Simulations for diffraction limited near-infrared adaptive optics systems for the AOF

Miska Le Louarn[a], A. Glindemann [a], N. Hubin [a],
E. Marchetti [a], P.-Y. Madec [a]
[a]European Southern Observatory, Karl Schwarzschildstr 2, 85748 Garching, Germany;
contact: lelouarn@eso.org

ABSTRACT

In this paper, we simulate different possibilities to upgrade the Adaptive Optics Facility (AOF) of the VLT, to reach the diffraction limit in the near infrared. We present simulations of Ground Layer AO, Laser Tomography AO, Multi-Conjugate AO, Dual AO and a hybrid system which is a simplified version of MCAO. We describe the strengths and weaknesses of each approach and summarize the studies to be still carried out.

Keywords: Adaptive Optics Facility, GLAO, MCAO, LTAO

1. INTRODUCTION

These simulations aim to investigate the performance of possible upgrades to the Adaptive Optics Facility (AOF). The goal is to have diffraction limited performance in the near infra-red (all simulations presented here are at 2.2um), taking advantage of the AOF infrastructure (4 Sodium Laser Guide Stars, a 1170 actuator deformable secondary mirror (DSM) and 40x40 Shack-Hartmann LGS Wavefront Sensors - WFSs). Re-using standard components (like the LGS-WFS cameras and lenslet arrays) and possibly the real time computer would allow for a relatively fast and cost effective development.

We investigate here different complexity levels, and what their benefits would be. From the simplest AO system implementation to the most complex, we have investigated:

- A Ground Layer AO (GLAO) system, based on GRAAL (see [1]), with LGSs brought closer to the optical axis to boost on-axis performance
- An Laser Tomography AO (LTAO) system, also based on GRAAL, with un upgraded reconstruction algorithm compared to the option presented above
- A "Dual AO system", allowing to boost sky coverage by sharpening the infrared tip-tilt star with an LGS and associated deformable mirror.
- A "hybrid" Multi-Conjugate AO (MCAO) system, combining a GLAO system driving the DSM with 4 LGSs, and a post-focal multi-NGS system driving a post-focal DM conjugated to 8-12 km.
- A full MCAO system, with 2-3 DMs (in total, including the DSM), 4 LGSs, and possibly 3 additional NGSs.

Because this studied aimed also at comparing the different options with instruments which are already in a later design phase, we could not use exactly the same seeing values and C_n^2 profiles for all our studies. Therefore, with each result, we specify the C_n^2 model and seeing value used. Two turbulence profiles were used, one called "Galacsi NFM FDR C_n^2 profile" and the other one "Unified C_n^2 profile". They summarized in the following table:

Galacsi NFM C_n^2 profile	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**	**Layer 9**	**Layer 10**	**Layer 11**	**Layer 12**
Height (m) *1.16	0	100	200	300	900	1800	4500	7100	11000	12500	14500	16500
Cn2 %	26.0640	13.776	8.16	6.36735	10.6122	9.55102	8.48980	5.30612	4.77551	3.71429	1.06122	2.12245
speed(m/s)	8	10	12	10	6.6	8.0	8.0	22	13	15	10.0	8.0

“Unified C_n^2 profile”	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**	**Layer 9**	**Layer 10**
Height (km) *1.16	30	140	281	562	1125	2250	4500	7750	11000	14000
Cn2 %	59	2	4	6	1	5	9	4	5	5
Speed (m/s)	6.55	5.86	5.06	4.48	5.06	8.28	16.33	30.24	34.27	17.48

2. GLAO AND LTAO

2.1 Baseline 40x40 wavefront sensors

In this section, we investigate a conversion of an already existing GLAO AO system into an LTAO system. Indeed, for both systems, the hardware is similar (4 LGSs driving the DSM). Therefore, we explore the performance increase of the GLAO system.

First, we explore the option that the LGSs are moved closer to the field of view center, but still using an average of the 4 slopes provided by the LGSs (no tomography). Moving the LGSs closer allows to weight the measurements more towards the center, therefore increasing on axis performance, at the cost of the wide field capability of the original GLAO system. The results are shown in Figure 1. We can see that as the LGSs are move closer, the performance towards the center improves, as expected. In the ultimate case, the LGSs point all in the same direction and one has the performance of a single LGS system, limited mostly by the cone effect (and other implementation errors of the AO system, like fitting, aliasing…). The only advantage of such a system compared to a single LGS system, is that the flux is multiplied by 4. In principle, this gain in flux should not bring a big improvement in performance, since the laser flux is not the limiting factor in this system (except possibly in cases of very low sodium abundance).

The second possibility is if the LGSs are moved closer, and a tomography algorithm is used to optimize performance towards the on-axis direction. The results are also presented in Figure 1. We can see that compared to the GLAO system, a significant boost of performance is obtained. This is due to the correction of the cone effect by the tomography algorithm. The optimum in the curve is a compromise between separating the beams to best measure the high altitude turbulence (better upper layer coverage) and increasing the overlap of the beams by getting them closer to have several measurements of the turbulence by several LGSs, allowing a better estimation of the height of the probed turbulence.

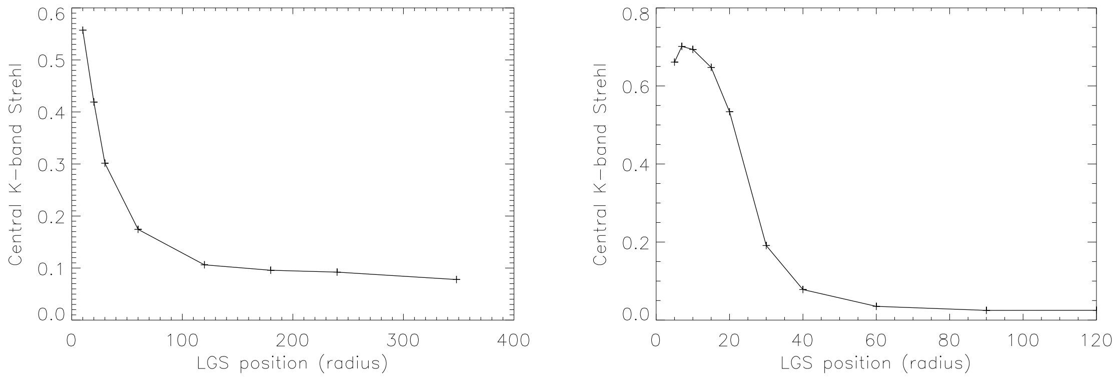

Figure 1: On-axis performance for the GLAO system (on the left), and the LTAO system (on the right), as a function of the LGSs. Seeing: 0.87’’, unified C_n^2 profile

As a conclusion, we can say that the LTAO scheme seems to be an interesting upgrade compared to GLAO, if an opto-mechanical mean of getting the LGSs close to the center is found.

2.2 20x20 Shack Hartmann LTAO scheme

The 20x20 Shack-Hartmann (SH) LTAO idea is different from the others presented here, since the WFS design is changed. Only one AOF high order WFS camera is used. In the other configurations, each LGS is observed with its own 40x40 WFS camera - a total of 4 cameras.

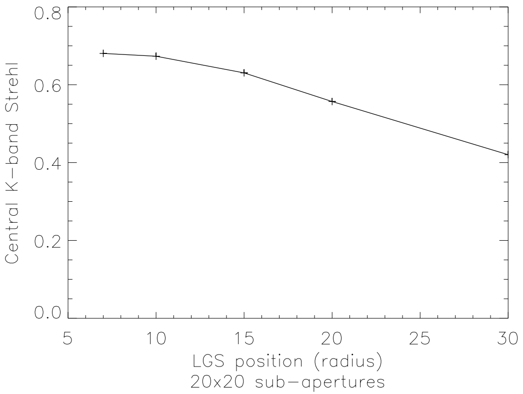

Figure 2: On-axis performance of the 20x20 SH system as a function of position of the LGSs. Seeing: 0.87'', unified C_n^2 profile

Here, the light from the four LGSs is fed into a single WFS camera, and the signals split in 4 quadrants of the detector – one quadrant per LGS. Therefore each quadrant of the detector analyzes the light from a single LGS. Because of this split, there is only room for 20x20 sub-apertures per LGS WFS, but the 4 LGSs are still used. We study the performance of such an arrangement in Figure 2.

The 20x20 LTAO performance is not significantly worse than other single DM solutions, it is not however as good as the full 40x40 solution with tomography. It is therefore an intermediate solution, with lower technological complexity, but also less performance.

3. MCAO

For MCAO, we studied a corrected field of view of 2' (implying a high altitude field of view of 2.8' to cover the square 2 arc minutes). Several options were considered, in terms of total number of DMs (2 and 3, i.e. 1 or 2 post-focal DMs after the Deformable Secondary Mirror), number of high order WFSs (4 LGS, and 4LGS + 3 mid-order (5x5 sub-apertures) NGS WFSs to increase the meta-pupil coverage of the high altitude DM(s) and improve tomography and stability in the field)

It was assumed that the LGS WFSs are all 40x40 sub-apertures (identical to the other AOF LGSs WFSs). To simplify, the spacing of the DMs was assumed identical to the DSM – but this remains to be optimized.

The simplest configuration is with a total of 2 DMs (conjugated to the ground and to 8km) driven by 4 LGSs and a single tip-tilt star. The results can be seen in Figure 3. We can see that the performance is already reasonably good, even off axis. Strehl ratios of ~60% on-axis and ~40% off-axis (at 0.7' arc minutes) in the K-band are obtained.

A second , more complex system was studied next. In that case, a third DM is added (second post-focal, with conjugation heights at 0, 8km, 12km). In addition, to improve tomography, 3 NGSs with "mid order" 5x5 sub-aperture NGSs are used. We also tested a system without these additional NGSs and found that the performance was not very good, presumably because of the high number of unknowns (DM commands) compared to the measurements (LGS WFS slopes). The results of the 3DM system are shown in Figure 4. The performance improved compared to the 2DM/4LGS case. Especially the performance off axis is improved significantly, thanks to one more DM and the extra tomography information provided by the NGSs.

The choice of 5x5 WFSs for the natural guide stars was taken to allow the use of relatively faint NGSs – to increase sky coverage. In addition, it was verified through additional simulations that increasing the order of these WFS did not significantly boost performance. We also chose the configuration shown in Figure 4 (NGS on the outside, LGSs in the inside) to boost sky coverage by allowing the largest possible patrol field to find the NGSs.

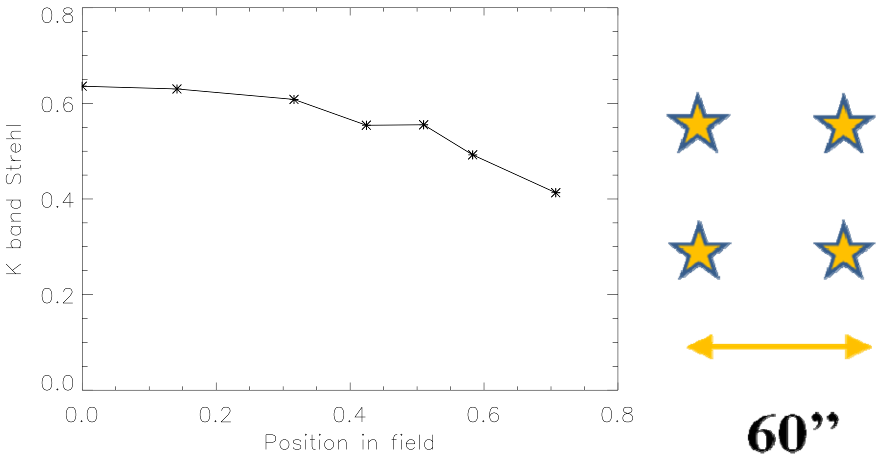

Figure 3: MCAO performance for the 2 DM, 4 LGS system (on the left) as a function of position in the field. On the right, configuration of the high order (LGS) guide stars. Seeing: 0.6'', Galacsi NFM FDR C_n^2 profile.

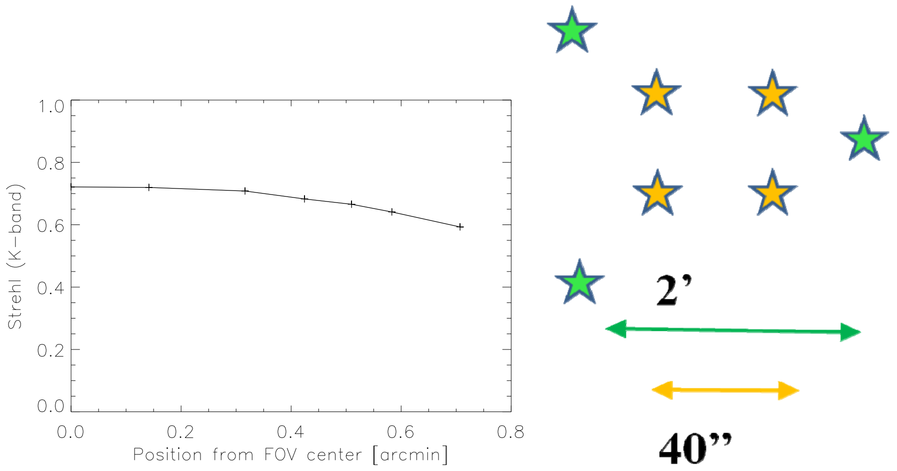

Figure 4: On the left, MCAO performance with 3DMs and 3 additional NGSs as a function of field position. On the right, positions of the LGSs and NGSs. Seeing: 0.6'', Galacsi NFM FDR C_n^2 profile.

To explore further the difference between the 2 and 3 DM approach, we kept the same guide star configuration, and investigated several C_n^2 profiles. The results are shown in Figure 5. We can see two series of curves (solid for 2 DMs, dash for 3 DMs) using 3 C_n^2 profiles (we chose profiles already used for the GRAAL study, they are described as "good", "median", "bad", according to their suitability for GLAO). We see that the more turbulence is in the ground layer (top curves), the less there is a difference between 2 and 3 DMs. On the opposite, if there is a lot of turbulence outside the ground, then the difference in performance increases. One can therefore say, that a third DM stabilizes the performance with respect to varying Cn2 profiles. However, it makes also the system a lot more complex.

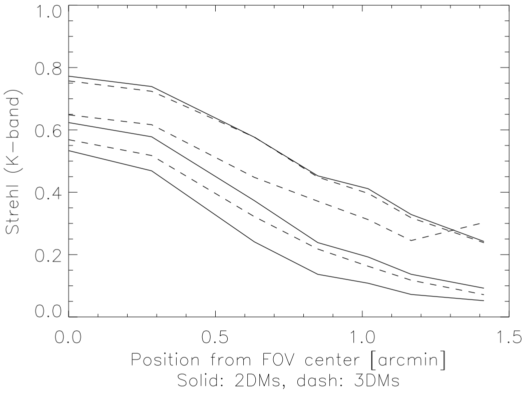

Figure 5: MCAO with 2 (solid) and 3(dash) DMs, with a seeing of 0.6''. Top to bottom: "Good", "median", "bad" C_n^2 profiles.

We can see that the MCAO approach can provide a 2' corrected field of view, with a reasonably stable Strehl over that field. The choice between 2 and 3 DMs deserve more attention, but a preliminary result is that 2 DMs seems already quite interesting, the third DM however provides more robust performance. Next, we study an evolution of the MCAO system, making it simpler to implement opto-mechanically.

4. HYBRID AO

The "Hybrid" system mixes two independent AO systems, with two independent AO loops. The first loop is a GLAO loop, where the 4 LGSs drive the DSM. The second loop is driven by 3 medium order (~5x5 sub-apertures) wavefront sensors, observing 3 NGS located in the 2' field of view. This loop drives a post-focal deformable mirror, conjugated to 8km.

The advantage of this system is simplicity, since there is no coupling between the two systems, while still obtaining MCAO performance. It also minimizes the intervention to the existing AOF facility, since modifications are concentrated in the post-focal module (NGS WFSs, post focal DM).

The performance is similar to MCAO, but with less complexity. This is shown in Figure 6, which plots the performance of the hybrid system, using the guide star configuration on the right. The series of curves is for different levels of photons detected from the NGSs (assumed identically bright). We can see that since the NGSs are towards the center, having them allows to improve the performance towards the center. We chose this constellation of stars (LGS and NGS), in order to allow a maximal re-use of existing AOF components. Indeed, leaving the LGSs far outside of the field of view allows to leave space for the NGSs WFS pick-offs, and it also allows to transmit the full 2' field of view without vignetting by the LGS pick-offs. In this configuration, both systems (LGS and NGS) are completely independent. The LGSs correct the ground layer (and can therefore be far from the center) and the NGS correct the upper layers by driving the extra DM. This also explains why the performance is more centered than the true MCAO system. It is possible that by improving the tomography algorithm of the NGS loop, we will be able to increase the performance in the field.

We also tested that running the two loops independently did not produce any problems in our simulation. This was done by first simulating the LGS loop and storing the DSM commands. Then, a second system was simulated, with both DSM (from which the commands were read from the previous system containing only the DSM) and a high altitude DM (which was driven only by the NGS, but saw the DSM shape).

We can conclude that this scheme works, and that the high altitude DM can be efficiently driven by an independent loop. Further studies will be carried out especially on the reconstruction algorithm, to improve the performance in the field of view, which is lower than the full MCAO one, but not dramatically so (the difference being in the size of the constellation used and not non-linearities in the hybrid system).

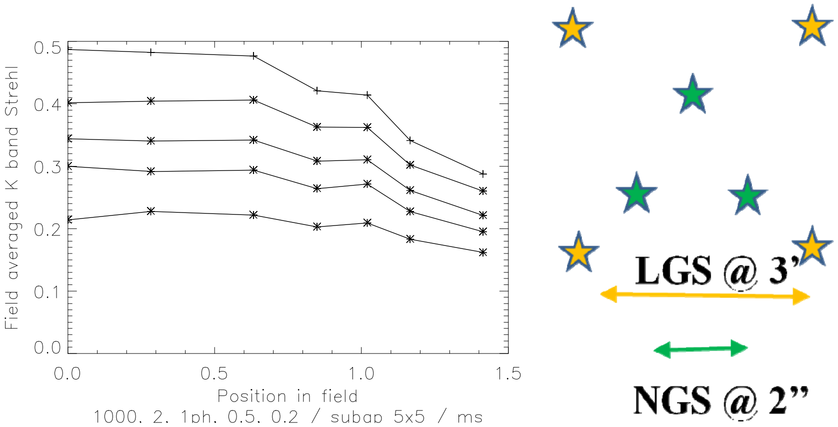

Figure 6: On the left, hybrid AO system performance as a function of position in the field of view (radius), for different NGS fluxes. From top to bottom, 1000, 2, 1, 0.5, 0.2 photons / subaperture / ms. Each sub-aperture is 1.6m in diameter. On the right, configuration of the LGSs and NGSs. Seeing: 0.6’’, Galacsi NFM FDR C_n^2 profile.

Next, we study a simpler system from the hardware point of view, where only 2 lasers are used, and the correction performed in a single direction.

5. DUAL AO

The Dual AO system is based on the concept presented by [2], but adapted to LGSs. It reminds also of more complex systems using specific DMs to sharpen NGSs, like NFIRAOS [3] or ATLAS [4].

In our scheme, 2 LGSs are used. The first one is pointed at a NGS. It is used to correct the wavefront in that direction, using a post-focal DM located in the tip-tilt sensing path. This corrected beam is then fed into the tip-tilt sensing part of the other “main” LGS WFS, which drives the DSM. The tip-tilt sensor functions in the near IR to benefit from AO correction of its own mirror, driven by its own LGS, and has a pixel scale adapted to the diffraction limited TT star.

The benefit of the scheme is to sharpen the NGS, allowing centroiding to be done on fainter stars, therefore increasing the sky coverage. This can be done at a relatively low cost, since one only uses 2 WFSs, and lasers already exist in the AOF. Of course an extra DM is needed for the Tip-tilt path.

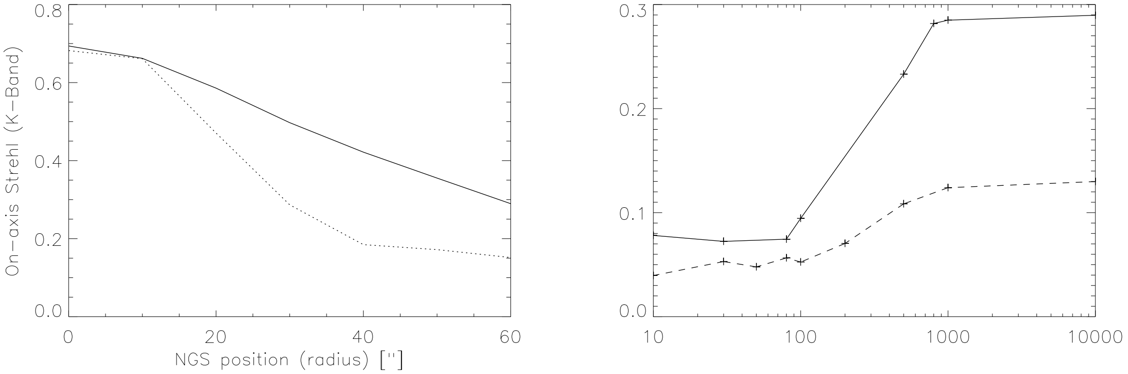

Figure 7: Performance of the Dual AO system (solid) and a “conventional” LGS AO system (dash). On the left, the performance is shown as a function of TT star position in the field of view. On the right performance, as a function of number of photons / 8m-pupil / ms in the tip-tilt sensing path. Seeing: 0.87’’, unified C_n^2 profile.

The simulations were done here too, like in the hybrid system, in two steps. In the first step, we ran a single conjugate AO loop on the tip tilt star, recording the DM shapes necessary to sharpen the tip-tilt star (located at 1’ (radius) off-axis).

In a second step, these DM shapes were injected into the tip-tilt path of the main AO loop, observing the science object (assumed on-axis). This allows the tip-tilt path of the main AO loop to see a corrected PSF (degraded by tip-tilt anisoplanatism, but well corrected in its high orders by the second LGS).

Figure 7 shows the simulation results. On the left, we can see in solid the performance of the Dual AO, in dash the performance of a "normal", unsharpened system, as a function of the position of the NGS in the field of view. The "conventional" AO system does not do as well as the dual AO system, because its tip-tilt sensor is optimized for on-axis performance. As one goes off-axis, the spot gets larger and larger, and its centroid gain increases, and very quickly, the spots becomes too large to fit in the field of view and is getting clipped. This is why the performance is reduced so quickly. By increasing the field of view of the TT sensor in that case, we could achieve the same performance as the corrected Dual AO case (which is limited by tip-tilt anisoplanatism). On the right, we compare the two (Dual and conventional) systems, for the case where the NGS is a 1' off-axis. We now reduce the flux of the TT star. Here we can see that the advantage of the Dual system is clear.

The following plot (Figure 8) demonstrates the efficiency of the high order correction (and clipping when this is not done), by comparing the spot entering the tip-tilt loop of the main AO system. On the left, with Dual AO, on the right, without.

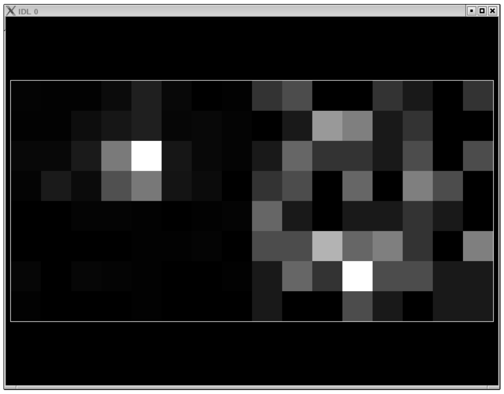

Figure 8: On the left, image on which the TT sensing is done in the Dual AO case. On the right, same thing, but in a conventional AO case. Notice how the dual AO allows to shrink the spot, allowing to use a smaller pixel scale and increasing the signal to noise ratio for faint stars.

From this very preliminary analysis, a large potential to boost sky coverage is identified, with a relatively small cost in complexity.

Many points still remain to be studied, like WFS optimization (what pixel scale for the NGS WFS), control of non-linearities and required stroke (TT / WFS loops, since the DM controlling the TT correction still "sees" the DSM correction), TT sensor DM specifications, optical design incl. TT path with DM.

6. CONCLUSIONS

In these simulations, we have explored different concepts to reach the diffraction limit in the near IR with "bricks" (WFSs, LGSs, DSM, RTC platform) provided by the ESO VLT Adaptive Optics Facility. We have shown the performance which can be achieved with LTAO, MCAO and Dual AO, in various configurations. These simulations provide a basis to start a deeper exploration of the most promising concept(s).

REFERENCES

[1] J. Paufique, "GRAAL: a seeing enhancer for the NIR wide-field imager Hawk-I" these proceedings, 7736-60
[2] Rigaut & Gendron, "Laser guide star in adaptive optics : the tilt determination problem", A&A, 261, p 677, 1992
[3] Herriot et al, "NFIRAOS: facility adaptive optics system for the TMT", these proceedings, 7736-08.
[4] Fusco et al.,"ATLAS: the LTAO system for the E-ELT: design, performance, and sky coverage", these proceedings, 7736-11.