Modelling Global Multi-Conjugated Adaptive Optics

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ABSTRACT

The recently proposed concept of Global MCAO (GMCAO) aims to look for Natural Guide Stars in a very wide technical Field of View (FoV), to increase the overall sky coverage, and deals with the consequent depth of focus reduction introducing numerically a quite-high number of Virtual Deformable Mirrors (VDMs), which are then the starting point for an optimization of the real DMs shapes for the correction of the -smaller- scientific FoV. To translate the GMCAO concept into a real system, a number of parameters requires to be analyzed and optimized, like the number of references and VDMs to be used, the technical FoV size, the spatial samplings, the sensing wavelength. These and some other major choices, like the open loop WFSs concept and design, will then drive the requirements and the performance of the system (e.g. limiting magnitude, linear response, and sensitivity). This paper collects some major results of the on-going study on the feasibility of an Adaptive Optics system for the E-ELT, based on GMCAO, with a particular emphasis on the sky coverage issue. Besides the sensitivity analysis of the optimization of the already mentioned parameters, such a topic involves the implementation of an IDL code simulation tool to estimate the system performance in terms of Strehl Ratio in a 2x2 arcmin FoV, when a variable number of NGSs and VDMs are used. Different technical FoV diameters for the references selection and various constellations can be also compared. This study could be the starting point for a dedicated laboratory testing and, in the future, an on-sky experiment at an 8m telescope with a "scaled down" demonstrator.

Keywords: Global-MCAO, E-ELT, Simulations

1. INTRODUCTION

Here we present the proposed method and current results of the first-order simulations, performed in different fields, in the framework of building a baseline for the main parameters involved in a study on the Global MCAO[1] (GMCAO) technique, being carried on for ESO. The GMCAO concept, aiming to increase the overall sky coverage, consists in a number of "very linear" wavefront sensors, each of them coupled with a Natural Guide Star (NGS), which look for references in a wide technical FoV and basically work in open loop. The measurements retrieved by the WFSs are numerically combined in a Layer Oriented fashion, to "drive" a number of continuously updated Virtual Deformable Mirrors (VDMs), which would optimize the performance in the NGSs directions. The VDMs are finally projected onto few real DMs, using as optimization criteria the performance in the Scientific FoV area.

In the following, we present some preliminary results of the on-going study on the feasibility of a real GMCAO system for the E-ELT, with the goal to give a first guess of the sky coverage that such an AO system could deliver.

2. MAIN PARAMETERS DRIVERS AND BASELINE CHOICES

The GMCAO involves several AO concepts, some of which are still quite innovative, but most of them are at least proven on sky, even if a further optimization is often possible. Being the increasing in sky coverage the major goal of this proposed new AO approach, two main parameters could be identified: the technical FoV size (the wider the field of view in which references can be selected, the higher the chance to find them) and the limiting magnitude (the fainter the guide stars can be, the higher the number of suitable reference one will find in a whatever field of view). Whatever the

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way in which you try to push, other issues arise. The size of the Technical FoV drives the number of VDMs, which are required to reproduce the turbulence properly, filling the atmosphere in terms of depth of focus. On the other hand, a higher number of VDMs to be computed will require more and more measurements, to make the reconstruction precise and free from any a-priori atmosphere knowledge. This, together with the meta-pupil filling at high altitude, will then drive the choice of the number of arms (i.e. wavefront sensors) to be implemented for the system. To increase the limiting magnitude, instead, very sensitive WFSs will be needed and the first candidate for this is the Pyramid wavefront sensor[2], working in locally closed loop, to take advantage of the gain in magnitude with respect to the Shack-Hartmann WFS[3][4]. This kind of choice would then require either a highly linear metrology system to monitor the local DM actual shape or new generation deformable mirrors equipped with high precision capacitive sensors (see [5] for a possible design of the Very-Linear WaveFront Sensor, VL-WFS).

2.1 Number of arms

In the “rich-end” regime, where there are plenty of stars, we estimated[6] that saturation of the metapupil coverage appears at about a number of eight stars while with six stars the same probability will reach a metapupil coverage only 15% smaller than the saturation figure. A number of six arms, corresponding to six references, has been fixed for the results presented in Section 5.

2.2 Number of Virtual DMs

A qualitative analysis, made gauging on MAD[7] (Multi-conjugate Adaptive optics Demonstrator) results on sky, made us assuming that, for a projected Strehl of 30% in K band, a reasonable number of Virtual DMs ranges from 4 to 8 for a 10arcmin FoV, depending upon the noise associated with each virtual DM and from the turbulence profile. Being the DMs noise propagation effect an outcome of our simulation, we decided to fix a number of six VDMs, which is in the middle of the just mentioned range.

2.3 Technical Field of View size

For the simulations, the current nominal technical FoV of the E-ELT (10arcmin in diameter) has been used.

2.4 Limiting magnitude

The magnitude of each star translates into a noise onto the WFSs measurement. We decided to use the real pyramid WFS performance data published by the FLAO[8] (First Light Adaptive Optics at LBT) team as a starting point. We performed simulations with different limiting magnitude. The result presented in Section 5 has a limiting magnitude of 18 in the R-band.

3. THE TOMOGRAPHIC SIMULATION TOOL

To compute a first order estimation of the behavior of the system performance in terms of delivered Strehl Ratio on the scientific FoV, we developed a quite-rough IDL tool reproducing the main aspects of the GMCAO system.

The simulation starts producing a synthetic frozen (i.e. not evolving) atmosphere, which obeys to a 40-layers model, with a seeing of 0.8” (@500nm, 30degrees off-Zenith) and a L_0=25m outer scale. The higher layer altitude is about 25km. Each of the screens representing the atmospheric layers has a modified Von Karman spectrum and an rms related to the outer scale and the local Fried parameter as rms $= 0.294 \cdot (L_0 / r_0)^{5/6}$. The wavefronts retrieved by the VL-WFSs, coupled with each of the references, are derived from the simulated atmosphere and the guide stars asterism, considering a 0.1m/pixel sampling. Afterwords, no a-priori knowledge of the atmosphere is used. The VDMs are computed back projecting the retrieved wavefronts in the NGSs directions and applying a fraction of their shape to each of the VDMs conjugation altitudes. Is then possible to compute the effect of such VDMs onto the measurements and realize a loop with the goal to minimize the difference between the actual measurements and the VDMs simulated projections onto the wavefront sensors, iteratively. Once the loop reaches a limit threshold, we can consider the VDMs as a best fit of the turbulence onto a number of altitudes. If the number of VDMs is too large with respect to the number of references, the problem becomes ill posed and there are a number of possible solutions, giving the same minimization level, meaning that it is possible, without any additional crosscheck, to obtain VDMs with odd shapes (they are not mimicking physically acceptable atmospheric layers, e.g. including discontinuities).

When required, to include the effect of different magnitude values onto the system, the code adds to each wavefront measurement (2nd step in the 4-steps approach) a random noise. The rms of such noise was consistent with the SR achieved in closed loop (remember that here the pyramid is actually working in locally closed loop, taking advantage of its full sensitivity power, provided that the local DM pitch allows that) for the FLAO@LBT system.

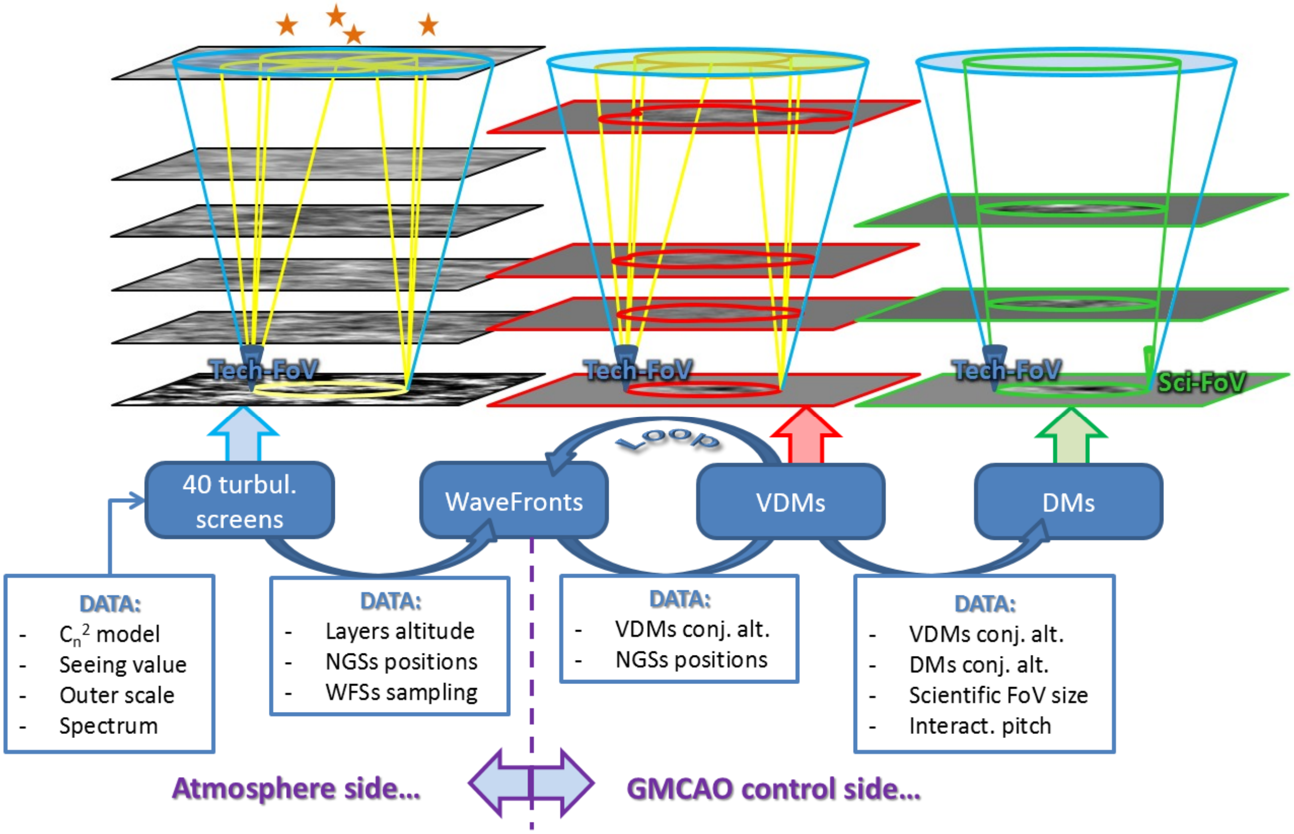

Figure 1 4-steps approach for the Tomographic Simulation Tool.

Figure 1 summarizes the described simulation path with a 4-steps approach, including the input required at each step. Please notice that the knowledge on the atmospheric model only enters in the turbulent screens definition and it is not used in the reconstruction, i.e. in the code no assumption about it is made after the wavefronts retrieval. The input C_n^2 profile plays a crucial role on the system performance estimation. This is true for all AO simulations, but it is particularly relevant in this case, because the wider the technical FoV involved is, the more sensitive to the C_n^2 profile the resulting performance will be. Whatever a-priori knowledge of the atmosphere (e.g. C_n^2 profile), then, would certainly help in getting a fully optimized performance.

4. TOOL VALIDATION IN THE PARAMETERS SPACE

The first goal of the tomographic simulation tool is to give an estimation of the performance of the system projected on the main parameter space. In other words, which is the best choice for the number of VDMs and VL-WFSs? Moreover, considering the technical FoV, is it worth to actually reach the 10’ limit, which is given by the telescope design? First, we tried to validate the code results comparing some of them with already existing and proved codes such as Octopus[9] by ESO. We expected some differences, being our code the result of many first order approximations and having it a mainly geometrical approach. The following crosschecks assume bright-end regime, i.e. no WFS noise was added to the measurements. To compare the results of the codes, we simulated the expected performance for a numerical correction of the scientific FoV (here considered of 2’x2’ size), performed applying the Virtual DMs to the simulated turbulence, as these mirrors were actual DMs. This should give us an idea of the reliability of the first three steps of the 4-steps approach, presented before. For a six NGS bright end (no noise on the wavefront measurements) circular asterism, with a 2’ radius, the expected K-band SR was 20% (from Octopus data) for the 40-layers atmospheric model we are considering in here. Figure 2, *left*, shows the simulated performance for our code, once the VDMs are conjugated at equidistant altitudes, which are not optimized for the actual atmospheric model, with the lowest and the highest altitudes fixed to 0km and 25km, respectively. Different curves in Figure 2 represent the results for different number of VDMs in the simulation. In the plot, the number of VDMs required to get the expected correction is seven and the performance starts to decrease when the number of VDMs exceeds nine. This, however, is because the Virtual DMs conjugation altitudes were not optimized, to completely avoid any a-priori knowledge of the C_n^2 distribution.

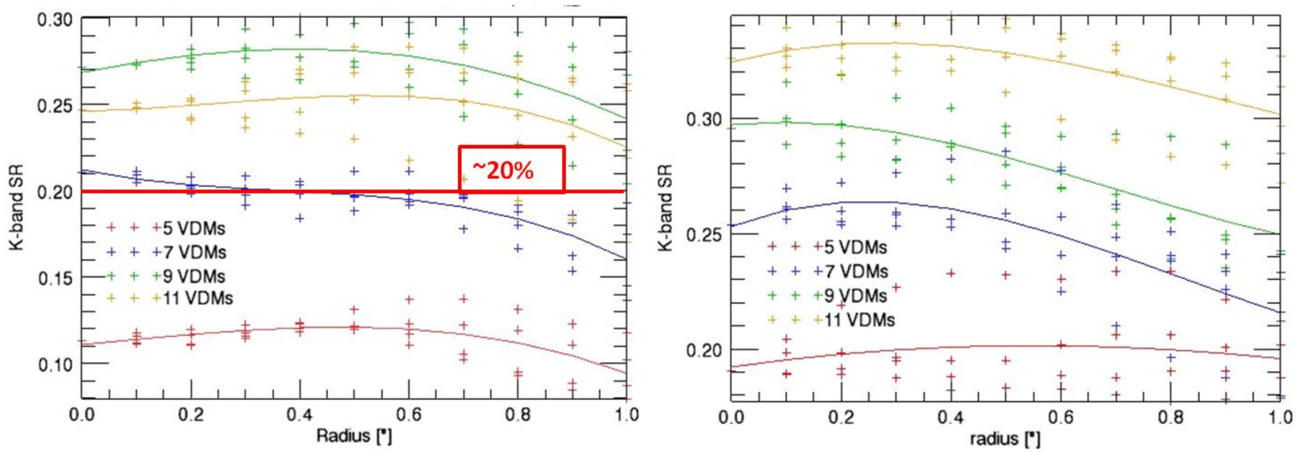

Figure 2 Performance obtained directly correcting with Virtual DMs (no projection onto actual DMs). *Left*: VDMs conjugated to non-optimized equidistant altitude. *Right*: VDMs conjugated to optimized altitude (turbulence a-priori knowledge required). Asterism consists in six NGSs positioned on a 2'radius circle.

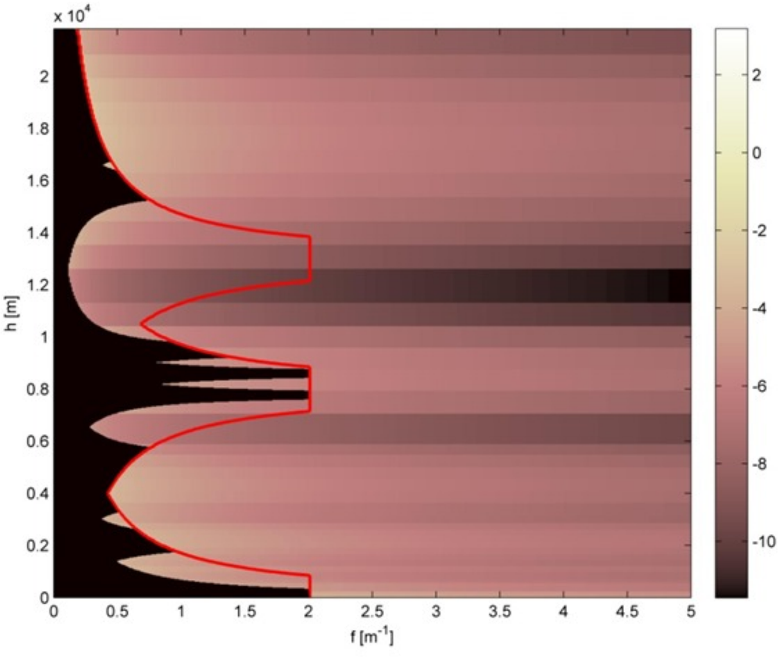

Figure 3 Frequency vs altitude plane. *Red line*: area of the plot accessible to real DMs (three, at the current nominal conjugation altitude of Maory DMs), correcting for a 2'scientific FoV. *Black area*: plane coverage limit for a number of Virtual DMs, "looking" at a technical 10' FoV. *Color bar*: C_n^2 strength in arbitrary units.

If we introduce a rough, first order, optimization of the VDMs conjugation altitude, in fact, the number of VDMs required to get a certain performance in terms of SR decreases. To verify this assumption, we computed the best positions of the VDMs in order to minimize the turbulence residual in the h-f plane, considering that, in principle, each of the VDMs has the capability to access (and, if properly driven, correct) only a specific area of such plane, as shown in

Figure 3. Figure 2, *right*, shows how the performance increase if the VDMs conjugation altitudes are optimized (and we expect there are many ways to do that in a more effective manner). It's noticeable, moreover, that the performance does not reach any maximum level for 9 VDMs, but it continues to get better as the number of Virtual DMs increases (please remember that in this simulation no noise on the measurements is introduced, so the only noise which could set a limit in the number of VDMs to be reconstructed is the computational one). The 20% SR level is easily reached also with five VDMs.

A crosscheck has been made also with popular results from Le Louarn[10], obtained for a six Laser Guide Stars asterism. In [10], the author computed the expected performance for different number of reconstructed layers that we can here consider as our VDMs. The corrector is a DM, which optimizes the on-axis performance. Figure 4 shows the results we obtain with the Tomographic Simulation Tool, compared with the ESO-Octopus gauge (*green lines*). *Black lines* report the performance obtained with an atmospheric correction performed using the Virtual DMs (which can be directly compared with the black lines), while *red lines* show the correspondent results, obtained with the 3 Maory-like DMs, to correct for a full 2' scientific FoV.

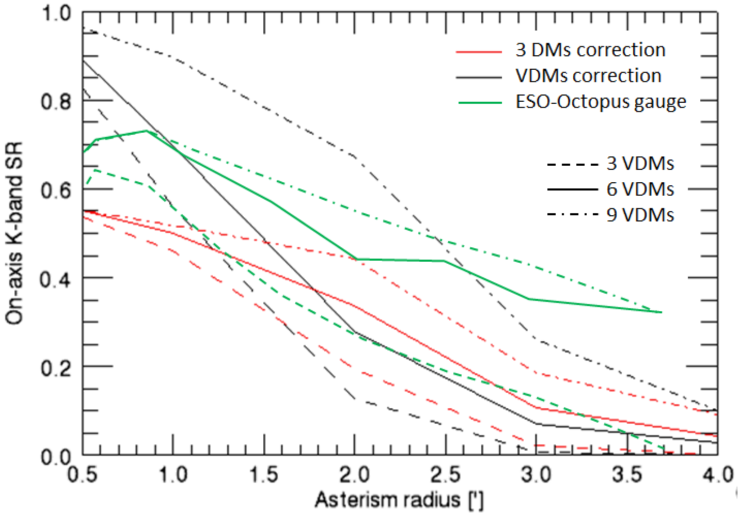

Figure 4 Performance obtained, for different number of reconstructed VDMs, directly correcting with the Virtual DMs (*black lines*) and after the projection onto the DMs (*red lines*), compared with ESO-Octopus results, obtained for Laser Guide Stars (*green lines*). Asterism consists in six NGSs positioned on a 2'radius circle. The atmospheric model used in this case is the 9-layers model from ESO.

What we here expect is the black and green curves in Figure 4 to be compatible, even if only at a first order comparison, because the codes complexities are very different and our tool only considers few error sources with respect to Octopus (remember the frozen atmosphere assumption, the infinite computing power, no noise introduced at the WFS level…). The results confirm expectations, with some major differences, which are, however, fully consistent with the intrinsic properties of the two AO systems, mostly related to the fact that we are considering NGS sources, while the black curves in Figure 4 are obtained for a LGS-based simulated system. For a low asterism radius, in fact, the better meta-pupil covering at high altitude, achievable with NGSs, allows for higher simulated performances. On the other hand, at large asterism radii the LGS system can take advantage of the fact that some of the rays entering the pupil are actually coming from skewed angles which are lower than the nominal asterism radius itself, allowing for a better performance. For actual GMCAO correction (correction projected onto 3 DMs – red lines in Figure 4) the on-axis peak Strehl Ratio is lower, because the system is optimizing for the full field of view, but the performance is more stable for variation of the number of Virtual DMs.

5. SKY COVERAGE ASSESSMENT

To assess the system sky coverage, we decided to focus on the South Galactic Pole (SGP) area, trying to deal with the most star-poor cases. We started simulating a number of South Galactic Pole-like fields, in the following way: we assumed a fixed number of NGSs on a "typical" polar field, for a set of magnitude bins; we then generated random positions of the stars inside the FoV and randomly assigned the expected magnitudes. One hundred fields were generated in this way. The number of stars for each considered magnitude corresponded to the predicted longitudinally averaged field star values based on the Bahcall-Soneira model in R-band for a square degree, scaled to our technical FoV size and shape and rounded to the higher magnitude bin (integer) value. For each simulated field, a total of 46 stars were randomly positioned in a 5' radius area, the expected magnitudes (from 13 to 20 mag) were randomly coupled with the sources, and the stars in the scientific 2x2 arcmin FoV were neglected, together with the stars with a relative separation lower than 10". Once all the simulated fields were generated, we compared the performance obtained using different subset of six stars as references for the GMCAO. Being it only a statistical first guess, we do not report here the full set of results for this first simulation and other sensitivity analysis. The main output, however, is a median SR ranging from about 10% to 20%, depending on the limiting magnitude considered.

After the simulated fields, we repeated the same exercise for real SGP fields, using USNO-B1.0 catalogue data for stars R-band magnitude and astrometry. In this case, we selected one hundred 10' Technical fields on a 10x10 grid with a 5' pitch, so to sample a quite large area (~1deg^2).

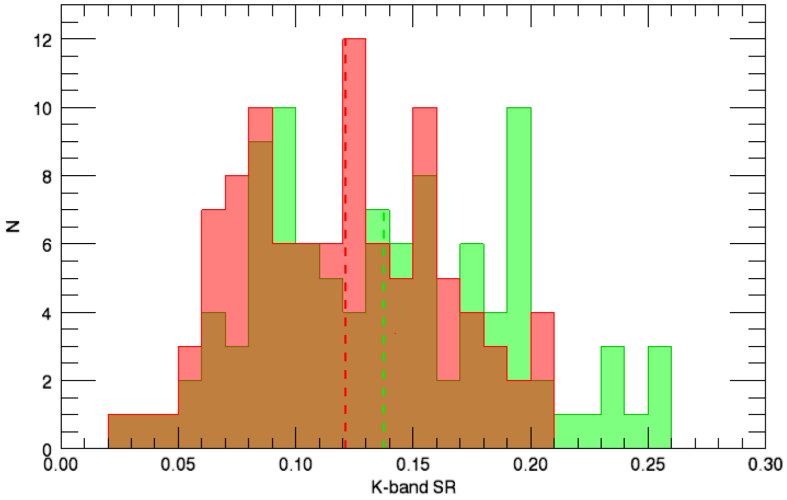

Figure 5 Simulated performance occurrence for 100 real fields in the SGP area. The technical FoV is 10' in diameter, while the scientific FoV for which the DMs are optimized is 2'. The limiting magnitude is 18 in R-band. *Red:* mean Strehl Ratio in a 2' FoV. *Green:* mean Strehl Ratio in a Micado-like FoV (~50" square). The dashed lines represent the median values obtained from the SR data.

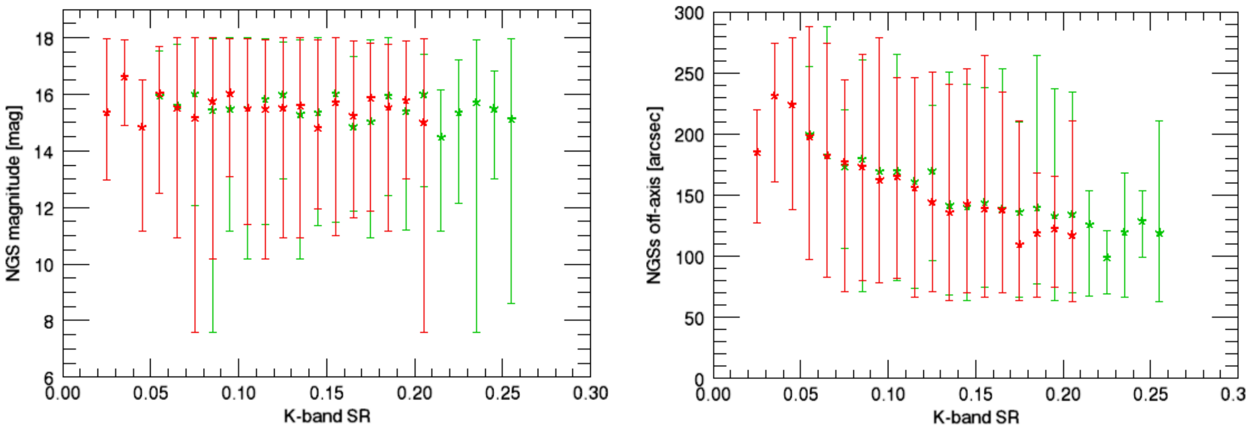

Figure 6 Parameters related to the 100 real fields in the SGP area, corresponding to the SR performance bins shown in Figure 5. *Left:* NGSs mean magnitude for each SR bin. *Right*: NGSs mean off-axis position for each SR bin. The plotted bars are not error bars, but represent the whole intervals in which the parameters range for each SR bin.

Figure 5 shows the result of the described SGP simulation, in terms of average K-band SR inside the optimized 2' FoV and a Micado-like FoV (~50" across). The median SRs resulting for the simulations are 12% and 14%, respectively, which we consider quite decent results for a first-order simulation (see Section 6, for the discussion). While the mean NGS magnitude for each of the histogram bins seems to be quite stable, Figure 6 (*right*) shows a clear dependence of the system performance on the mean off-axis of the selected references. This result is quite expected: when all the other parameters are fixed (technical FoV, number of NGSs and VDMs) or only slightly changing (NGSs magnitudes), the closer the references to the FoV to be corrected, the better the performance that can be reached.

6. CONCLUSIONS

We obtained a median K-band SR of ~14% for a Micado-like FoV looking at the SGP area. We consider this an encouraging result, because, even if some simplifications are intrinsic to the code, there still is margin for improvement. First, we must consider that this value is representative of the South Galactic Pole, which is intrinsically star-poor and we should expect better SR in other fields. We already made some steps in analyzing other scientifically interesting fields[11], not reported here. As I already mentioned, the 40-layers turbulence model includes very high layers, above 20km. Recent works on this field[12], however, seem to consider such a stratospheric turbulence quite negligible, especially above 20km. Keeping the same Fried parameter, a more compact atmosphere would increase the performance of any MCAO system, but GMCAO is especially sensitive to the atmospheric model altitude, due to its wide technical FoV, so larger improvements are expected. New (and lower) 35-layers models should be available in the next future for further analysis. As pointed out earlier, the WFSs noise injected in the loop is the value measured on-sky by FLAO@LBT. Any further gain which could arise using a pyramid WFS on an ELT instead of an 8-meter class telescope is not considered here. Finally, we recall that the code follows a purely geometrical numerical Layer Oriented approach, without any a-priori information about the atmosphere, which would help the Virtual-DMs shape optimization.

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