The Multi-Conjugate AO system of the EST: DM height determination for best performance using real daytime statistical turbulence data

I. Montilla[a], L. Montoya[a]

[a]Instituto de Astrofísica de Canarias, C/ Vía Láctea s/n, La Laguna, Tenerife, Spain

ABSTRACT

The 4-meter diameter European Solar Telescope incorporates an innovative built-in Multi-Conjugate Adaptive Optics system to be able to measure the properties of the solar magnetic field with great accuracy and high spatial resolution. The MCAO system features 4 high altitude DM's, and combines a narrow field high order wavefront sensor, providing the information to correct the ground layer, and a wide field lower order sensor to control the higher altitude mirrors. The wavefront sensing is performed using correlations on images of the Sun with a field of view of ~10", averaging wavefront information from different sky directions, affecting the sensing and sampling of high altitude turbulence. We have determined the DM heights analyzing the performance of the EST MCAO system for a broad range of daytime turbulence profiles and telescope elevations, comparing the results of the static simulations of the Fractal Iterative Method combined with the analytical error budget, with the end to end simulations performed with DASP-solar. We present the results of our study which determines the DM heights that ensure best performance of the EST MCAO system.

Keywords: adaptive optics, reconstruction algorithms, solar adaptive optics, wide field sensing

1. INTRODUCTION

The European Solar Telescope is a 4-m planned facility designed to have high spatial resolution capabilities to understand the mechanisms of magnetic coupling in the chromosphere and the photosphere. It will feature both a conventional and a multi-conjugate adaptive optics (AO) system of similar complexity than the systems for night-time Extremely Large Telescopes. Such a system have a complexity not only related to the number of degrees of freedom, but also related to the specificities of the Sun, used as reference, and the sensing method. The wavefront sensing is performed using correlations on images with a field of view of ~10", averaging wavefront information from different sky directions, affecting the sensing and sampling of high altitude turbulence. Also due to the low elevation at which solar observations are performed we have to include the generalized fitting error and the anisoplanatism, as described by Ragazzoni[1] and Rigaut[2], as non-negligible error sources in the Multi Conjugate Adaptive Optics error budget. For the development of the next generation Multi Conjugate Adaptive Optics systems for the European Solar Telescope we need to study and understand these issues, to predict realistically the quality of the achievable reconstruction. That study is the first part of this paper.

With the knowledge acquired in our study we have chosen the adequate height and number of the DMs for the EST MCAO system. With the results of the numerical simulations run in FrIM[3] using real atmospheric profiles from ORM and OT we show that after correction we have an homogeneous Strehl higher than 40% over the 1 arcmin FoV for all the elevation range. These numerical results are validated with the analytical equations and the complete error budget that was described in a previous paper[4].

In this paper we also summarize the lessons learned with past and current solar adaptive optics systems[5], and focus on the discussion on the new alternatives to solve present open issues limiting their performance.

2. SPECIFICITIES OF SOLAR AO

2.1 The WFS extended field of view

2.1.1 Averaged turbulence

One of the challenges of solar AO is that the WFS has to work on extended and low-contrast objects such as sunspots or solar granulation because a correlating SH is used to sense the wavefront[6]. The FOV has to be large enough to contain structure for the correlation algorithm to work robustly, but not too large, to avoid averaging the wavefront information from the upper layers of the Earth's atmosphere. Usually a FOV of 8-10 arcsec is used. With such FOV, the anisoplanatism affects the measurements of the correlating SH WFS, averaging the wavefront information over the FOV and thus decreasing the sensitivity to wavefront distortions introduced at large heights above the telescope aperture. For low elevation observations, the increased line-of-sight distance to the turbulent layers leads to a wider wavefront area to be averaged for a given FOV and to a larger image degradation, as is shown in Figure 1. Therefore, the contribution of this anisoplanatism to the AO measurements must be taken into account in solar AO performance evaluation, as was explained in previous works[7,8,9].

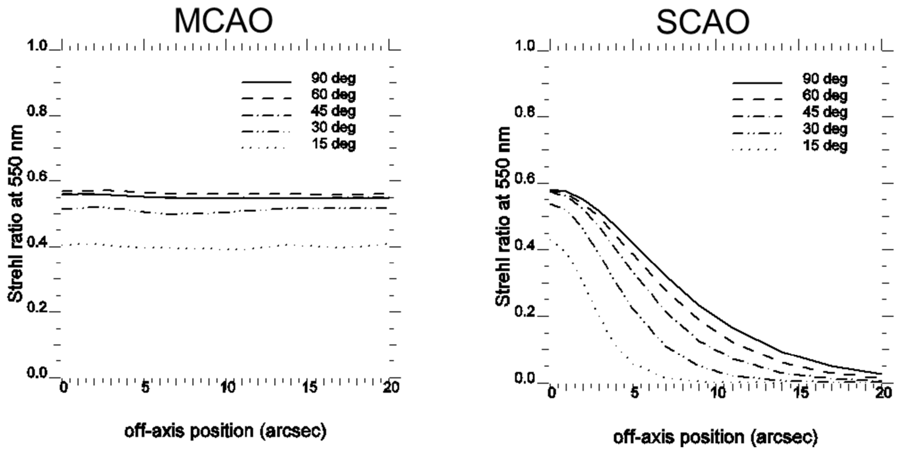


Figure 1: Estimated performance including the fitting, temporal delay, WFS measuring and bandwidth errors, obtained with the Fractal Iterative Method (FrIM)[bechet2006]. The Strehl decreases with the zenital distance.

2.1.2 Undersampled high altitude layers

Not only the turbulence is averaged, but also the upper atmospheric layers are undersampled due to the extension of the sources used for the sensing[4]. We observe two limiting cases: when the telescope diameter is smaller than the projection of the FOV on the upper layer, and when it is much larger than it. In the first case, the tip-tilt information is acquired from a surface bigger than the telescope diameter, but it is corrected on the telescope aperture, rising an error for small diameters, larger than the error when only the tip-tilt is corrected. As the diameter of the aperture approaches the projection of the FOV on the layer, the error approaches that of a system where only the tip-tilt is corrected, and at a certain point it starts to be smaller, because the pupil is sampled and the system starts to be able to correct more modes, as can be seen in Figure 2.

Therefore, for telescope diameters larger than the projection of the FOV of the WFS on the upper layers, what limits the performance of the system is the diameter of the projection of the FOV of the WFS on the layers rather than the size of the subapertures. The reduction in the Strehl ratio for low elevations is an effect of the generalized fitting error. Therefore, we need to consider this parameter, and not only the Fried's parameter r_0, when designing a MCAO system for a solar telescope. In Figure 3 we show the effect of a turbulent layer at different altitudes when using a 10 arcsec WFS. Even though the DM is conjugated at the layer in these simulations, the residual error increases with the height of the turbulent layer due to the undersampling of the high altitude turbulence.

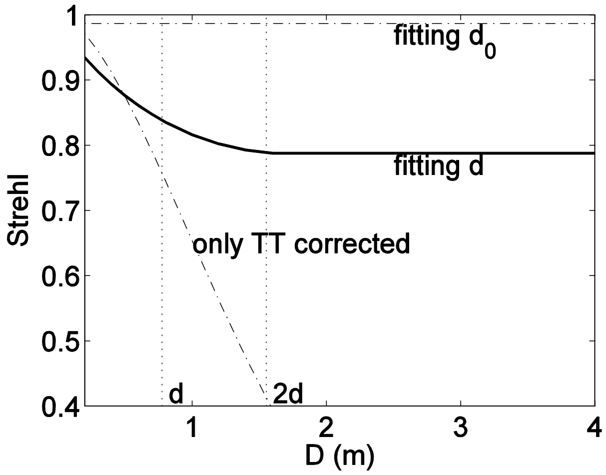


Figure 2: Analytical Strehl ratio for a WFS FOV of 10 arcsec, when the DM is located at the pupil (SCAO). The atmosphere has been represented by a single turbulent layer at 8 km, the r_0 is 50 cm at zenith, the elevation 30 deg and the subapertures size, d_0, is 8 cm.

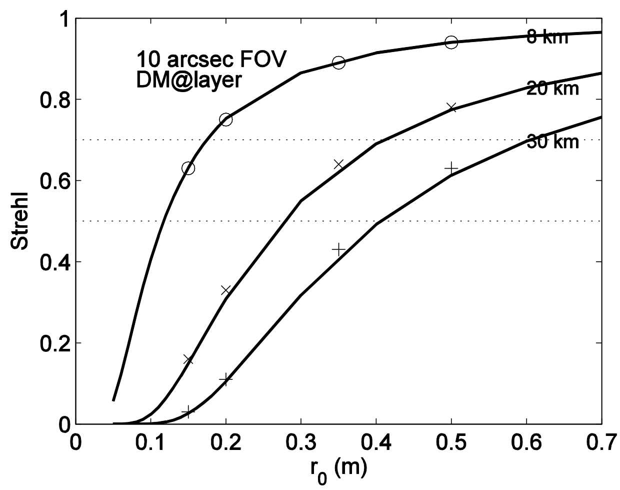


Figure 3: Effect of the height of the layer and the r_0 on the performance of a system with the DM conjugated to the turbulent layer. Comparison of the theoretically predicted Strehl ratio and the numerical result of the simulations. Solid lines are the predicted theoretical performance and symbols represent the numerical results obtained with FrIM[3].

2.2 The order of the DMs in the optical train

In a MCAO system, the perturbations induced by the atmosphere can be corrected placing the DMs in the optical train in two different ways: (a) correcting the layers in the same order as they are optically conjugated (we refer to this option as "direct correction") and (b) correcting the layers in the inverse order to conjugation ("inverse correction"). A total cancellation of phase and amplitude is only achieved in the latter case, however a major disadvantage is that relay optics is required to conjugate the DMs. Direct correction is commonly adopted for MCAO systems in night-time astronomy. It has been claimed in the literature[10] that the direct correction degrades the AO system performance for visible wavelengths and low elevation angles, and that this degradation is due to amplitude fluctuations originated by the wavefront propagation. Simulations have been performed in order to quantify this effect for a 4 meter solar telescope[11]. It has been demonstrated that the direct correction approach degrades the performance to 50% for low elevation angles and poor seeing conditions. A compromise between both approaches has been adopted for the GREGOR telescope[12]. The ground layer is first corrected and thereafter the higher layers from the upper one to the lower one. This solution in theory ensures good performance at any elevation angle and poor seeing conditions. In practice, it has been found that having the altitude DMs in the optical path after the pupil DM causes a misregistration between the later and the HOWFS, degrading the wavefront control[13] and making the loop unstable. Therefore in the GREGOR systems the HOWFS is placed before the high altitude DMs. The HOWFS is consequently blind to whatever happens to the altitude mirrors. To be able to stably close the loop all the low order modes are controlled exclusively by the LOWFS, and the HOWFS is used to control only the high order modes of the pupil DM[14]. The performance obtained using this control strategy was not the expected, and probably the performance would benefit of using an open loop control algorithm similar to those used for Multi-Object AO systems[15]. Recently the NST AO system[16] demonstrated the superiority of MCAO correction over GLAO, working with the same WFS for the high and low orders and placing the mirrors in the inverse correction. Even though the quality of the correction was qualitatively quantified and not quantitatively, it may worth it to explore this approach for the EST MCAO system.

3. EST MCAO SYSTEM PERFORMANCE SIMULATIONS

With the parameters of Table 1 we performed open-loop simulations for different telescope elevations and atmospheric conditions with the Fractal Iterative Method (FrIM3D), a fast algorithm for tomographic wavefront reconstruction developed at CRAL. Our goal was to find the best configuration of DM numbers and height, and we found out that 5 DMs are enough to cover all the elevation range required by a solar telescope, with heights at 0, 5, 9, 12, 25 kms respectively. Even though, only 2 of the altitude DMs have to be actuated at the same time. This is important from the control point of view of the system. We have reconstructed layers at the altitude of the DMs (no projector was used). The simulations featured 10 realizations of the turbulent atmosphere. The atmospheric profiles are described in a paper in this same proceedings[17], and are real profiles from ORM and OT. Both the narrow field HOWFS and the wide field LOWFS are simulated. The correlating SHWFS was simulated providing an approximate average of the measurement over a 10 arcsec field of view, in order to include the anisoplanatism effect. Only the fitting error, that is the error term due to the limited number of actuators, is considered in these simulations. The results are plotted in Figure 4.

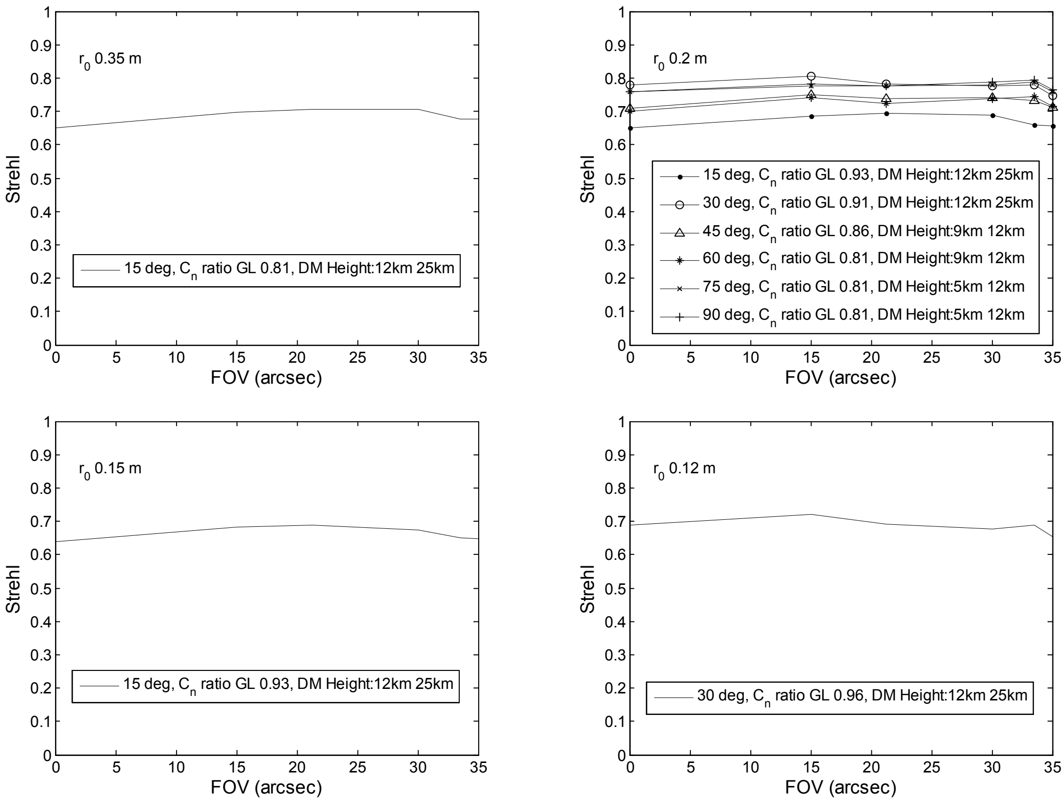
Parameter	AO	MCAO
DM heights (km)	0	0, 5, 9, 12, 25
Spatial sampling (cm)	8	8, 30, 30, 30, 30
Sensing field points	1	19
FOV (arcsec)	10	60
Wavelength (nm)	550	550

Table 1: EST MCAO system parameters

What we show in the figures are the worst atmospheric conditions in which the system can work and still reach a 40% total Strehl (~65% Strehl fitting error only). One important conclusion from the study is that the C^2_n ratio of the ground layer affects the performance of the system as much as the integrated r_0. This is good news since the turbulence in the Canary Islands tend to be concentrated in the ground layer (usually >95%) We see that for a very good day (r_0=35 cm) we can reach the specified Strehl even at the lowest elevation (15º) and with only 80% of the turbulence at the ground layer. For a good day (r_0=20 cm) we can also reach the specified Strehl at the lowest elevation (15º) but we need at least 93% of the turbulence at the ground layer. We see the same situation for an average day (r_0=15 cm). As the atmospheric conditions get worse, we see that we need more of the turbulence concentrated at the ground layer to reach the specifications. For example for a bad day (r_0=10 cm) to reach the specified Strehl at 45º elevation we need at least 96% of the turbulence at the ground layer. It means that to reach the 40% Strehl in the 1 arcmin FOV at elevations lower that 45º we would need more than 96% of the turbulence concentrated at the ground layer, what is not impossible (we have measured profiles with 98% of the turbulence at the ground layer) but is less common.

We have to remark that the worst atmospheric conditions happen usually at mid-day, when the Sun has been heating up the ground, and at that moment the telescope would be pointing close to zenith and could reach the specified Strehl with less of the turbulence concentrated at the ground (~93%). Therefore, we can conclude that the chosen configuration of DM heights and numbers will let us correct the turbulence and be into specifications for most of the atmospheric conditions that occur at ORM and OT.

These simulations show that with 5 DMs at 0, 5, 9, 12 and 25 kms we can obtain a homogeneous Strehl higher than 40% over the 1 arcmin FoV for all the elevation range.



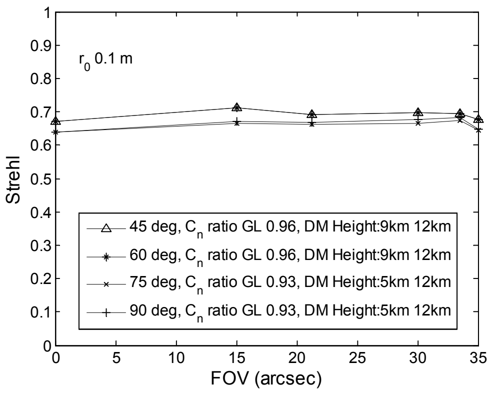


Figure 4: Strehl ratio with regard to the FOV, we show the worst atmospheric conditions in which the system can work and still reach a 40% total Strehl (~65% Strehl fitting error only). For each elevation the minimum Ground Layer C_n^2 ratio necessary to reach the specification given and also which DMs are actuated.

4. PRELIMINARY ERROR BUDGET

With the equation for the generalized fitting[4] we can estimate the error budget including the fitting, temporal delay, WFS measuring and bandwidth errors, for a 4 m telescope, as was done in a previous work. We use the following parameters and atmosphere:

λ (nm)	τ_0 (ms)	τ (ms)	SNR	contrast	m (pix)	n_r (pix)	f_S (kHz)	f_G (Hz)
550	2	1	223	3%	4	15	1	213

Table 2: error budget parameters

- integrated r_0=15 cm (conservative)
- 2 layers:
  - low elevation case: Ground Layer r_0=16 cm, altitude layer @ 25 km r_0=50 cm
  - high elevation case: Ground Layer r_0=16 cm, altitude layer @ 15 km r_0=50 cm
- 2 DMs; pupil DM d_0=8 cm, altitude DM@layer d_0=30 cm

The error budget for the low elevation case is:

σ^2 (rad^2)	σ^2_{delay}	σ^2_{WFS}	σ^2_{BW}	$\sigma^2_{fitting\ th}$	$\sigma^2_{fitting\ sim}$
d_0@25 km	0.303	0.078	0.076	0.456	0.415

Table 3: rms error due to the temporal delay, the WFS measurement error and the bandwidth.

And the Strehl obtained from the analytical error budget is:

	Strehl (theoretical)	Strehl (simulated)
d_0@25 km	0.40	0.41
d_0@15 km	0.50	0.50

Table 4: theoretical (error budget with generalized fitting) and simulated (FrIM) Strehl including the generalized fitting, delay, WFS measuring and bandwidth errors.

A homogeneous Strehl higher than 40% over the 1 arcmin FoV can be obtained even for low elevations and despite the intrinsic anisoplanatism of the WFWFS.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have summarized the particularities of solar adaptive optics and we have applied the conclusions of our study to choose the best configuration for the EST MCAO system. There are mainly two things that limit solar AO performance: the extended field of the correlation SH WFS and the visible wavelengths. The implication of the first one is a degradation of the performance, even for the case of SCAO, as we explained. The implication of using visible wavelengths is not only that the order of the system is close to extreme AO. Also, the order of the DMs in the optical train has to be in the order inverse to the conjugation of the layers. Therefore, reimagination is needed. In practice, in the GREGOR MCAO system it was found that the presence of the altitude DMs create misregistrations between the pupil DM and the HOWFS. Their solution was to place it before the altitude DMs, in open-loop with regard to them. According to them this configuration has been proven difficult to control. We think that further work on alternative control strategies for such systems, or using only 1 WFS as recently done at the NST, is needed to assure a good performance of the future MCAO system of the EST.
We applied the knowledge acquired in our general study to the case of the EST MCAO system and set a configuration of DMs number and heights that gave us the best performance for most of the

elevations and atmospheric conditions at OT and ORM. The conclusions of the simulations we did with the chosen configuration are:

- FrIM end-to-end static numerical simulations: 5 DMs at 0, 5, 9, 12 and 25 kms are needed to have an homogeneous Strehl higher than 40% over the 1 arcmin FoV for all the elevation range. Only 2 altitude mirrors are actuated at the same time.
- Analytical error budget: an homogeneous Strehl higher than 40% over the 1 arcmin FoV can be obtained even for low elevations and despite the intrinsic anisoplanatism of the WFWFS.
- DASP-solar (Durham collaboration) end-to-end dynamical simulations confirm FrIM static numerical simulations and analytical error budget results.

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