

SIMULATIONS OF A SCAO SYSTEM FOR AN E-ELT TELESCOPE USING THE PYRAMID WAVEFRONT SENSOR: RECENT RESULTS

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Abstract. Updated results obtained from simulations of a single-conjugated adaptive optics (SCAO) system for a 42 m telescope are presented in this work. The modulated pyramid wavefront sensor (PWFS), which has been preferred in some projects for its versatility and sensitivity, is used in these simulations. The main objective of this work is to evaluate the performance of such SCAO system under different parameters (loop gain, modulation, truncated SVD mode), sensing wavelengths, atmospheric coherence lengths and NGS magnitudes. Always measuring the Strehl ratio in the K-band, we have verified that the overall performance tends to be poorer as the sensing wavelength becomes shorter. The loop gain optimal range is dependent on the SVD truncation threshold used to build the command matrix, and a non-modulated PWFS produces in general poorer results when compared to modulated cases, being this especially true for the R-sensing band. The default atmospheric model adopted was a von Kármán with $r_0=0.13$ m (@ 500 nm) and outer scale of 25 m, but poorer and better seeing conditions have also been tested. We also show how the Strehl is affected by the incidence of different photon fluxes at the PWFS detector and by the system working in different frame rates.

1. Introduction

The idea of using the pyramid wavefront sensor (PWFS) for astronomical adaptive optics applications was introduced by [1], and since then its use has increasingly gained force along the years. Differently from the Shack-Hartmann wavefront sensor (SHWFS), it works in the focal instead of the pupil plane, with a functioning principle that relies on the Foucault knife-edge test [2], in which the electric field of the focused beam is separated by a hard edge according to its aberrations. In the case of the PWFS, there are four hard edges, and four pupil images are formed on a CCD detector after the light passes through the pyramid+lens ensemble.

Just like in the simple knife-edge test, a static setup for the PWFS can only give information on the sign of the wavefront reaching the tip of the pyramid. For that reason a modulation is introduced, and only after a whole cycle the wavefront slope calculation is carried out. The slope calculation is similar to that of the SHWFS, being the “quad-cell” elements those pixels

Adaptive Optics for Extremely Large Telescopes II

with correspondent locations in each of the four imaged pupils. The role played by the modulation is to introduce a linear response in the signal for spatial frequencies lower than β/λ , being β the modulation radius and λ the sensed wavelength. In this mode, the PWFS shows a behavior similar to that of the SHWFS, being even more sensitive - by $\lambda/(2d\beta)$, where d is the subaperture size - than this other sensor for small modulation regimes (see [3]). This property makes the PWFS ideal for high sensitivity applications, such as in the case of high-contrast adaptive optics (XAO). Moreover, it is possible to tune the pyramid modulation in real time, decreasing it as the correction improves in order to increase sensitivity.

The debut of the PWFS in sky observations occurred in 1999 at TNG, where for the first time the loop was closed with this sensor on tip-tilt and higher orders [4]. Since then an extensive number of properties has been found and experimentally verified. The MAD experiment carried out at the VLT, in 2007, has shown the validity of the layer-oriented MCAO mode using the PWFS [5]. At the LBT, the First Light AO (FLAO) system recently obtained, using the adaptive secondary mirror and a PWFS in a SCAO configuration, Strehl ratios above 80% in the H-band (Quirós-Pacheco, this conference).

In the case of the next generation of giant telescopes, the challenges for AO systems are huge. Being not only a scaled-up version of the instrumentation currently available, the future AO systems face problems such as larger cone effects, significant windshaking, difficulties in co-phasing the several mirror segments and in controlling a large number of system parameters, just to mention a few. On the XAO side, simulation studies have been carried out involving this WFS for specific instruments in ELTs such as, e.g. EPICS [6]. When using LGS, the beam elongation itself is known to mimic a modulation, and studies are underway to estimate the performance as a function of the beam size [7]. Quirós-Pacheco et al. presented in this conference a heuristic approach to estimate the performance of an E-ELT AO system with a PWFS based on FLAO results, along with some preliminary results from simulations. Despite some differences in their system input parameters (outer scale, sensing wavelengths, etc) with respect to ours, they use approximately the same number of modes and predict Strehls above 80% in the K-band for a non-limited photon regime.

In this paper we extend the results presented in [8], synthesizing what we have obtained so far and adding some more constraints on the optimization of a SCAO system that uses the PWFS as a sensing device.

2. Simulations

Simulations for a SCAO system have been carried out using the parallelized code OCTOPUS on the ESO cluster, using about 70-80 machines [9]. This code is run by setting the simulation parameters through a file that contains information about the WFS and DM characteristics, atmospheric models, telescope parameters, etc. The specific module for the PWFS simulations was written by Christophe Vérinaud, and uses the phase-mask approach, which takes into

Adaptive Optics for Extremely Large Telescopes II

account diffraction contamination between the four output pupils. The idea is to optimize some setup and loop parameters of the system, in a 42 m mirror telescope with a central obstruction of 28%. Telescope wind-shake and co-phasing are neglected throughout this work. The parameters tested in the simulations are listed in Table 1, whereas the default ones are listed in Table 2. Whenever a parameter is being tested, others are kept in their default values.

A simulation is assumed to have converged when the long-exposure (LE) Strehl ratio reaches an asymptotic behavior such that from iteration 500 to 1000 the standard deviation is no larger than 1%. How fast the convergence occurs, if that happens, depends on the main input simulation parameters in different degrees.

In what follows, we present updates on this work and discuss results obtained from examining the main simulation parameters. The reader should refer to [8] for further figures and details. A summary of some optimal results is given in Table 3.

Table 1. Parameters tested in the simulations; while one parameter is tested, others are kept in the default values (shown in Table 2).

Parameter	Values
PWFS modulation (β)	[0 - 8] λ/D
sensing bands	[R, J, K]
TSVD mode	[2000 - 5000]
loop gain	[0.2 - 1.4]
r_0 (@500 nm)	[0.10 - 0.20] m
frame rate	[250 - 1000] Hz
# of photons subap ⁻¹ frame ⁻¹	[10 - 10000]

2.1. Modulation

The modulation regulates the sensitivity of the PWFS. If tuned to a too small value, it enters easily the non-linear regime; if tuned to a too large value, it can lead to a substantial decrease in sensitivity [3]. The modulation can be either circular or square; the latter one is adopted here for simplicity. We scrutinized in this work the effects of the modulation by adopting four values for this parameter (in units of λ/D): 0 (natural

Adaptive Optics for Extremely Large Telescopes II

modulation), 2, 4 and 8. The natural modulation - i.e. introduced by the turbulence itself - has been verified to produce a worse performance with respect to the modulated cases for all sensing bands (this is specially true for the R sensing band, where the LE Strehl measured in K can be around 40% smaller than for a modulated pyramid). It was in general verified that bluer sensing wavelengths require a larger modulation amplitude to reach the maximum performance, which is always lower than the K-band performance.

Table 2. Default parameters in the simulations.

Parameter	Value
telescope aperture	42 m
obscuration	28% (no spiders)
AO mode	SCAO
observing band	K
actuators geometry	square
# of active actuators	5402
# of active subapertures	5040 (out of 7056)
PWFS FoV	2.5 arcsec
# of photons subap ⁻¹ frame ⁻¹	10000
readout noise	5 e-
frame rate	1 kHz
atmospheric model	von Kármán
r_0 (@500 nm)	0.13 m
L_0	25 m
# of simulated layers	10 (from 0 to 18.5 km)
# of iterations/simulation	1000

2.2. TSVD mode

The simulations use Karhunen–Loève modes. The dependence of the LE Strehl on the truncation mode of the matrix inverted by SVD (called hereafter TSVD mode) was investigated in [8], adopting initially values between 2000 and 5000, with a good coverage of this grid. TSVD modes of 3000 and 4000 seemed to provide in general the best performances, so we concentrated mainly on this interval throughout the work.

2.3. Loop gain

The loop gain is the parameter with the largest effect on the performance of the PWFS. For different TSVD modes and modulation amplitudes it constrains the intervals in which the highest K-band LE Strehls are obtained. The TSVD mode seems to define how broad is the range of acceptable loop gains, whereas the modulation amplitude seems to have a direct effect in defining the loop gain of the peak performance, specially in the R-sensing band. Optimal loop gain values for modulated cases seem to lie between 0.4 and 0.6 for a TSVD of 4000, or between 0.4 and 0.8 for a TSVD of 3000.

2.4. Seeing conditions

We evaluated the dependence of the performance on the main turbulence parameter (r_0) for conditions normally observed at good quality sites (at Paranal the standard seeing is of 0.83", which for a von Kármán model with $L_0 = 25$ m implies in $r_0 \approx 10$ cm @ 500 nm). Figure 1 (top) shows the dependence obtained for $r_0 = 0.10, 0.13$ and 0.20 m (@ 500 nm). The dependence with r_0 is very strong in the non-modulated case, specially for bluer sensing wavelengths.

2.5. Frame rate

We ran simulations to check the dependence of the optimal LE Strehl ratios on the frame rate, when adopting $\beta = 2\lambda/D$ as the modulation amplitude, TSVD modes of 3000 and 4000, and loop gains ranging from 0.2 to 1.0. Figure 1 (middle) shows the LE Strehl behavior for the 3 sensing bands, with its value dropping by, e.g. at least ~30% (K) when the frame rate is divided by 4. It was verified that the smaller the frame rate, the larger the loop gain values required to obtain high Strehl ratios, what is specially true for the R sensing band.

Adaptive Optics for Extremely Large Telescopes II

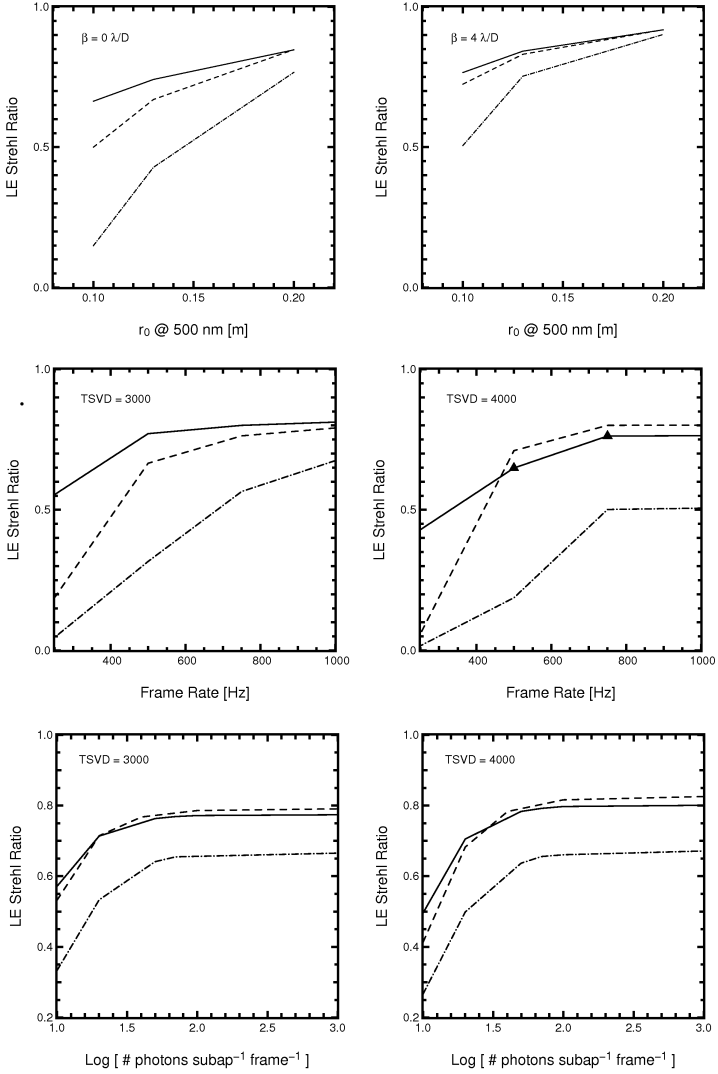


Fig. 1. Examples of optimal performances in the K-band obtained for some of the investigated parameters, for K (solid), J (dashed) and R (dot-dashed) sensing bands. Top: LE Strehl vs. coherence length (considering only TSVD = 4000) for two modulated cases ($\beta = [0, 4] \lambda/D$). Middle and bottom: LE Strehl vs. frame rate and photons subap⁻¹ frame⁻¹, respectively (considering only $\beta = 2\lambda/D$, TSVD = [3000,4000]). Triangles: convergence criterium not achieved.

2.6. Photons per subaperture per frame

The performance seems to reach a *plateau* for all sensing bands when the number of incident photons per subaperture per second is around 100. In a photon-limited regime the LE Strehl is highly dependent on the loop gain and TSVD mode, and lower values for this latter seem to be favored.

Table 3. Best performance parameters for each sensing band and modulation amplitude (β). LG: loop gain; TSVD: truncation mode of the SVD; S: LE Strehl ratio. Parameters not shown in the table have been kept in their default values. Table reproduced from [8].

	K			J			R		
β	LG	TSVD	S	LG	TSVD	S	LG	TSVD	S
0	0.4	2500	75%	0.6	3000	69%	1.0	4000	43%
2	0.4	3000	81%	0.4	4500	83%	0.6	4000	68%
4	0.4	4000	84%	0.4	4000	83%	0.6	4000	75%
8	0.4	4000	83%	0.4	4000	82%	0.6	4000	76%

3. Summary

- The highest LE Strehls are obtained when the wavefront sensing is done in the K-band, and the performance decreases as one adopts bluer wavelengths. A *plateau* in performance seems to be achieved for all probed sensing bands for modulations larger than about $4\lambda/D$.
- The non-modulated case (natural modulation) seems to show in general a poorer performance when compared to the modulated cases.
- The system takes longer to stabilize its LE Strehl for smaller modulations. This might be explained by the non-linear behavior of this wavefront sensor in such regimes. Accordingly, the system takes longer to stabilize its LE Strehl for bluer sensing bands.
- For a $8\lambda/D$ modulation the asymptotic behavior of the LE Strehls seems to fluctuate more than for smaller modulations.

Adaptive Optics for Extremely Large Telescopes II

- The optimum loop gain varies with sensing band and only slightly with modulation. In addition to that, the spread of loop gains varies with the TSVD mode. When comparing 3000 and 4000 TSVD modes, for instance, we see that the overall best performance is achieved with the latter, but the range of acceptable loop gains becomes narrower.
- Simulations under different seeing conditions show that for a fixed TSVD mode (e.g. 4000) a better stability and performance is also achieved under a modulated case. Non-modulated cases require a larger range of loop gains to achieve the best performances under different sensing bands.
- A smaller NGS photon flux does not affect much the performance of the system, as long as it is kept above ~ 100 integrated photons subaperture⁻¹ frame⁻¹. In a photon-limited regime the system requires smaller TSVD modes to achieve its peak performance.
- The performance drops significantly with the decrease of the frame rate. For the K sensing band, this means a decrease between 30-40% for 250 Hz, depending on the TSVD adopted. In the R sensing band, the K-band LE Strehl can go below 5% at this rate.

4. References

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