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GMCAO for E-ELT: a feasibility study

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ABSTRACT

In this paper, we discuss the feasibility and the performance assessment of a possible MCAO system for E-ELT, based on the novel concept of Global MCAO, which takes advantage of a very wide technical FoV to perform adaptive optics correction using only natural guide stars, with the aim to increase the sky coverage. The technique envisages the definition of Virtual-DMs, as tools for the global reconstruction. This investigation has been carried out during a feasibility study we performed for ESO, in which we combined computations, simulations and literature. The aim of this analysis is to identify and review the main parameters and the technical issues, which would act as error sources in a real GMCAO system, evaluating their contribution to the overall performance. The study involves both issues related to the Pyramid WFS in general, and to the GMCAO case in particular, including the wavelength and FoV size selection, the number of guide stars and reconstructed Virtual-DMs, and actual components parameters.

Keywords: GMCAO, Pyramid WFS, Simulations

1. INTRODUCTION

Global MCAO[1] is a technique proposed a few years ago, aiming to perform MCAO[2] on a relatively small Scientific Field of View, taking advantage of a much larger technical Field of View to find suitable reference stars, with the goal to increase the overall sky coverage. The technique itself combines a number of concepts, some of them already well known or even proven on sky, including the Pyramid wavefront sensing[3] and the Layer-Oriented technique[4].

In this paper, we report a summary of the main results obtained during a study we performed for ESO, aiming to show the conceptual feasibility of GMCAO on the E-ELT (European Extremely Large Telescope[5]), and to identify, under some assumptions and approximations, the main issues to be analyzed, with the final goal to assess the performance, which can be expected applying this technique.

2. GMCAO RECIPE

Given a MCAO system, with a known number of correcting devices (e.g. Deformable Mirrors, DM) conjugated to different atmospheric altitudes, the goal of a wavefront sensor aiming to retrieve the information required to properly control the loop is to sample the atmosphere in the most efficient way. A certain turbulence profile can be described with a C_n^2 function and depicted as done in Figure 1 (*left*) in the spatial frequencies vs conjugation altitude plane (*h-f plane*). The area which can be accessed by three DMs conjugated to 0, 4 and 12 km, aiming to correct for 2 arcmin FoV, is the one inside the red line: the best way to sense the atmospheric turbulence, to be then corrected with this AO system, is trying to fill the area inside the red line itself. To do that, GMCAO technique introduced Virtual DMs (VDMs), which are numerical entities evolving in an optimization loop, taking information from a larger FoV (here we consider 10 arcmin), represented by the black shadow in Figure 1 (*left*). A wider technical FoV translates into a higher probability to find suitable references, but it reduces the depth of focus of the VDMs, requiring a larger number of VDMs with respect to the real DMs. Once the shapes of the VDMs are optimized, the correction is back-projected onto the real DMs.

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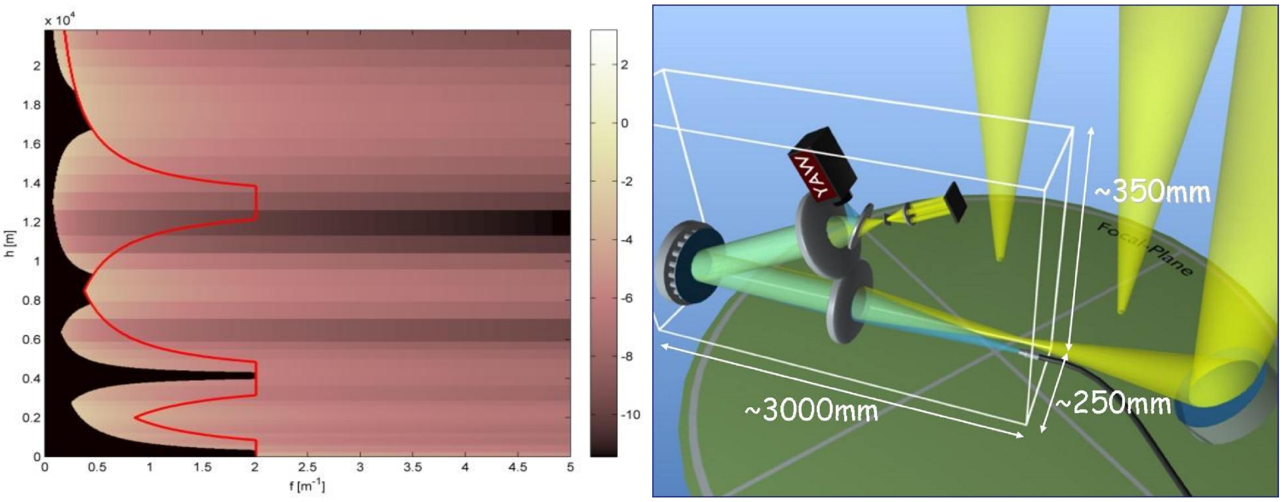

Figure 1 *Left:* Atmospheric turbulence (ESO 40-layers Paranal profile, see also Figure 3, *left*) in the frequencies vs altitude plane. The red line defines the area accessible to an AO system using three correctors aiming to optimize a 2 arcmin FoV, while the black areas represent the frequencies, which are sensitive to VDMs taking information from a wider 10 arcmin FoV. *Right*: sketch of the VL-WFS, as described in [7].

The optimum number of VDMs to be used is related to the technical FoV size, because of the FoV vs thickness rule ([6]), while the required number of WFSs (or references) can be linked to the probability to properly fill the meta-pupil, and to statistical considerations on NGSs availability in poor fields. In GMCAO, the reference stars are outside the scientific FoV to be optimized, so the system delivers only a partial correction to the WFSs themselves, even in closed loop. For this reason, the WFSs will always see a quite large aberration. In order to take advantage of the high sensitivity of a Pyramid WFS (PWFS), we devised an optical configuration in which the loop is locally closed with a small DM on-board each arm, to let the pyramid work in its best regime (see Figure 1, *right*). The residuals measured by the PWFS are then combined with the shape of the local mirror, either retrieved with an optical referencing system or capacitive sensors on the DM itself. We call this Very Linear WFS (VL-WFS)[7]. As one can imagine, a number of issues shall be investigated, in order to select the parameters for which finally assess the performance. In the next Sections, we summarize the main analyses done to quantify, usually in a first order approximation, the main parameters of a GMCAO system to be used on board the E-ELT.

3. PYRAMID WFS ISSUES

The first block of issues considered in this study concerns the PWFS concept. In fact, the results of these analyses are not only applicable to the GMCAO technique, but also to other concepts involving the use of PWFSs in different configurations.

3.1 Gain in limited Strehl Ratio regime

To estimate the gain in limiting magnitude of a non-modulating PWFS with respect to a Shack-Hartmann WFS (SHWFS), we extended the analysis performed in [8] to the case in which only a partial correction is obtained, that is to say the Strehl Ratio (SR) is lower than 1 in closed loop. The analysis has been already presented in [9]. Figure 2 (*left*) shows the maximum gain in limiting magnitude for an E-ELT-like telescope as a function of the SR, for different wavelengths, in a low SR regime. We learned from FLAO@LBT results ([10]) that, if we focus on the faint-end regime, say NGSs fainter than 15 mag, the maximum SR which can still be achieved is between 0.2 and 0.3, depending on the wavelength in the NIR band. In this regime, we expect the PWFS to show a gain in magnitude with respect to an equivalent SHWFS up to about 1.5 mag, which is still a non-negligible increase. In Section 4.2, we also consider the effect of a lower spatial sampling on the local DM.

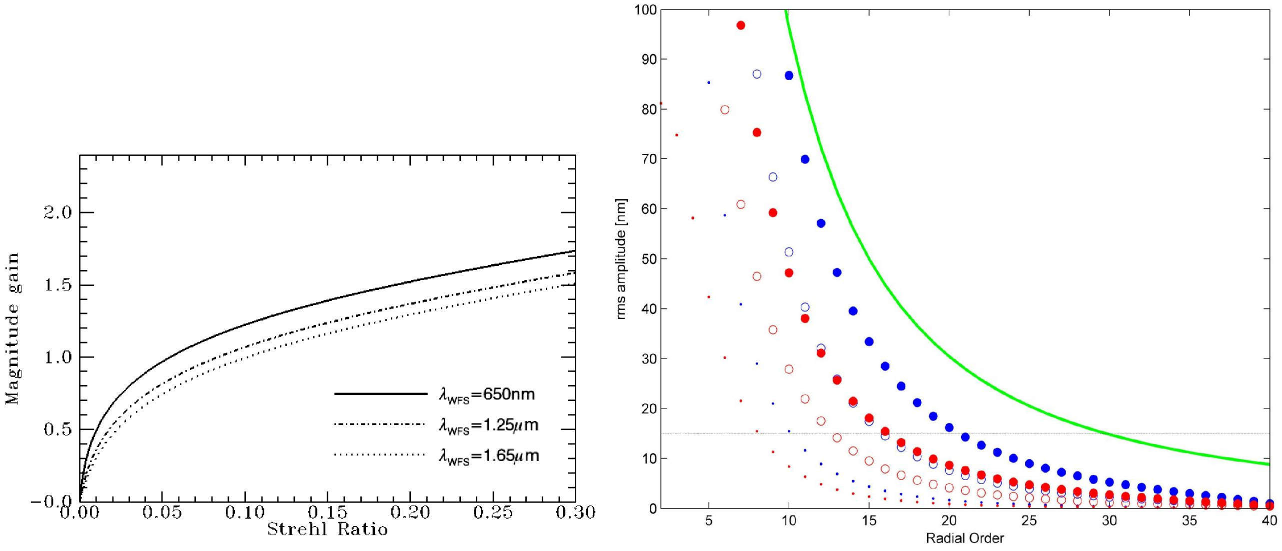

Figure 2 *Left*: Gain in limiting magnitude of a PWFS with respect of a SHWFS in closed loop, as a function of the SR delivered to the WFS, for different wavelengths. *Right*: non-linearity error of an ideal PWFS, as retrieved in [9] at λ=1.4μm. The *green line* represents a typical amplitude for the aberration on a single mode (Von Karman spectrum), while the *dots* show the aberrations for the non-modulated (*blue*) and 3*λ/D* modulation (*red*) cases. The *small dots* report the single mode non linearity error, the *empty circles* represent the overall effect on each radial order and the *filled circles* are the cumulative residual non linearity error, once the lower radial orders are perfectly corrected by the system.

3.2 Linearity

As already mentioned, in GMCAO, the PWFS works in closed loop with a local DM to enter the regime where the sensitivity is higher. The residual measured by each WFS has then to be properly added to the measurement achieved on the DM. To establish the effect of Pyramid non-linearity on such measurements we developed a full simulation with Fourier wave-optics propagation of a perfect PWFS. This analysis is described in [9], thus here we only report the final result. Let us just recall here that since the non-linearity error for a given mode depends on the absolute input aberration, we introduced in the analysis an assumption on the atmospheric aberrations strength to retrieve the residual global non-linearity error. The latest has been estimated as the cumulative RMS sum of non-corrected modes, assuming an AO system perfectly correcting the wavefront aberration up to a certain radial order, which we can assume as half the number of actuators on a diameter. Given the results reported in Figure 2 (*right*, *blue dots*), we assumed to correct 20 radial orders, translating, as a first approximation, into a need of 40 actuators on a diameter and adding about 16 nm of Wavefront Error (WFE) due to non-linearity to each WF measurement, which we consider an acceptable compromise.

3.3 Modulation

A possible way to decrease the non-linearity consists in the insertion of a relative small modulation (a few *λ/D*) of the PWFS. The effect for 3 *λ/D* is shown as *red filled circles* in Figure 2 (*right*). In the 20 radial orders case, for example, we obtained a decrease of the WFE rms amplitude to less than 10 nm. In literature (e.g. [11]), we can find studies which show that the introduction of a small modulation on the Pyramid results in a negligible decrease of performance in terms of SR and, then, in sensitivity. Anyway, we decided to keep the non-modulating approach as a baseline.

4. VL-WFS ISSUES

This Section explores some issues related to the Very Linear WFS. For the time being, we did not investigate the referencing system, if required, but we concentrated on the main parameters for the local DM and the detector.

4.1 Local DM dynamic range

In the configuration we assumed for the E-ELT case, the VL-WFSs will pick up the light from the outer region of MAORY[12] entrance focal plane. This means that each VL-WFS will see the Ground-Layer correction performed by M4, reducing the local DM stroke required to close the loop. To estimate the order of magnitude of the residual medium and high layers turbulence, we used ESO 40-layers atmospheric model (see Figure 3, *left*), assuming a Fried parameter of about 0.13 m at a 500 nm wavelength. Simulations report a residual perturbation whose peak-to-valley value ranges between 5 to 7 μm, translating into a local DM stroke requirement of 2.5 to 3.5 μm.

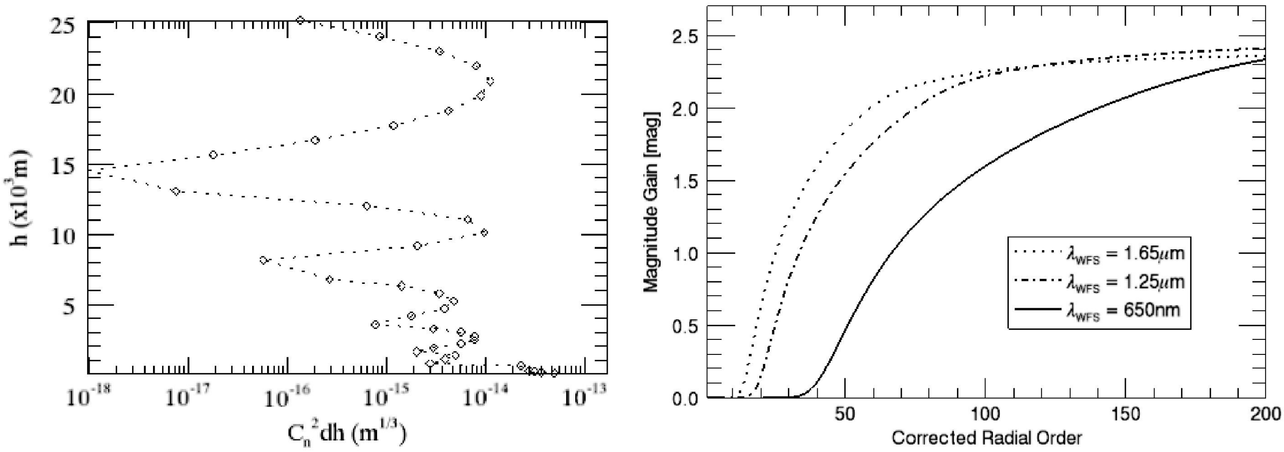

Figure 3 *Left*: C_n^2 profile of ESO 40-layers atmospheric model for Paranal. A 30° off-Zenith projection is included in the *h* values. *Right*: magnitude gain of PWFS vs SHWFS depending on corrected radial order.

4.2 Local DM spatial sampling

A further parameter to be assessed is the required minimum local DM spatial sampling. In the VL-WFS, in fact, changing the number of actuators of the local DM, the maximum SR that can be achieved on the pyramid pin changes. It translates into different sensitivity (or gain in magnitude) and different non-linearity error. A poor spatial sampling of the local DM, of course, limits the number of modes, which can be corrected. As we already mentioned, the pyramid non-linearity analysis results show that at least 40 actuators on the diameter are required to keep the rms WFE below 20nm (without modulation). On the other side, a local correction limited to low orders also affects the Pyramid gain in sensitivity. Figure 3 (*right*) shows our estimation of the magnitude gain reduction due to a limited correction in terms of radial order for different wavelengths. In the case of 20 radial orders corrected by the local DM, we can see that 0.5 mag can still be gained, if the NIR bands are considered.

4.3 Detector sensing wavelength

As mentioned in the previous Section, to take advantage of the gain of the PWFS in the locally closed loop, either an extremely large number of actuators (>100, which seems not to be practicable) in the local DM or a NIR sensing wavelength (~40 actuators) is required. Generally speaking, we found that, as a rule of thumb, to obtain a Δ*mag* higher than 0 mag, 1 mag and 2 mag, the spatial sampling of the pupil shall have a pitch lower than 5-6r_0, ~ 3r_0, and ~ r_0, respectively (*paper in preparation*). Because of this, it seems mandatory to stick to NIR band (J to H) for the Very Linear wavefront sensing.

5. GMCAO ISSUES

The last issues analyzed are related to the GMCAO technique as a whole. They include the optimization of the number of VDMs and references, taking into consideration the additional information, which could come increasing these numbers, but balancing it in order to keep the complexity of the system at a reasonable level.

5.1 Number of Virtual DMs

Which is the best compromise in the number of VDMs to be used? As it can be understood looking again to Figure 1 (*left*), of course, the higher the number of virtual DMs, the better the turbulence reconstruction, since the area in the *h-f* plane which is accessible to the DMs is better sampled. However, at some point, the noise associated with each VDM will start to play a significant role and after a certain number of reconstructed layers, the advantage will become negligible. In order to estimate the number of VDMs necessary to obtain a given correction, we introduced the VDMs, one by one, and we computed the residual in the frequency vs altitude plane, assuming that each virtual DMs is capable to correct perfectly all the spatial frequencies inside the black areas in Figure 1 (*left*).

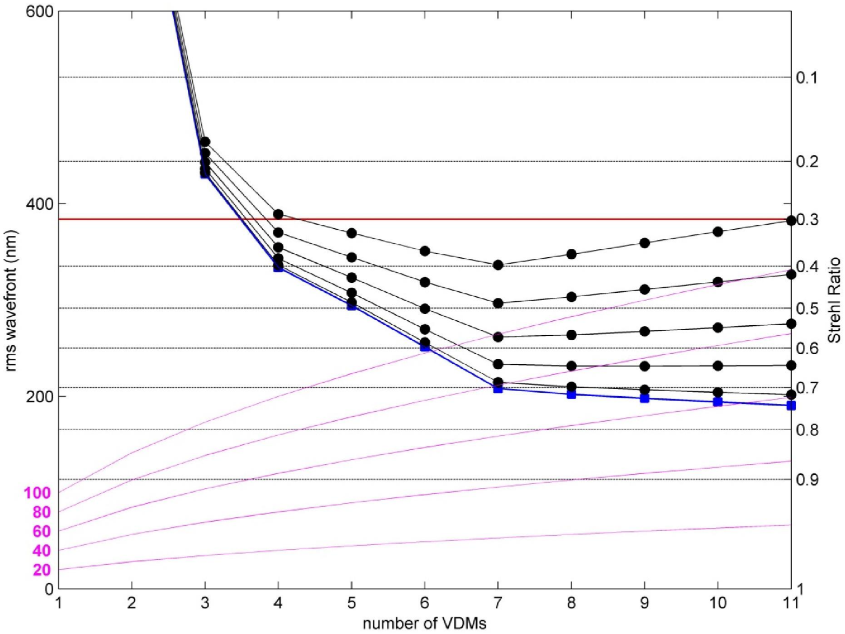

Figure 4 Noise introduced onto the wavefronts measurement increasing the number of the VDMs. *Blue circles* represent the turbulent residuals, obtained perfectly removing the power at the frequencies accessible both to VDMs and DMs in the *h-f* plane. *Magenta curves* represent the cumulative noise to be associated to the increasing number of VDMs, for different noise levels assumed for a single VDM. Finally, the *black circles* correspond to the WFEs obtained combining the atmospheric residuals to the VDMs noise.

Figure 4 shows the residual WFE, which can be expected increasing the number of VDMs in the system, assuming ESO 40-layers atmospheric profile and different noises to be associated to each VDMs. The resulting region in which we can still appreciate a decrease in the WFE is ranging from 4 to 7 VDMs, for the considered noise levels. To limit the system complexity, we fixed the number of VDMs to 6 for the performance estimation.

5.2 Number of arms (VL-WFSs)

The number of WFSs to be implemented is another key parameter, since it limits the maximum number of references, which can be used to retrieve the atmospheric behavior. First of all, we do not want to be limited in the possibility to use bright stars in poor star fields (if they are available) by the number of arms. Then, how many stars brighter than about 15 mag (limiting magnitude we already used as a threshold in Section 3.1) can we expect to find in a 10 arcmin diameter poor field? Using a statistics, based on Bahcall-Soneira model ([13]), we can obtain that the median value for the number of suitable stars in a South-Galactic-Pole-like field is 5. We then decided to set this as the minimum value for the number of arms. We then performed a further check on the probability to cover the metapupil with a different number of stars in a random asterism. Generating synthetic stars fields, we computed the 2 arcmin metapupil fraction coverage probability at high altitude (maximum altitude considered in the ESO 40-layers Paranal atmospheric model) as a function of the number of NGSs in the 10 arcmin FoV. We obtained that with 6 stars randomly distributed, we already have a very high probability (approximately 1) to cover at least the 70% of the metapupil, computed at 25 km altitude.

In the baseline design we proposed, then, we assumed to implement 6 arms, which is a good compromise between the reported results and the need to increase too much the opto-mechanical complexity.

6. PERFORMANCE ASSESSMENT

The last bullet in our list was an assessment of the sky coverage. Being this parameter related to the kind of performance required by the scientific case considered, we decided to estimate it computing the SR over the FoV for different NGSs densities. We implemented an IDL code simulation tool to compute the resulting SR in a 2 arcminutes FoV varying the following parameters: number, positions and magnitude of NGSs, technical and scientific FoVs sizes and number and conjugation altitude of VDMs.

Some details of the simulator have been described in [14]. Basically, to produce the synthetic atmosphere, we used the already mentioned C_n^2 profile of the ESO 40-layers Paranal turbulence model, with a seeing value of about 13 cm at 500 nm wavelength, and a modified Von Karman spectrum, with an outer scale of 25 m. We then fixed the main GMCAO parameters (number of VL-WFS, spatial sampling, residual noise…) and considered a certain distribution of stars in the field, in order to produce the un-corrected wavefronts. Then, after defining the VDMs conjugation altitude (without any a-priori information from the C_n^2 profile), a loop optimizes the shape of the VDMs, in order to minimize the residuals on the wavefronts detected by the WFSs. An infinite computing power is assumed, namely, the loop speed is not optimized and the number of iterations is the one required to obtaine the desired residual on the wavefronts. Once the VDMs are optimized, their shapes are projected onto the real DMs, in order to enhance the correction only in the central part of the field (2 arcmin).

Therefore we started producing synthetic fields with star density comparable with the South Galactic Pole (SGP) ones (star-poor example). For each generated field, we randomly positioned a number of stars in a 10 arcmin FoV; the expected magnitudes (obtained from statistics based on Bachall-Soneira model) were randomly coupled with the stars positions and the stars in the scientific 2x2 square arcmin FoV or with a relative separation lower than 10 arcsec were neglected. Figure 5 (*left*) shows the result of 100 runs, obtained changing the selection criteria for the 6 NGSs to be used as references, in terms of limiting magnitude and distance from the inner 2 arcmin FoV. The median SR obtained is ranging from about 0.06 to 0.17.

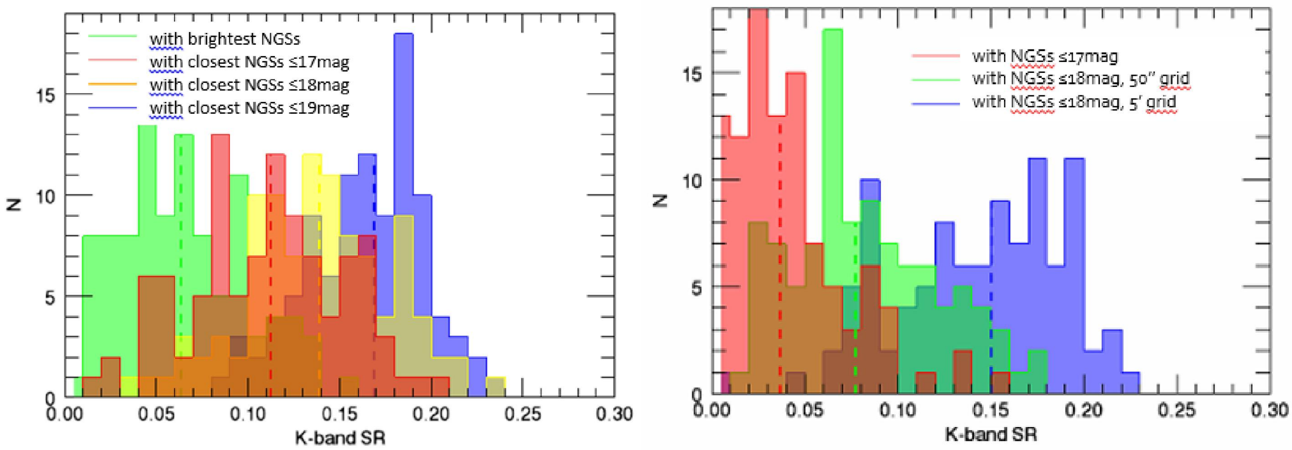

Figure 5 SR occurrence for different stars selection criteria in the SGP synthetic fields (*left*) and the CDFS real fields (*right*). Dashed lines represent the median values for each set.

Analogously, we compute the expected SR on real fields. In particular, the results obtained for the Chandra Deep Field South (CDFS) are shown in Figure 5 (*right*). In this case, the 100 determinations were obtained shifting the center of the FoV on a 10x10 grid, either with 50 arcsec (MICADO[15]-like size) or 5 arcmin (to better sample the area) pitch. The median SR obtained for the 18 mag limiting magnitude in the more spaced grid is about 0.15, which is comparable with what we found for the SGP and the mean SR is 0.17. The resulting Strehl map has been used as a starting point in [16] to investigate the performance of the GMCAO in an extragalactic science case.

7. DISCUSSION ON PERFORMANCE

When comparing the results shown in Section 6 with corresponding assessment performed for other techniques, we have to keep in mind some things that make this particular estimation very conservative. First of all, a purely Layer-Oriented-like approach has been used for the reconstruction of the VDMs shapes, avoiding any a-priori knowledge either of the C_n^2 profile strength or of the layers altitudes. The DMs configuration used for the simulation is the MAORY baseline (0 km, 4 km, 12.5 km conjugation altitude), which is not optimized for the 40-layers atmospheric model. To take into account the effect of different NGS magnitudes, we gauged the noise that we introduced onto the measurements on the results, in terms of SR, obtained with FLAO, so any further gain in sensitivity, going from 8 m to 40 m class telescope, was not considered. Last and maybe most important, the atmospheric model (which is far more pessimistic than most – if not all – the models usually considered) plays a major role in the results. As it can be seen in Figure 3 (*left*), in fact, an important part of the overall turbulence (20% of the residual, once removing GL<1 km) is situated above 20 km in altitude. This corresponds to the volume in which the metapupil is sampled in the poorest way (often with light coming from only one star) and this affects significantly the resulting SR. Just to have the feeling of this, we performed the same test (18 mag limiting magnitude, 5 arcmin grid) on a mock atmospheric model in which the turbulence strength was set to zero above 20 km (of course re-normalized to get the same seeing value).

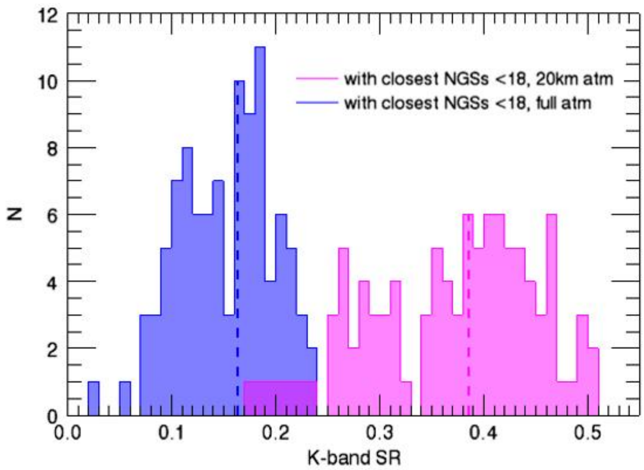

Figure 6 Comparison of the SRs resulting from the same test performed with the full ESO 40-layers Paranal model and a model in which the turbulence was confined below 20km. Dashed lines represent the median values for each set.

The result of the comparison is shown in Figure 6, where the median SR obtained with the thinner atmospheric model is twice the result we can get with the full ESO 40-layers atmospheric model.

8. CONCLUSIONS

We reported here the results of the analysis and simulations carried on during the GMCAO feasibility study for E-ELT. Such analysis has been performed under a number of assumptions, some of them related to the GMCAO system overall baseline layout, whose main parameters have been derived in this paper. These are the number of arms and Virtual DMs (both six, in the performance assessment), the 10arcmin diameter Technical FoV, the sensing wavelength (NIR) and the local DMs parameters (sampling: ~40 actuators on a diameter). Other major assumptions, described in the previous Sections, have been made in the performance and sky coverage simulations. Using a tomographic simulation tool, we estimated a median expected SR of 0.15/0.17 in very poor, but scientifically appealing, star fields. Even if very conservative, the results we obtained make us confident that the GMCAO system can provide interesting performances in very poor fields, which are prohibitive for most of the other AO techniques, giving the possibility to explore different scientific, mainly extra-galactic, cases also in these peculiar areas of the sky.

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