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MCAO numerical simulations for EST: analysis and parameter optimization

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ABSTRACT

The European Solar Telescope (EST) will be a new generation Solar telescope with the challenge of achieving a corrected field of view (FOV) of 1 arcminute with a minimum Strehl of 40% in the whole range of elevation angles of observation. For this purpose the EST will be equipped with a MCAO (Multi- conjugate Adaptive Optics) system. The proposed MCAO system for Solar telescopes combines a narrow and a wide extended Shack Hartman (SH) wavefront sensors (WFS) taking as references the spot or granulation of the sun. The number and position of deformable mirrors (DMs), the wavefront field of view (FOV), and asterism geometry have to be correctly settled as a function of the site turbulence conditions. We have performed numerical simulations using real turbulence profiles obtained at Observatorio del Teide in order to optimize the MCAO parameters for EST.

Keywords: Solar MCAO, wavefront correction, wavefront sensing,

1. INTRODUCTION

The new generation of Solar Telescope EST is a 4-m class telescope to be located in the Canary Islands. It will be optimized for studies of the magnetic coupling between the deep photosphere and upper chromosphere. To achieve these goals, the EST must provide high spatial and temporal resolutions, thus EST will have a unique powerful MCAO system. Conventional solar AO systems have been successfully implemented in GREGOR and VTT ([1]), two solar facilities working at Observatorio del Teide. The AO system is composed by one WFS and one DM to measure and correct the ground layer turbulence. Unlike night AO WFS, which measures the displacement of a star image centroid of each subaperture, the Solar AO WFS uses sun spot or sun granulation to make correlations between different subapertures. Therefore the FOV of the WFS must be large enough to ensure good image contrast for the correlations. We will analyze the limitation of such a wide WFS to retrieve the turbulence errors induced at high altitudes.

The corrected FOV is increased by using MCAO. The solar MCAO system proposed in this work has two WFSs, a high order wavefront sensor (HOWFS) for the center of the FOV, and a low order WFS (LOWFS) to sense field dependent aberrations originated at high turbulence layers. The MCAO optical design depends on the turbulence stratification with height above the telescope site. The aim of this study is to simulate the MCAO system for the EST to set the optimal configuration with the specific atmospheric conditions at Observatorio del Teide.

Another important issue to consider in a MCAO design is the order of conjugation of the turbulent layer with the DMs. For small perturbations, as is the case of infrared observations, the order of conjugation does not affect the performance of the system, while it has an impact in the case of visible observations.

We have used a simulation tool developed by Thibeaut & Tallon ([2]). The algorithm applied to reconstruct the wavefront is FRIM (FRactal Iterative Method), which allows an excellent tomographic reconstruction of the atmosphere. FRIM is an iterative method with fast convergence designed for the Extremely Large Telescope (ELT) with huge number of unknowns. To solve the regularized problem, they use the conjugate gradient method, which takes advantage of the sparsity of the wavefront sensor model matrix and avoids the storage and inversion of a huge matrix. They propose an effective preconditioning that yields the solution in five to ten conjugate gradient iterations for any number of unknowns, which is must faster than conventional AO method.

In the following we first describe how synthetic profiles are generated, and the baseline of the simulations. In section 3 we study the performance of the simulation as a function of number and position of DMs, and the FOV of the wavefront sensor. Finally we discuss in section 4 the impact of order of conjugation of turbulent layers with DMs.

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2. PARAMETERS OF THE MCAO SIMULATIONS

In order to optimize the performance of the Solar MCAO system a good knowledge of the site turbulence profile is required. The number and positions of the DMs are related to the seeing and turbulence profile distribution. Unfortunately there is no instrument able to measure the turbulence distribution at high altitudes during day time. Therefore we have generated Cn2 profiles combining real day and night data. Night data are measured with the SCIDAR ([3]) instrument, while day data are obtained from SHABAR instrument at Observatorio del Teide. Averaged day data have been calculated for different elevation angles. SHABAR provides reliable measurements up to 3Km in the line of sight. For convenience the profiles have been vertically projected. A synthetic profile is generated with day time data up to a height of 3cos(α), being α the zenith distance, whereas the contribution from 3cos(α) up to the upper layer H is filled with night time data. Night time data must be scaled according to the complete day time profile.
The synthetic profile is calculated as follows:

$$C^2_{n\_TOTAL}(0-H) = C^2_{n\_day}(0-3km) + C^2_{n\_night}(3km-H)\frac{\int_{3km}^{H} C^2_{n\_day}(h)dh}{\int_{3km}^{H} C^2_{n\_night}(h)dh}$$

Figure 1 shows the averaged night profile (green), an averaged day profile at sun culmination (red) and the combined synthetic profile (black). As noticed day turbulence is dominated by a very strong ground layer while night time turbulence is more distributed, aside of the ground layer, there is an important turbulent layer around 15Km.
We have run the simulations considering a profile with 21 heights (in meters) at zenith: 0, 1130, 2260, 3390, 4520, 5650, 6780, 7910, 9040, 10170, 11300, 12430, 13560, 14690, 15820, 16950, 18080, 19210, 20340, 21470 and 22600. The SH sensor computes correlations between subapertures to retrieve the wavefront. The FOV of the WFS is set to 10 arcseconds (in section 3.2 we discuss impact of this parameter on the performance). Subaperture sizes are set to 8cm for the HOWFS and 30cm for LOWFS, according to the averaged seeing. The choice of an asterism of 19 subfields has been discussed by Montilla ([4]). The statistics is done over 10 iterations. The wavelength is set to 500 nm. Our simulations are run in open loop, and no delay is included. In the next section we present the results obtained for different atmospheric conditions.

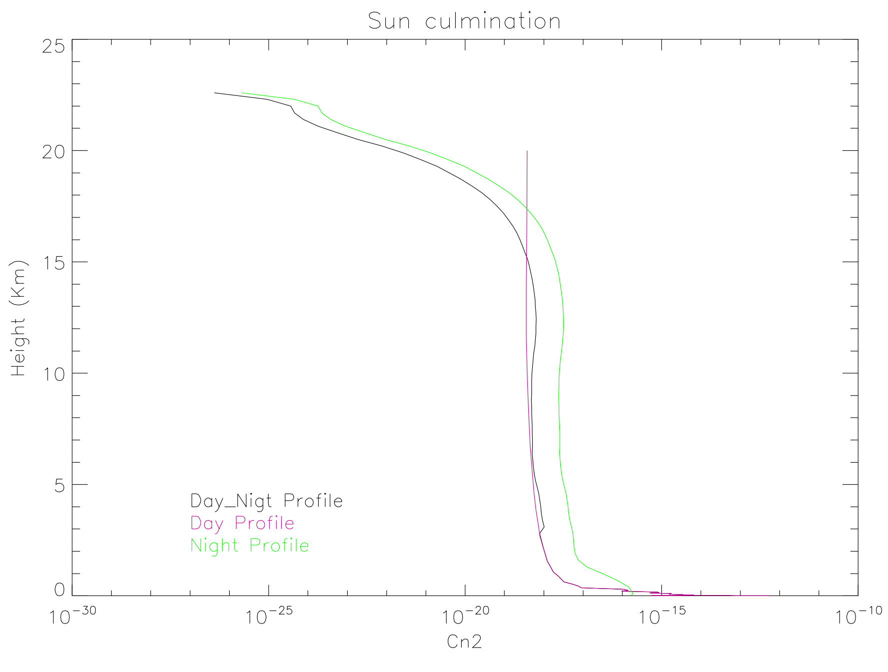

Figure 1. Cn2 profiles for day at sun culmination (red), night (green) and synthetic day-night (black)

3. MCAO PERFORMANCES

3.1 Performance with number and heights of DM

The technical requirements for the EST are very demanding in what regards spatial resolution; thus the goal is to achieve Strehl of 40% at all elevation angles in a FOV of one arcminute. The EST will be equipped with an MCAO system to enable such resolution. The optimal solution for a MCAO system is a set of DMs placed at different heights in such a way that a good performance at any elevation angle is enabled. The knowledge of the atmospheric profile distribution is critical for a good correction and optimal design. Most of the turbulence during day time is concentrated in the ground layer. During sun rise, seeing is better but high turbulent layers are more weighted. During the afternoon the seeing becomes worse but turbulent layers are lower. Even though most of the turbulence is concentrated in the ground layer (>90%), the pupil DM will not give a good performance in the whole FOV due the generalized fitting error ([5]). The thickness of a slab of turbulence to be efficiently corrected depends on the FOV and on the spatial sampling of the pupil. DMs must be perfectly conjugated at the height of turbulence layer in order to achieve good correction in a large FOV (1 arcminute) for a 4 meter class telescope. We simulated different configurations for synthetic atmospheric profiles and integrated seeing at different elevation angles. Figure 2 shows Strehl maps for 1 arcminute FOV. Blue circles represent the 19 directions of wavefront measurements, while stars represent the position where the Strehl has been estimated. A first conclusion assessed from Figure 2 is that at least 4 DMs are required for low elevation angles while 3 DMs suffice for high elevation angles. At low elevation angles turbulent layers move away: the 7 Km layer at 20 degrees moves to 20 Km, and this is the reason why a DM placed at 20Km can correct some turbulence while it introduces noise at elevation angles higher than 50 degrees. On the other hand the generalized fitting error increases for low elevation angles because the turbulence is more distributed, being requested more DMs to achieve a good correction. Under poor seeing conditions it is not possible to achieve good corrections for low elevations angles even with 4 DMs.

The study presented in this work includes only error fitting. When other error sources are considered, as delay or bandwith, the performance is reduced 40%, therefore at least 70% Strehl (including just error fitting) is required to achieve the MCAO requirements. Table 1 shows the minimum turbulence conditions to reach 40 % Strehl. As stated above, if the turbulence profile is more distributed, the integrated r_0 must be better. In any case this turbulence conditions comply with standard conditions at Observatorio del Teide.

Elevation (degrees)	**Cn ratio ground layer**	**r_0 (cm)**	**Height DMs (Km)**
20	95%	12	0,5,12,20
20	90%	18	0,5,12,20
80	80%	15	0,5,12
80	90%	10	0,5,12

Table 1. Minimum turbulence conditions requested at different elevation angles to achieved Strehl of 40 %

Elevation Angle: 80 degrees

3 DMs: 0km,5km,12km

4 DMs: 0km,5km,12km,20km

Elevation Angle: 20 degrees

3 DMs: 0km,5km,20km

4 DMs: 0km,5km,12Km,20km

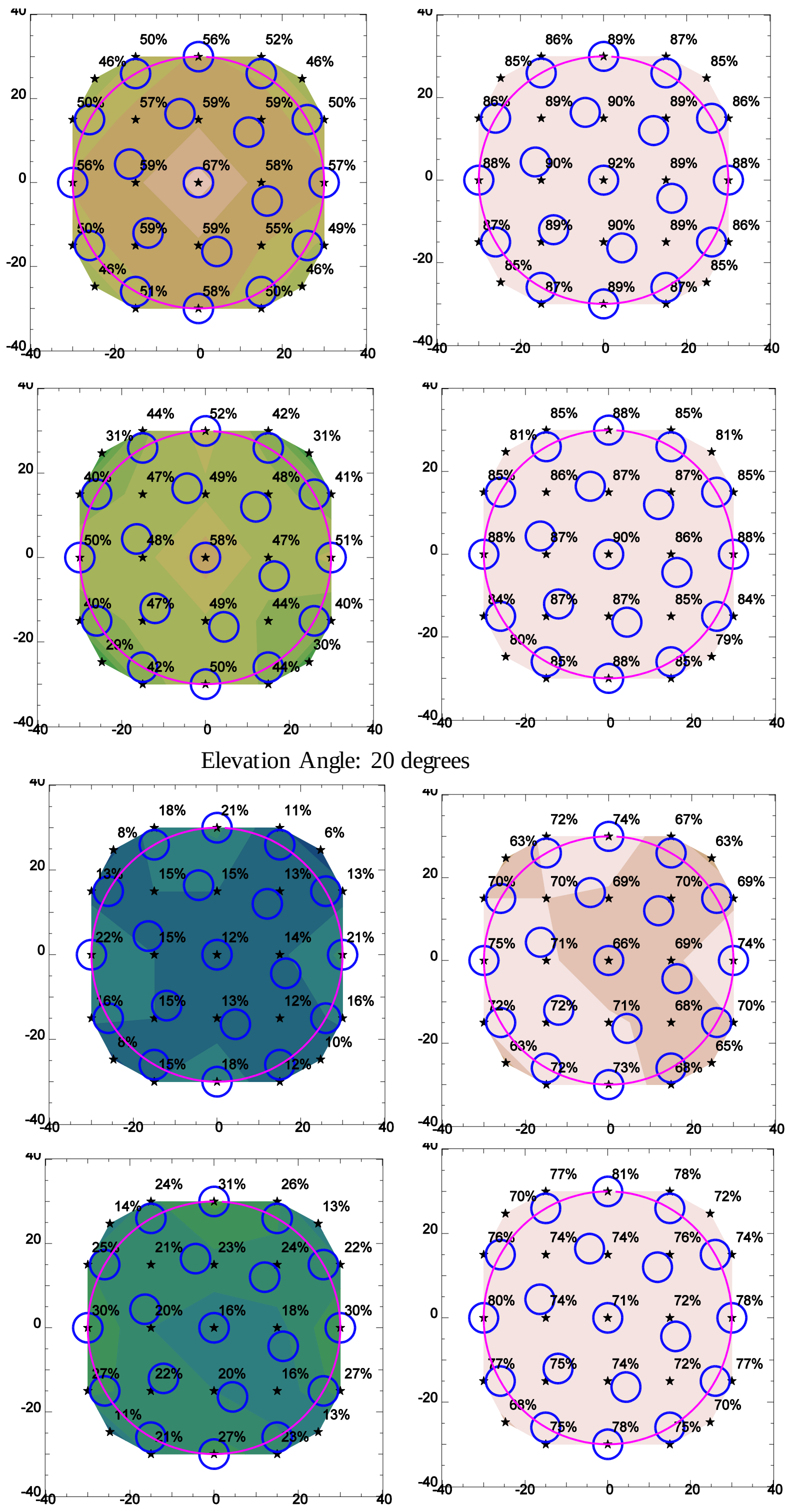

Figure 2. Strehl in 1arcmin FOV as a function of number of DMs, elevation angle and seeing conditions (left column: 10cm r0 and Cn ratio of 80% in ground layer, right column: 20cm r0 and 90 % in ground layer)

3.2 Performance with FOV of WFS

The WFS for Solar AO employs extended sources instead of point-like sources. The fact that the correlations are performed in extended objects with low contrast enforces to have a large WFS FOV. However the inconvenient is that the turbulence information from different direction at high altitudes is blurred. A minimum of 8" WFS FOV is necessary to compute correlations with images of the Sun. An analytical study of the effect of the FOV of solar WFS on the AO performance is presented in this conference ([6]). The performance of an MCAO is reduced while increasing the FOV of WFS. The capability of an extended WFS to retrieve the wavefront depends on the relation between the projection of the WFS FOV onto the turbulent layer versus pupil diameter. At low elevation angles turbulent layers are further away and the projection of the WFS FOV does not sample the pupil, therefore the wavefront is not correctly retrieved.

Figure 3 shows the Strehl of the MCAO system for different elevation angles. A profile with 93% Cn ratio on the ground layer and 10 cm integrated r_0 has been chosen, the DM set up is the same used in previous section. For high elevation angles the degradation is of the order of 10% between FOV of 8" and 16" while is increasing up to 20% for low elevation angles. It might be possible to decrease the FOV of the WFS for low elevation angles when contrast improves under good seeing conditions.

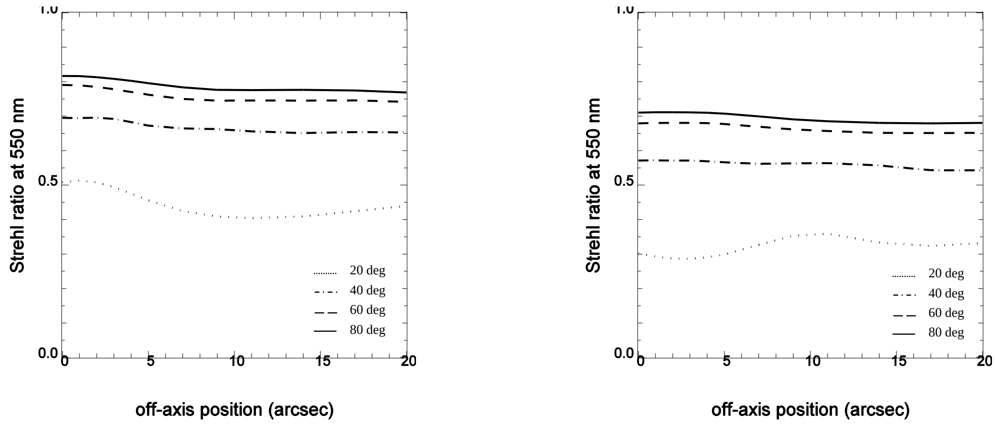

Figure 3. Strehl over the 1 arcminute FOV for different elevation angles (20, 40, 60 and 80 degrees) and FOV WFS of 8" (left) and 16" (right)

4. DEPENDENCE WITH ORDER CORRECTION

The aim of this study is to analyze non-linear effects due to wavefront propagation as a function of height and r_0 of turbulent layers. A wavefront propagating through a turbulent medium suffers phase and amplitude perturbations. For weak turbulence and short propagation distances, diffraction effects can be ignored. Thus amplitude variations are negligible compared to phase variations. In adaptive optics, deformable mirrors (DM) are able to correct phase deformation but not amplitude deformation, therefore amplitude residual errors must be negligible in order to achieve good image quality. The perturbations induced by turbulent layers can be corrected in the inverse order of layer occurrence. In that case perfect cancellation of phase and amplitude is achieved, with the drawback that each layer has to be reimaged using relay optics, as showed in red, Φ'_H in Figure 4 . Furthermore, residuals in phase and amplitude remain if correction is applied in the order of layer occurrence, i.e. when the turbulent layers are optically conjugated with the DMs, as showed in black, Φ'_H in Figure 4. Our simulations have been designed to quantify this residual amplitude and phase error as a function of the position and seeing of high turbulent layers.

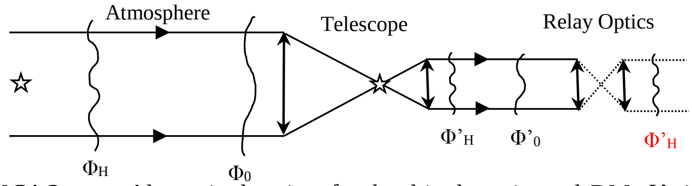

Figure 4. Schematic two DM-MCAO setup. Alternative locations for the altitude conjugated DM: Φ'_H in red with reimaging of upper turbulence layer behind the conjugation of ground layer (direct correction) and Φ'_H in black without reimaging (inverse correction).

For this purpose we have used PROPER ([7]). It is a code written in IDL which simulates the change in the electromagnetic field of the wavefront along a given trajectory. We have simplified our study and consider propagation of the wavefront through the entrance space. The turbulence has been simulated with static phase screens following a Kolmogorov statistic placed at different heights. The correction has been done with the same phase screens but with opposite sign. Figure 5 shows Strehl for residual amplitude, phase and total error as a function of the position of the higher layer for a two layer model if the correction is done in the order of turbulence layer occurrence. The degradation due to uncorrected amplitude variations is of the order of 10% while the uncorrected phase fluctuations degrade the performance up to 60% as the layer moves away. In the following we ignore the amplitude errors induced by the wavefront propagation and we focus our study on the phase errors.

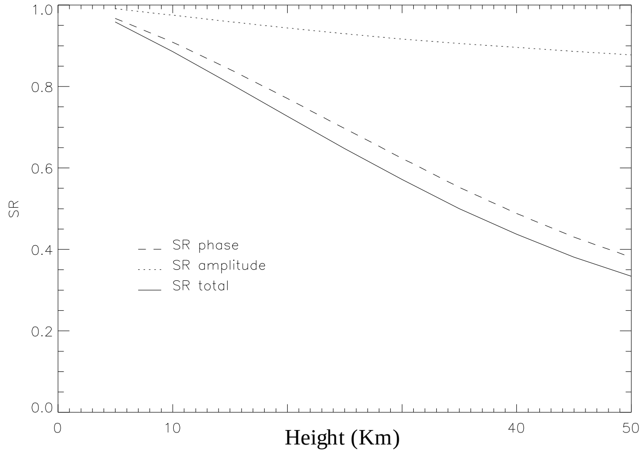

Figure 5. Strehl as function of the height of high layer with 30 cm seeing and ground layer seeing of 15 cm.

We have analyzed two correction approaches. In the first one, hereafter the direct correction, the correction is applied from the higher to lower layers. In the second approach, hereafter the pseudo-inverse correction, the ground layer is first corrected and thereafter the higher layers from the upper to the lower. This last case is the one employed at GREGOR telescope. We have used the same synthetic turbulence profile as described in section 2. The results are plotted in Figure 6. In the pseudo-inverse case (left), the Strehl is reduced by less than 5% in most cases. For low elevation angles, thus turbulent layers are further away, the Strehl decreases for poor seeing (less than 10cm r_0). On the other hand, in the direct case the Strehl drops down to 50%. From this analysis we conclude that the order of correction is relevant for elevation angles lower than 40 degrees and r_0 less than 15cm, therefore a pseudo-inverse correction must be applied to ensure good performance at any elevation angle.

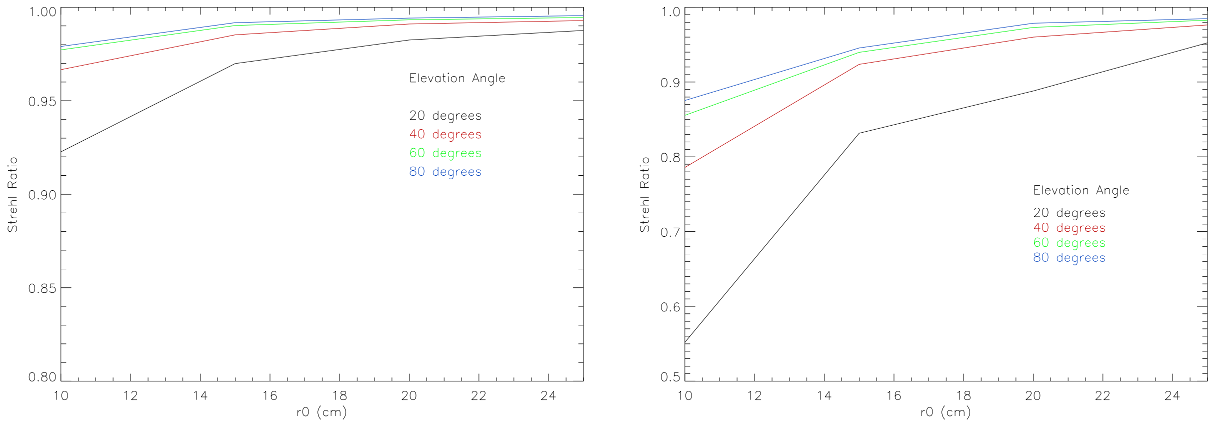

Figure 6. Strehl as a function of r0 for different elevation angles (20,40,60 and 80 degrees),left: pseudo-inverse correction, right: direct correction.

5. CONCLUSIONS

In this paper we have analyzed the performance of the MCAO system for the case of the EST using numerical simulations. We have generated synthetic atmospheric profiles built from real data obtained at Observatorio del Teide. The knowledge of the site turbulence profile enables to define the MCAO setup. We have performed a set of simulations in order to optimize the number and heights of DMs. Although during day time most of the turbulence is concentrated on the ground and one DM conjugated to the ground would be sufficient, it has been demonstrated that at least 4 DMs for low elevations angles and 3 DMs for high elevation angles are required to comply with the requirements. We also have simulated how the performance is affected by the fact that the solar WFS used extended sources, being more critical for low elevation angles. Finally we have studied the effect of the order correction in the performance. It has been demonstrated that the best performance is achieved correcting ground layer first and thereafter the higher layers from the upper to the lower. Practical implementation with small number of correctors to verify the simulations remains to be addressed.

ACKNOWLEDGEMENTS

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