Simulations of Adaptive Optics Systems for the E-ELT

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ABSTRACT

In this paper, we present simulation work done on AO systems for the E-ELT. We study the influence of the number of Laser Guide Stars (LGS) on system performance. Then, we investigate the impact of the conjugation height of the M4 adaptive mirror on GL/LT/MC-AO. Finally, we compare the results of a Fourier code and end-to-end models on the position of the LGS in the field of view.
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1. INTRODUCTION

In our simulations, we have assumed a 42m telescope, with a central obstruction of 0.28 (linear). Unless otherwise noted, simulations are carried out with Octopus, the ESO end-to-end simulation tool. The atmosphere is modeled with 9 layers (unless otherwise noted), a seeing of ~0.8'' and an outer scale of turbulence L0=25m. We run 500 time steps to allow low order decorrelation, and verified that in that amount of time, the Long exposure Strehl ratio has converged.

We use a pure center of gravity centroiding method, and the Laser Guide Stars provide a high flux to the WFSs (→ loss of flux due to truncation is not critical). Tip-tilt is measured from the LGSs, for simplicity. We assume 84x84 sub-apertures on LGS wavefront sensors, and a corresponding deformable mirror pitch. For tomographic algorithms, 9 layers are reconstructed.

Please note also that the full error budget not included and therefore our results will be optimistic compared to the final simulations provided for a full system study.

The table below shows the default atmospheric turbulence profile.

C_n^2 profile	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
Height (km)	47	140	281	562	1125	2250	4500	9000	18000
Cn2 %	52.24	2.60	4.44	11.6	9.89	2.95	5.98	4.30	6.0
Speed (m/s)	15	13	13	9	9	15	25	40	21

2. WHAT IS THE PERFORMANCE IMPACT OF THE NUMBER OF LASERS ?

In this section, we investigate a Laser Tomography AO system (LTAO). This system resembles the ATLAS AO system, although does not completely represent it. The performance is evaluated on-axis, while the LGS position is variable (to see where their optimal position is). With natural guide stars, this position would be on-axis, but with lasers, the cone effect needs to be corrected. Therefore, the lasers need to be further apart from the center.

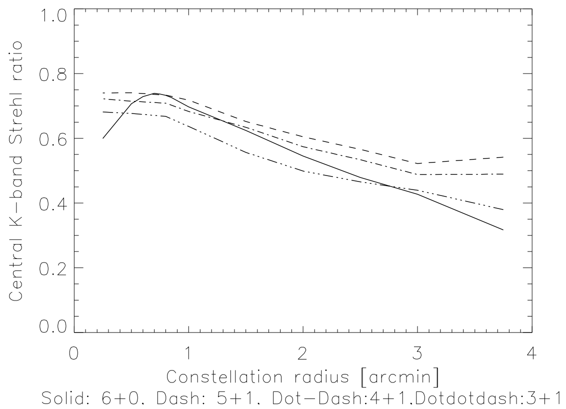

Figure 1: On-axis Strehl ratio (K-band) as a function of position of the LGS (in radius) for different LGS constellations.

We compared our standard 6 LGS in a circle (called 6+0) constellation, to 5 LGS in a circle plus one in the center of the field (called 5+1). We also investigated the possibility to use less LGS (but always with a central star: configurations 4+1 and 3+1, with 5 and 4 LGSs respectively). From Figure 1, we can conclude that if the LGSs are located close to their optimum position (at ~0.8'-0.9' radius), then using 6LGS (6+0 in the curve) in a circle or 5 in a circle plus a central one (5+1) doesn't make a big difference. However, if the LGS constellation is larger, the central star helps maintaining the on-axis performance.

Reducing the number of LGS does not significantly impact performance in the 4+1 configuration. The 3+1 starts already to see a significant performance loss.

If the LGSs are at their optimal position, a central star does not help to improve the performance when 6LGSs are used. It may be possible to use 5 LGS only without much loss of performance.

Note that here we didn't take into account spot elongation – which could have an impact, since less (side launched) lasers provide less redundancy. We also assumed zenith pointing, which could be too optimistic.

Conclusion: Reducing the number of LGS could be possible without affecting performance dramatically.

3. WHAT IS THE IMPACT OF THE NUMBER OF LAYERS ONE RECONSTRUCTS OR SIMULATES ON THE LTAO PERFORMANCE ?

In a tomographic AO system, one can estimate more layers than one actually corrects. For example, in an LTAO system, only one deformable mirror is present. But there is an advantage to reconstruct more layers than that (and then project those reconstructed back to a single DM), in order to improve the tomographic performance.

In order for this simulation to accurately represent reality, more layers need to be simulated than reconstructed. Indeed, in reality, there are thousands of layers in the atmosphere and simulating only a few is a crude approximation. We try here to analyze what is the minimum number of layers one needs to simulate (to save computation time) to accurately represent a tomographic system.

First, we use only 9 layers (as was used in our previous studies) to represent the atmosphere. We then see how the simulated performance changes as the number of estimated layers (out of the 9 simulated) is increased. We can see from Figure 2 on the left that estimating the correct number of layers is **critical** ! Indeed, if 9 layers are simulated, estimating only 3 of them dramatically reduces performance. The difference with 9 estimated layers is very large, especially if the LGSs are far from their optimal position.

The number of layers may depend heavily on the number of actual turbulence layers. Here we only simulated 9 layers (and in the extreme case, reconstruct all of them). This is the upper limit of performance.

With 9 simulated layers, it looks like at least 6 need to be reconstructed and there is still an improvement going to the full 9.

So how many layers do we need to simulate? In Figure 2 (right) we simulate 26 layers, and reconstruct 6, 9 and all 26. We can see that the performance saturates and that reconstructing 9 layers out of 26 simulated ones is enough. This is reassuring for example for the real time computer architecture.

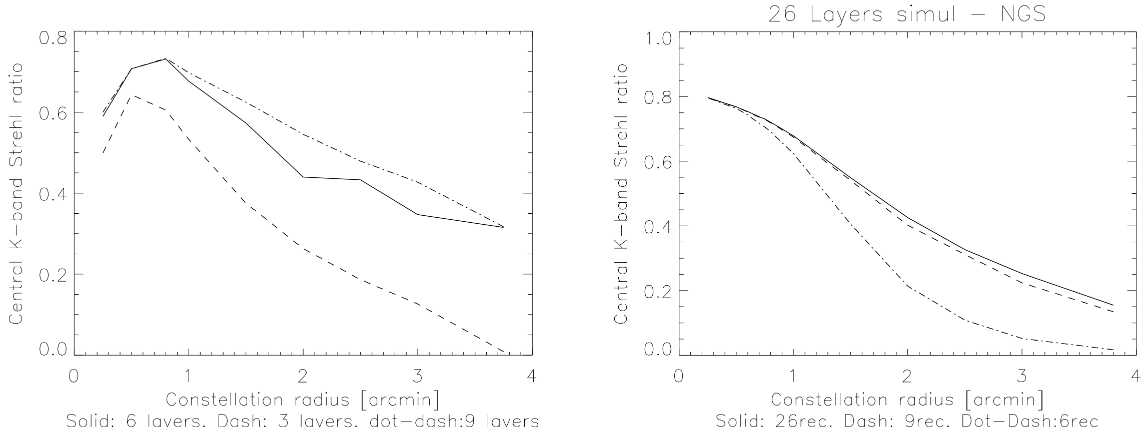

Figure 2: On the left, for 9 simulated layers, performance as a function of LGS position, for different numbers of reconstructed layers. On the right, for 26 simulated layers, performance as a function of LGS position, for different numbers of reconstructed layers

Conclusion: The number of reconstructed layers has a critical influence on system performance. With Frim3D, about 9 layers provides close to optimal performance if 26 layers are simulated. One has to simulate ~30 layers to accurately estimate performance.

4. M4 CONJUGATION HEIGHT: IMPACT ON GLAO, LTAO, MCAO

The purpose of this section is to evaluate the impact of changing the conjugation height of M4, the adaptive deformable mirror in the E-ELT. In previous versions of the optical design of this telescope, the conjugation height was ~400m. Now we want to see what would happen, if this height was increased to ~500m. Here we simulate different AO systems (GLAO, LTAO, MCAO), to see if performance is impacted by the change.

The first system we look at is Laser Tomography AO. We change the conjugation height of the DM, and plot the on-axis performance (in K-Band) as a function of the DM height.

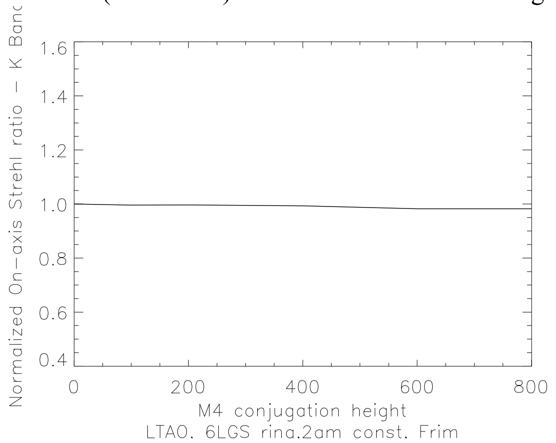

Figure 3: LTAO (à la ATLAS) Strehl ratio, normalized to the performance of an M4 conjugated to the ground.

We can see in Figure 3 that performance is not much affected by M4 conjugation height, only a 2% variation of on-axis Strehl is seen, when DM conjugation height is changed from 0m to +800m. Note that here the tomographic algorithm reconstructs 9 layers out of 9 simulated, and projects them back to the conjugation height of the DM.

Next, we move to ground layer AO. This system uses 3 natural guide stars to correct for a 4’ constellation (diameter).

In Figure 4, we show GLAO performance as a function of M4 conjugation height. Solid line is the Paranal "good" atmospheric model, dash is the "median" model and dot-dash the "bad" model. PSSn (Point source sensitivity – normalized) is defined as the integral of the square of the corrected PSF divided by the square of the open loop PSF.

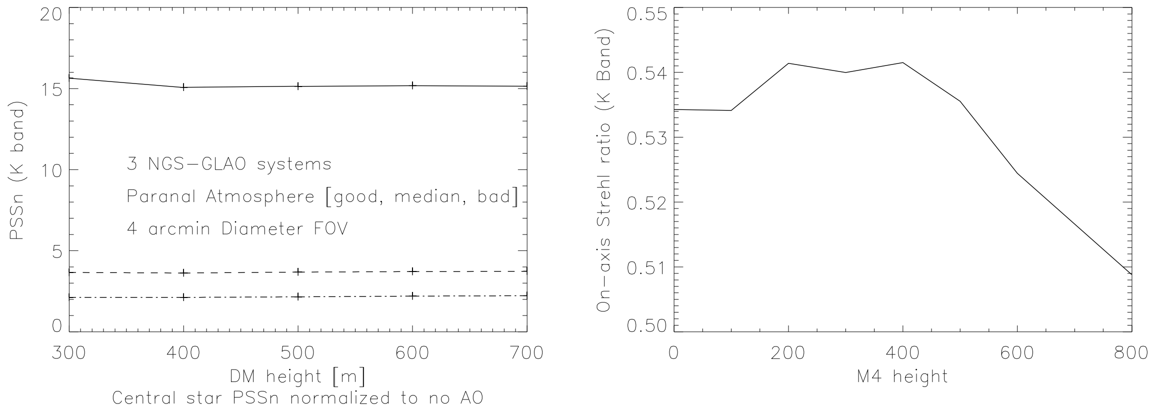

Figure 4: On the left, PSSn (K-Band) as a function of DM conjugation height for a GLAO system. On the right, Strehl as a function of conjugation height for 3 mirror MCAO system.

Finally, we have a look at an MCAO system, with 3 deformable mirrors (including M4), à la MAORY. The DMs are conjugated to 0km (variable here), 4km and 12.7km. It uses 6 LGS, on a circle of 1' radius. The total reconstructed field of view is 2.8' (diameter). We can see also in Figure 4 that performance is not much affected by the M4 conjugation height.

Conclusion: Conjugation altitude in the 400m-500m range of M4 is not a very sensitive parameter for GLAO, LTAO, MCAO (simulated with our parameter set) with current knowledge of C_n^2 profile.

5. COMPARING FOURIER CODE TO END-TO-END SIMULATIONS

We want to compare the ATLAS phase A study results (see for eg. [2], [3]) with end to end simulations. In particular, we want to know the influence of the asterism radius on system performance, i.e. where should the LGS be placed ? Indeed, because we use LGS, we know there is an optimal radius (which is not for a minimum LGS separation, because of the cone effect). Beyond the optimal position, performance starts to decrease.

A larger asterism radius makes the ATLAS mechanical design easier. How large can the asterism be with affordable loss in performance? During phase A, the answer was given by ONERA's Fourier code analysis, which showed a slow increase of the tomographic error with the asterism radius ~ up to 2 or 3 arcminutes (radius).

Comparison of Fourier results with end-to-end simulations of ATLAS with Octopus and FRIM-3D [4]:

Unfortunately, there is a difference between the E2E simulations done with Octopus+_Frim3D and the Fourier code. This can be observed in the figure below., where the red curves stand for the Fourier code results (provided by ONERA) and the black curves represent the E2E results with Octopus and FRIM-3D. The dashed lines are for an asterism of 6 NGS, and the solid line for an asterism of 6 LGS(so we can check that the cone effect leads to the optimal performance at a non-zero radius for the asterism).

The decrease of the performance with increasing radius is significantly steeper with the E2E simulations than with the Fourier approach. Fourier predict a loss of 5 % of strehl going from 1.5' to 2.5' radius, while E2E simulations predict a loss of 15% of Strehl for the same change in radius.

All the simulations parameters are identical between Fourier and E2E, and many tests and comparisons have been done in order to eliminate from the list of possible causes the following points:

- coding bugs

- geometry discrepancies between the codes
- flux / noise levels
- Non optimal reconstructor performance at great LGS separation

In Figure 5, we superimpose different results, combining end-to-end simulations with two independent reconstructors, the ONERA Fourier code results (both with LGS and NGS, both curves in red) and Frim3D in pure reconstruction mode. The Fourier curves show a distinctive slowly decreasing slope when guide star distance is increased. The Kaczmarz reconstructor [6] used with Octopus (curve in green) shows exactly the same slope as Octopus+Frim3D (in black). Even if the peak performance is slightly less than that of Frim3D +Octopus, the results are very close. The similar slope between two independent reconstructors gives confidence in this slope. We then used Frim3D in pure reconstruction mode, **completely independently** of Octopus. In this mode, FrIM-3D simulates data, reconstructs layers, and computes rms wavefront residuals of the on-axis beam. In this case the exact some model is used both for simulation and reconstruction. Doing this eliminates some of the AO errors which are only simulated by Octopus (like aliasing, fitting, WFS linearity…) and possible mismatch between FrIM-3D and Octopus models, but it still is capable of accurately simulating the tomography aspects which are of interest here (conical propagation, beam overlap…). **Again, the slope stays the same, steeper than the Fourier results**.

Fourier codes (ONERA's code as well as B. Ellerbroek’s CIBOLA code [5]) assume that the telescope diameter is infinite for the wavefront sensing. Is a 42m-telescope big enough to validate this assumption? E2E simulations and reconstructions involve spatial discretization and interpolations that are avoided in Fourier approach. Figure 6 tries to answer the question of impact of the diameter. We show the effect on performance decrease of an ATLAS-like system when the telescope diameter is increased (all the rest remaining constant), as given by E2E reconstruction with FRIM-3D algorithm. The CIBOLA Fourier code shows a decrease of 5% Strehl going from 1.5' to 2.5', while E2E reconstruction shows a loss of 10% Strehl from 1.5' to 2.5'. A range from 16m to 100m telescope was spanned. NGS asterisms have been considered to isolate the problem from the cone effect. Only open-loop reconstruction is chosen in order to remove the contribution from the closed-loop. The Fourier curve here has been obtained by CIBOLA code, which shows the same behavior as Onera’s Fourier code, **so we can exclude a bug**. We can see that even a 100m-telescope hardly reach the performance predicted by Fourier analysis, although the increasing diameter tends to push the performance curves of E2E closer to the Fourier one. Diameter plays a role in the difference between Fourier and E2E results.

Our results points towards the fact that the Fourier code underestimates the loss of performance when LGS radius is increased, in the conditions we have simulated.

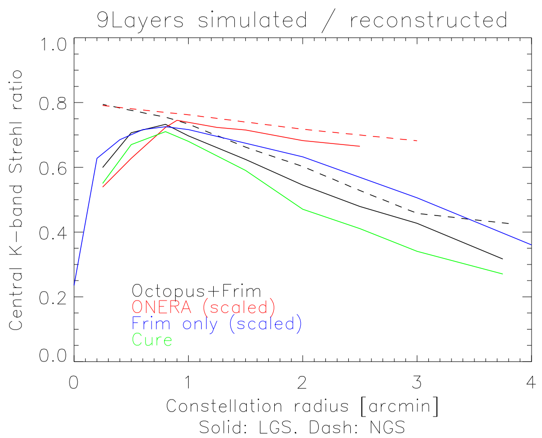

Figure 5: On-axis Strehl for ATLAS as a function of the high-order guide stars asterism radius (6 stars on a circle). Dashed : 6 NGS. Solid: 6 LGS assuming they can measure tip-tilts. Atmosphere is simulated with 9 layers. Very high flux is considered to avoid p photon noise influence. Red curves: Results from ATLAS phase A, with Fourier code developed at ONERA. Black curves: Results from end-to-end closed-loop simulations with Octopus,

ESO simulator, and FRIM-3D for reconstruction and control. Green curve: Octopus with the Kaczmarz reconstructor. Blue curve: Frim3D only, used in pure reconstruction mode.

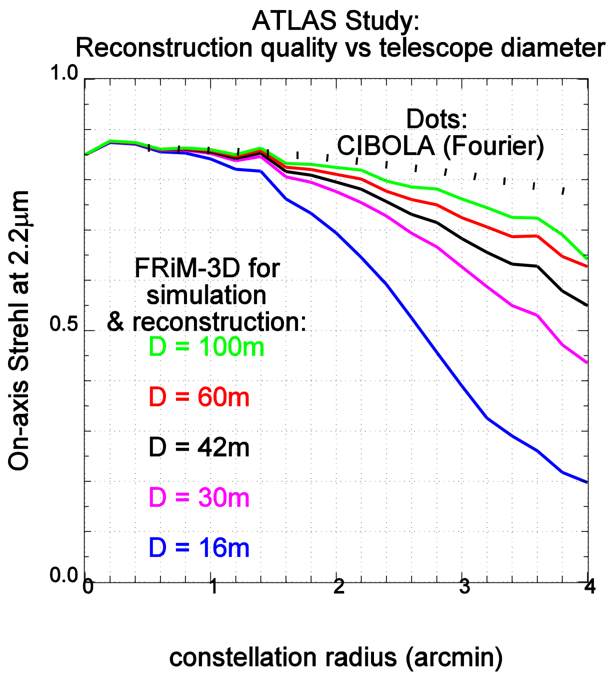

Figure 6: On-axis Strehl for ATLAS as a function of the high-order natural guide stars asterism radius (6 stars on a circle). Open-loop correction is considered. The average performance over 500 random realizations of the turbulent 9-layers atmosphere is provided. Dashed : CIBOLA results (another Fourier approach, also assuming infinite size telescope aperture). Solid : End-to-end results using FRIM3D as a simulator and FRIM3D as a reconstructor too. Several colors show the dependence of the performance as a function of the telescope aperture diameter, in meters.

Conclusion: The LGS should be positioned at ~0.8' (radius) from optical axis for best LTAO performance, with current C_n^2 profile data, and for observations at zenith.

6. CONCLUSIONS

We have shown various results from end-to-end simulations for a 42m E-ELT. The main results can be summarized as:

- The conjugation height of the M4 adaptive mirror around ~400m-500m is not a very sensitive parameter for the performance of the modeled MCAO, GLAO and LTAO systems.
- It may be possible to reduce the number of LGSs in the ATLAS AO system without much loss of performance.
- One has to simulate ~30 atmospheric layers for this LTAO system to get representative results. About 9 layers need to be reconstructed by the AO system to get maximal performance.
- We have investigated the optimal position of the LGSs in an LTAO scheme, and for this, we get about ~0.8 arcminutes (in radius) from the field center.

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