Simulations of E-ELT telescope effects on AO system performance

Miska Le Louarn*[a], Pierre-Yves Madec[a], Enrico Marchetti[a], Henri Bonnet[a], Michael Esselborn[a]
[a]ESO, Karl Schwarzschild strasse 2, 85748, Garching bei Muenchen, Germany

ABSTRACT

We study the impact of various telescope effects (like effect of phasing errors, missing segments, etc) on the performance of SCAO systems. This paper is using the E-ELT with 798 primary mirror segments. For example, we will show what kind of AO system (number of sub-apertures, frame-rate) is necessary to compensate for these effects, to get a fully seeing limited performance from the telescope.
Keywords: Adaptive Optics, simulations, wavefront sensing, Extremely Large Telescopes

1. INTRODUCTION

In this paper, we present numerical simulations made with the ESO Octopus simulation software [1]. We simulate a Single Conjugated AO system, observing an on-axis bright natural guide star (NGS). The system has 74x74 sub-apertures, and the M4 adaptive mirror model of the E-ELT is used. A presentation of the E-ELT status can be found in [3]. This deformable mirror is conjugated to 625m above ground. The simulated seeing is 0.8''. The performance is evaluated in the near infrared, in the K-band (2.2μm). Unless otherwise noted, the following parameters were used. Simulation time is 500 AO loop iterations. When the system is running at 500Hz, this corresponds to 1s in real time and for systems running at 50Hz, the final simulated time corresponds to 10s.

In order to simulate the aberrations that the E-ELT telescope does not fully correct, we use phase screens which represent the wavefront seen by the AO system's wavefront sensor, before a correction is sent to the adaptive M4 mirror. We evaluate in this paper the impact of the AO system on these aberrations, and show how they can be corrected.

We inspect there different errors: the scalloping error, the kind of AO system needed to correct the full telescope aberrations enough to achieve seeing limited performance, and finally we investigate how missing segments on the telescope primary mirror affect the performance of the AO.

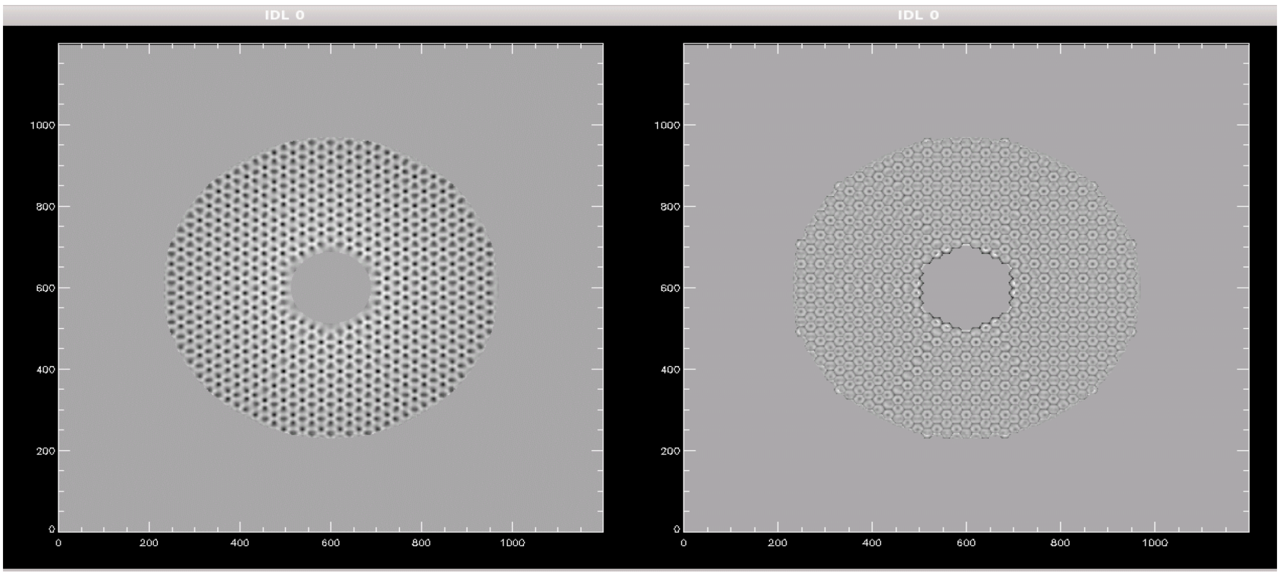

Figure 1: DM shape (on the left) and residual phase after fitting by the M4 (right), for screen002.

*lelouarn@eso.org;

2. SCALLOPING ERROR

The scalloping error we study here is a wavefront aberration arising from the compensation by the secondary mirror of a shape deformation of the primary (which is segmented). In our case, segment shape is fine, there is no need to warp the segments. It is just that an M1 deformation (e.g.focus or astigmatism) is compensated by M2.
The result is a high spatial frequency aberration, which can only be partially compensated by the adaptive M4 mirror.

Only a fraction of the scalloping error can be compensated by the AO system, because it is a high spatial frequency error. If it needs to be removed, we show that the AO system's DM commands can be used as a "sensor" to drive a "scalloping actuator".

This is demonstrated in the curve in Figure 1. At first, a large amount of scalloping is introduced in the system (much more than the telescope is likely to introduce) to make it easier to see the correction. In the first 0.2s, the AO system corrects what it can by itself, by deforming M4. We can see that the Strehl is increased to about 10% (in the K-band) thanks to the pure DM correction. This is however not perfect, as the AO system only has about ~3 actuators per segment.

While the AO system is running, the DM shape is analyzed by a supervisory loop, and it is used to calculate the amount of scalloping that the DM is compensating. This external measurement is averaged (we assume a static scalloping), and after ~0.2, a "scalloping actuator" is moved, to remove the amount of scalloping seen by the DM. This scalloping actuator is much better at removing this aberration (in fact, it removes it perfectly, if the right amount is specified). We can see that after this actuator is used, the Strehl jumps to ~70%. In practice the scalloping is not anymore limiting the AO performance.

Notice that the scalloping actuation is instantaneous, so for 2 loop iterations, the AO system is correcting a scalloping that is not anymore present. This is because the AO system is modeled with 2 frames of delay. This effect explains short the dip at 0.2s.

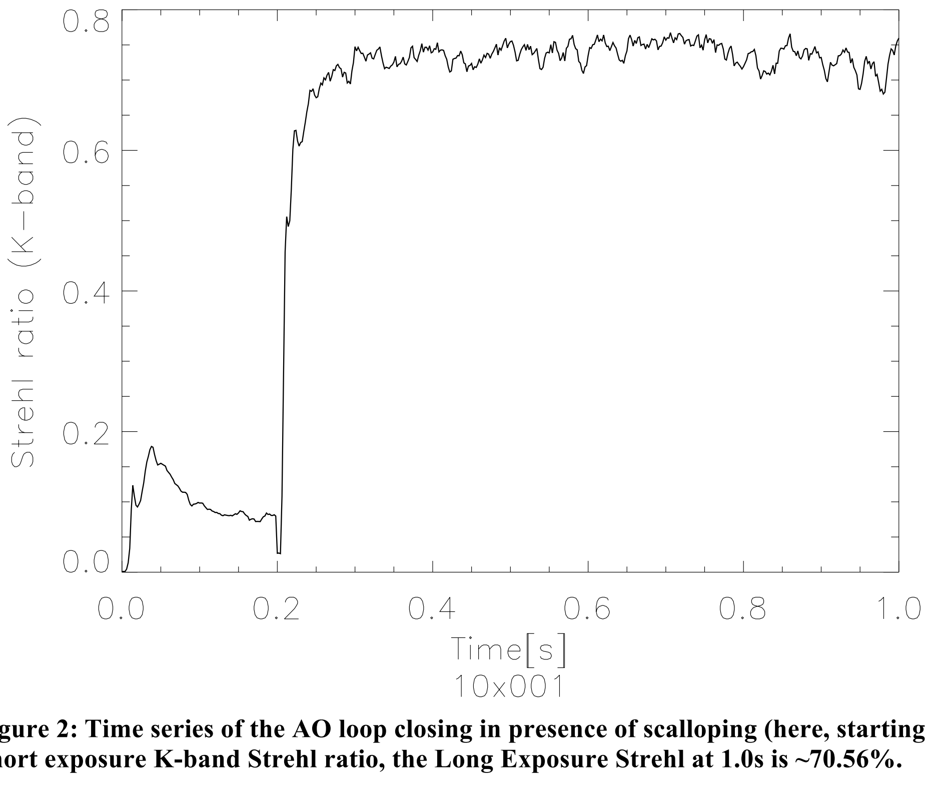

Figure 2: Time series of the AO loop closing in presence of scalloping (here, starting with 10* 001). This is the Short exposure K-band Strehl ratio, the Long Exposure Strehl at 1.0s is ~70.56%.

For more details on how this error is extracted from the AO system and how the simulation corrects the scalloping, see details in Le Louarn et al. [2].

In the next section, we investigate what kind of AO system is needed to correct some telescope errors, and deliver a seeing limited PSF to the user.

3. SEEING LIMITED AO SYSTEM

Because some residual telescope aberrations are, by design, left for the AO system to correct (mostly low order aberrations), then if the M4 adaptive mirror is flat, the telescope delivers an image quality slightly worse than seeing. This means than some (very limited) AO correction is needed to achieve the seeing limit. We study here, what this AO system could be.

In order to make the AO system as simple and robust as possible, we investigate very low order systems, with 5x5 and 10x10 sub-apertures across the 39m telescope pupil. To simplify the problem further, we use a matched deformable mirror. In reality, of course, we would use the M4 deformable mirror integrated into the telescope.

The telescope aberrations (including their temporal evolution) are included as time series of phase screens that are input into the simulation. At each AO time step, a new screen is entered and corrected by the AO system, in addition to the temporally evolving atmospheric phase screens.

In the plot below, we show a seeing limited PSF and a telescope limited PSF (without atmosphere). We can see that:

- Most of the aberration is tip-tilt. Here, we have not enabled field stabilization of the telescope, so this is normal.
- The remaining aberrations are fairly low order (mostly), and therefore it is likely that a low order system will do a good job at correcting them.

The plot on the right compares different systems: a 5x5, 10x10 and 74x74 sub-aperture systems (from bottom to top, in solid line). The high order (74x74) is there just to show what a "conventional" AO system aiming at the diffraction limit would do. We also show, in dash, the seeing limited + telescope aberrations (bottom) and seeing limited performance (top). We plot, instead of the Strehl ratio, the fraction of energy inside a box of varying diameter.

We can see that where the AO system has an influence (at smaller radii), both the 5x5 and 10x10 get the EE close to the seeing limited case, with the 10x10 doing, as expected, a slightly better job. The diffraction limited AO system shows a much better performance, as expected, the Airy rings being clearly visible.

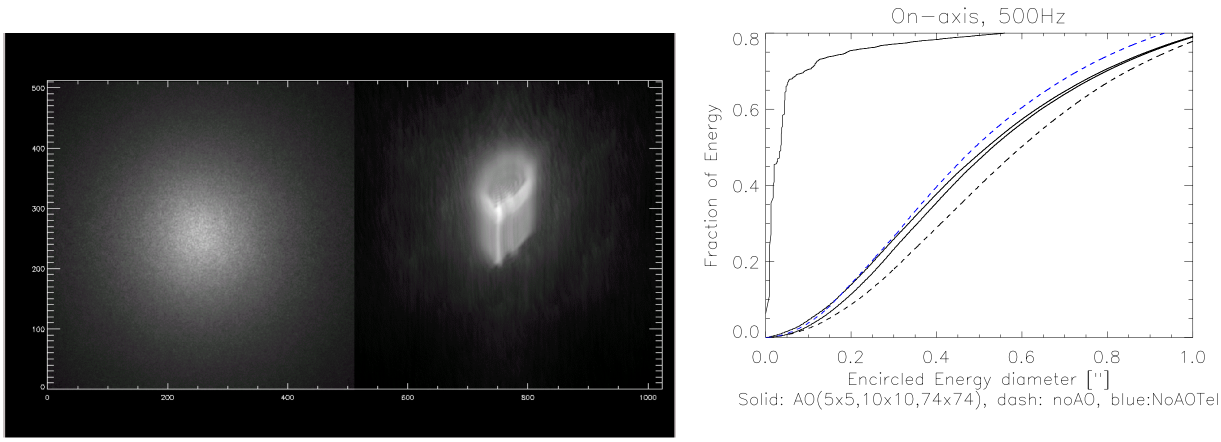

Figure 3: On the left, we show a seeing limited PSF, and a telescope limited PSF. On the rightmost figure, we compare the performance (ensquared energy as a function of pixel size in K-band) for different AO systems. We can see that even a 5x5 system gets a very nearly seeing limited performance for the smaller pixel scales. For comparison, a "full" AO system, with 74x74 sub-apertures is shown.

The second question addressed by the simulations is the frame-rate required to achieve the seeing limited performance. This is investigated in the following figure (Figure 4). We compare two frame-rates, 50Hz and 500Hz. Note that because the real simulated time is different (1s vs 10s), we cannot directly compare the different curves. However, it is clear that the AO system does not need to be very fast, and that 50Hz should be fast enough to correct most of the telescope effects. There is a small gain to go to 500Hz, but it is not clear if this is worth the effort.

The following curve looks at the field effects. Indeed, the adaptive M4 is conjugated at around 625m above the ground (and telescope primary). This means that it cannot fully correct the errors of the primary mirror, everywhere in the field. If we decide (like here) to use an on-axis WFS, then the correction in the field of view will degrade. This is clearly shown here, where we compare the EE on axis, to the EE 4.5' off axis. The difference is non negligible.

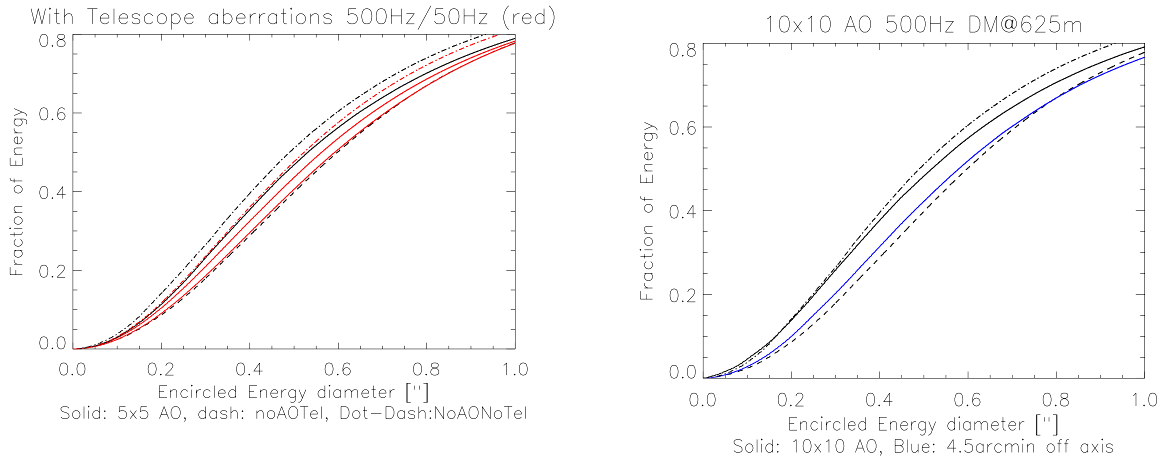

Figure 4: On the left, the plot on the left shows the impact of AO frame-rate on performance. We can see that the telescope aberrations are slow, and can therefore be corrected at low frequency. On the right, the impact of anisoplanatism is shown.

In conclusion for this part, we can say that while on-axis performance with the low order sensor is good enough, it degrades as expected as one goes off axis.

Very low order (5x5 Shack-Hartmann) & low temporal frequency (~50Hz) is enough to reach seeing limit. In case a wide field of view is to be corrected, we probably need to use a multi-WFS approach (GLAO-like). Since M4 is not ground conjugated, some tomography may be necessary to obtain best performance in multi-WFS case.

The next aspect we are going to investigate net is the impact of missing segments on the telescope primary mirror.

4. IMPACT OF MISSING SEGMENTS

One possible source of error in the AO system is the absence of some segments from the telescope primary. Several causes could be expected:

- Re-coating that is not completed within a day.
- Defective hardware that causes the segment to be tilted (and perhaps intentionally to prevent its light from perturbing the system)
- Other forms of maintenance on the segments are performed.

Here we study the impact of such missing segments. We go from a very small number (1-2) to an unrealistically large number (20).

We introduce a phase mask as presented in the figure below into the system, without creating a new interaction matrix or otherwise disabling the sub-apertures below the missing segments. The results are shown in Figure 5. We can see that for the likely case where only a few segments are missing, the wavefront error increases by a negligible factor. Only when a large number of segments are missing (10-20), does the error increase. Note that here, we have an extremely pessimistic case, since the AO system has not been re-adjusted.

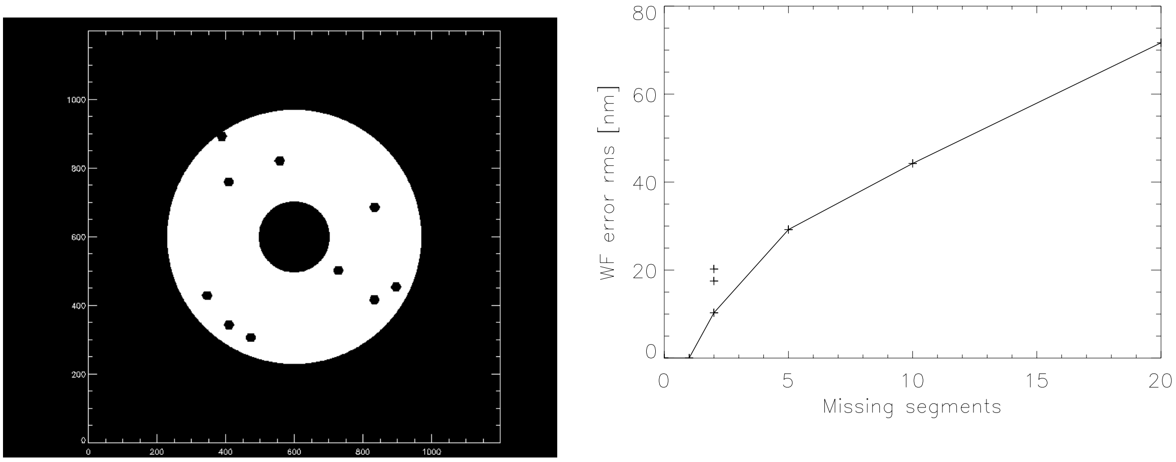

Figure 5: In this plot, we show the error due to missing segments, IF nothing is done to recalibrate the AO system. This is clearly a worst-case scenario. The multiple points at 3 missing segments correspond to different locations for the missing elements.

We expect that if the AO system was recalibrated (new command matrix, with the sub-apertures below the missing segments being disabled) it would perform much better – perhaps even almost as well as if the segments were present. This will be our next step in the investigation of this effect. However, it is reassuring to see that even if nothing is done, a few missing segments do not significantly affect system performance.

In order to understand where the error appearing in the previous figure comes from, we plot the difference in deformable mirror shape between the case of zero missing segments, and 20 missing segments. This is shown in Figure 6. We can see that the missing segments create ripples around their position, increasing the wavefront error.

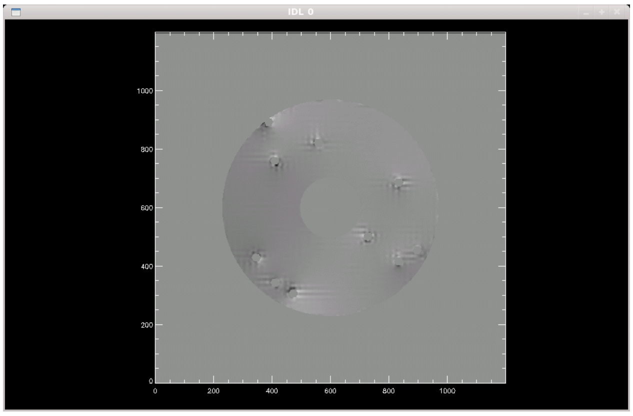

Figure 6: In this figure, we have subtracted the DM shape, in closed loop, with and without missing segments. We can clearly see the "ripples" near the missing segments.

We expect that re-generating the command matrix would reduce the impact of this problem significantly.

Future work in this area is clearly needed. We would like to study:

- Calibration & optimization with missing segment should improve performance, perhaps even to point where there is no extra error.
- Test with more segment configurations (location of missing segment on pupil) for each number of missing segments.
- Coupling with pupil fragmentation (if a missing segment is under spider).

5. CONCLUSIONS

In this paper, we have investigated the impact on SCAO performance of various telescope related aspects. We have shown that if a scalloping actuator is provided, it can be driven from measurements on M4.
The telescope aberrations can be corrected with a low order AO system (in the range of 5x5 to 10x10 sub-apertures across the pupil), running at a low frequency (50Hz), insuring a very high sky coverage. However, if a very large seeing limited field of view is required, a multi-WFS scheme should be considered.
Finally, preliminary work on the impact of missing segments shows that if a few of them are missing, the impact on the AO system is minimal, even if the AO system'scommand matrix is not updated. We suspect that if the sub-apertures that are affected were removed from the command matrix, the impact of the missing segments should be considerably reduced.

6. REFERENCES

1. Le Louarn, *SPIE* 7736, 2010
2. Le Louarn et al, AO4ELT4, 2016
3. Tamai et al, SPIE 9906, 2016