the AO system, others provide the input necessary for the simulation, or display and save the results.

- The guide star has a magnitude of $\mathrm{V} = 10^{\mathrm{mag}}$. However, since our simulated wavefront sensor is noise-free, the brightness of the guide star does not influence the results.
- The telescope module simulates the VLT as seen from the Nasmyth focus, with a diameter of 8 m and a central obscuration of 13 % of the diameter.
- We simulate an ideal deformable mirror with the same resolution as our simulated atmospheric wavefronts (400 samples/actuators across the pupil) and unlimited stroke.
- The pyramid WFS has 40x40 subapertures and a fixed pyramid (no modulation). The detector has no read-out-, photon-, or any other noise source.
- To compute the slope from the differences of the four pupil images, we divide by the intensity in the same sub-aperture, not by the total intensity.
- The reconstruction uses a modal correction model with a basis of Karhunen-Loeve functions. This was one of our modifications to the CAOS code.
- The corrected wavefronts are recorded and analyzed to compute the RMS of the phase and the Strehl ratio at a wavelength of 800 nm.

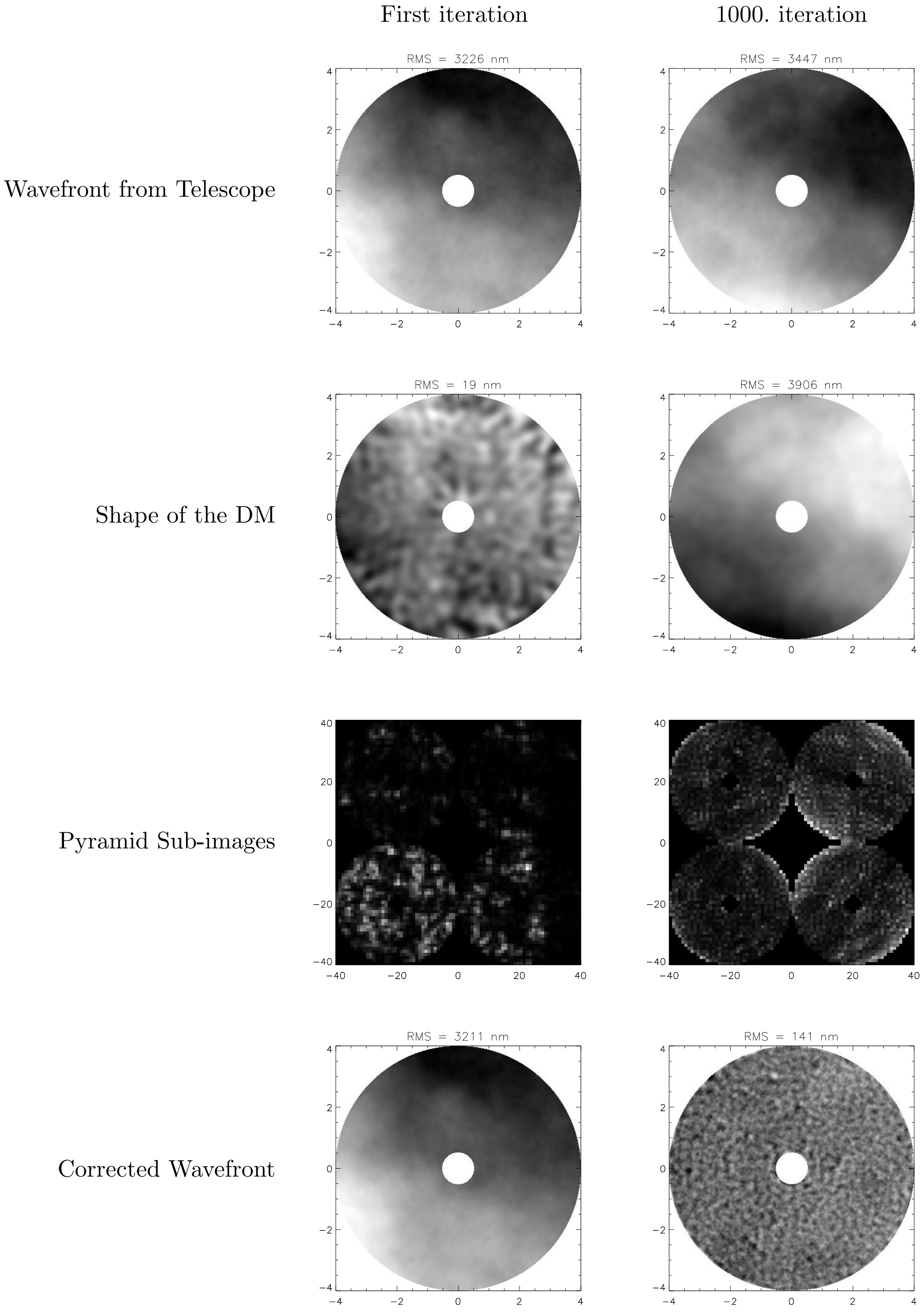

Figure 1. The wavefront coming from the telescope into the AO system, the shape of the deformable mirror, the four sub-images produced by the pyramid, and the corrected wavefront, all at the beginning of the simulation and after 1000 iterations (0.25 seconds in real time). The RMS numbers above the plots give the root mean square of the wavefronts and mirror shape.

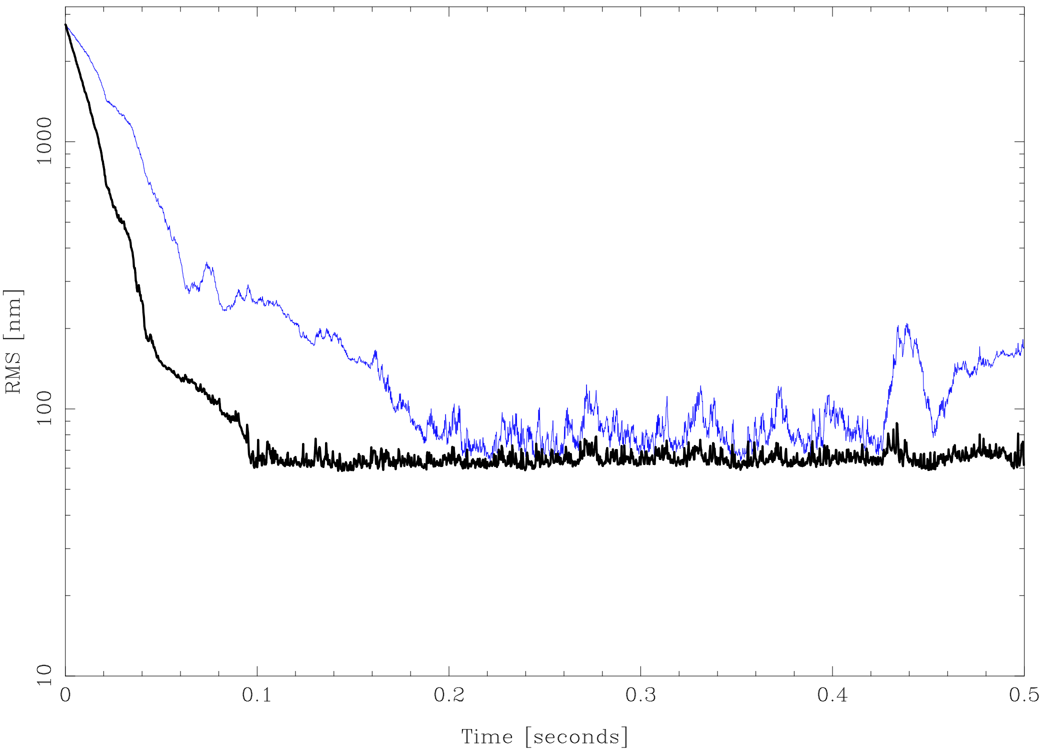

Figure 2. The RMS of the corrected wavefront in the course of two simulation with 0.6″ seeing and 860 modes corrected. The thin blue line shows the simulation with a control loop frequency of 2 kHz, the thick black line the one with 4 kHz. With a higher frequency, the final correction level is reached sooner, and the correction is more stable.

The images in figure 1 show the wavefront before and after correction, the shape of the deformable mirror, and the four sub-images produced by the pyramid, at the beginning of the simulation and after 1000 iterations (0.25 seconds in real time). In this simulation, we used the atmosphere model with 0.6″ seeing, a loop-frequency of 4 kHz, and no delay (i.e. the reconstructed wavefront is applied to the DM immediately after the end of the integration of the WFS).

The thick line in figure 2 shows the RMS of the corrected wavefront as function of time in the same simulation. It takes about 0.1 sec after the AO loop is closed to reach the level of correction that is then kept for the rest of the simulation. This is because the pyramid WFS is saturated in the beginning, mostly by the tilt of the wavefront. Therefore the correction applied to the DM is too small, but it is large enough to “pull” the wavefront in the right direction. After about 400 iterations, the wavefront is flat enough for the WFS to produce an unsaturated signal, so the real closed-loop operation starts, where the wavefront distortions are fully measured in each step (within the limits of the finite sampling of the pupil and the modal correction approach).

The thin line in figure 2 shows the RMS of the corrected wavefront for a simulation with the same parameters as above, expect for the control loop frequency, which is 2 kHz. With this lower loop frequency, it takes longer to “pull” the WFS out of saturation, and it takes longer to adapt for changes in the atmosphere, which results in a less stable correction and thus a somewhat higher RMS.

3. RESULTS

3.1. Number of Modes

CHEOPS will use modal control in its XAO system to reconstruct the wavefront from the WFS signal. The line labeled “fitting error” in figure 3 show the strehl ratios that can be achieved under good atmospheric conditions

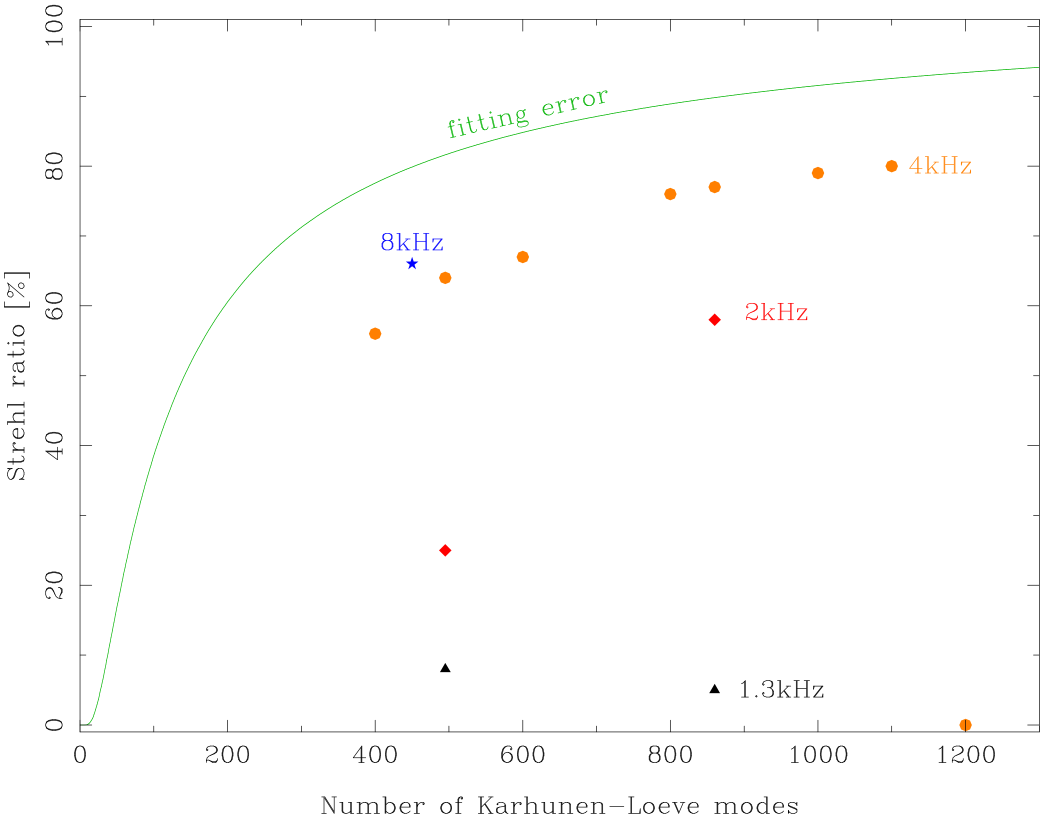

Figure 3. Strehl ratios reached under good atmospheric conditions as a function of the number of modes and for different AO-loop frequencies. The line marked "fitting error" shows the Strehl ratio reached if a certain number of modes is completely removed from the wavefront. The points show the results of numerical simulations that take temporal fitting errors into account, they are labeled with the control loop frequency used. The 8 kHz point is the result of a simulation with our custom software described in.[5]

(0.6″ seeing) as a function of the number of Karhunen-Loeve basis functions that are fully corrected by the AO system.

3.2. AO control loop frequency

An additional degradation of the Strehl ratio is caused by the temporal delay due to the non-zero integration time of the WFS. This effect has been simulated numerically with our custom software package described in,[5] and the CAOS system described in section 2.2. The results are shown by the dots in figure 3. So far, we could reach the Strehl ratio of 70 % envisioned for CHEOPS only with a loop frequency of 4 kHz and at 800 Karhunen-Loeve modes. With a more realistic loop frequency of 2 kHz, we achieved only about 60 % Strehl. Adding a delay between the WFS measurement and the application of the corrections to the DM – which is of course unavoidable in a real system – would lower the Strehl further.

Note that the attempt to correct 1200 modes results in an unstable system that provides no noticeable correction at all. This indicates that our WFS can sense at least 1100, but less than 1200 modes.

3.3. Atmospheric conditions

Figure 4 shows simulations with a fixed number of 860 modes, but different loop frequencies (since the simulations do not take into account delays between the end of the measurement of the wavefront and its correction, the loop frequency is the inverse of the detector integration time). Again, under good atmospheric conditions with 0.6″ seeing, a loop frequency of 4 kHz is needed to achieve a Strehl ratio of more than 70 %. Under less favorable atmospheric conditions, even a loop frequency this high is not fast enough.

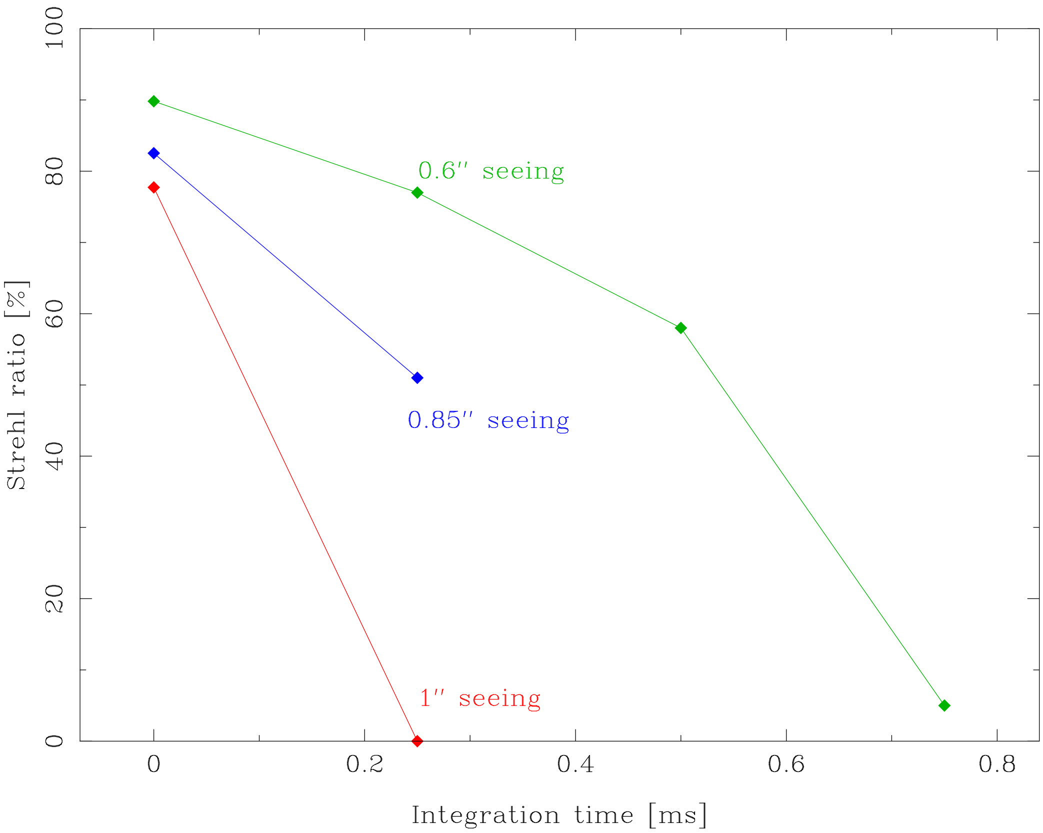

Figure 4. Strehl ratios under three different atmospheric conditions as function of detector integration time, i.e. in our case the inverse of the loop frequency. Integration time 0 corresponds to the fitting error described in figure 3.

4. OUTLOOK

A number of points have to be improved in our simulations to make them more realistic:

- The read-out noise of the detector in the WFS has to be taken into account, as well as photon noise. Then we can study how the brightness of the guide star influences the performance, and give estimates for the limiting magnitude of the system.
- The DM should be modeled with a realistic number of actuators. The shape of the DM has to be interpolated to the full resolution of the atmospheric phase screens, in a way that matches the behavior of a real DM. Additionally, effects like crosstalk between actuators should be simulated. On the other hand, the limited stroke of a real DM is not so much an issue for the simulation, but for the final design of the real system. This will have to provide enough stroke to correct the atmospheric distortions, for example by combining two DMs: one with a relatively small number of actuators and high stroke that corrects only low-order modes, plus one with a large number of actuators and more limited stroke, which will still be enough to correct the remaining high-order modes.
- The delay caused by the computations necessary to reconstruct the wavefront have to be taken into account.
- Finally, the influence of the spatial filter introduced by the Lyot stop mentioned in section 1 should be studied.

The most important task is to work on the algorithm used to reconstruct the wavefront. We think we can compensate for the errors introduced by additional delays in the control loop, but further simulations will show if we can improve the Strehl ratio with loop frequencies of 2 kHz or less.

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