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PRELIMINARY PERFORMANCE ANALYSIS OF THE MULTI-CONJUGATE AO SYSTEM OF THE EUROPEAN SOLAR TELESCOPE

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Abstract. The European Solar Telescope (EST), a 4-meter diameter world-class facility, has been designed to measure the properties of the solar magnetic field with great accuracy and high spatial resolution. For that reason, it incorporates an innovative built-in Multi-Conjugate Adaptive Optics system (MCAO), featuring 4 high altitude Deformable Mirrors (DMs). It combines a narrow field high order wavefront sensor, providing on-axis information, and a wide field lower order sensor to control the higher altitude mirrors. The field of view of the low order wavefront sensor is larger than the isoplanatic angle. This anisoplanatism effect introduces additionnal wavefront sensing errors, in particular for low elevation observations. So far these effects have not been studied in MCAO. We analyze this effect by using the Fractal Iterative Method (FrIM), which incorporates a wide field Shack-Hartmann, and we performed simulations of the EST MCAO system to analyze the performance of this system for a large range of elevations, as required in solar observations, and depending on the asterism geometry and number and height of DMs, in order to find the best system configuration.

1 THE MCAO SYSTEM OF THE EST

The European Solar Telescope (EST) is an ambitious project to build a 4-meter class solar telescope. It is promoted by the European Association for Solar Telescopes (EAST), a consortium formed by research organizations from 15 European countries [1]. It will be built to perform accurate high-spatial and high-temporal resolution polarimetry in many wavelengths simultaneously to study the magnetic coupling of the solar atmosphere, from the photosphere up to the upper chromosphere. It will reach the required spatial accuracy thanks to its built-in MCAO module, that will provide a corrected 1 arcmin field-of-view with 50% Strehl at 500 nm.

To reach such a Strehl we need to deal with some of the challenges of solar AO, as compared to night-time AO. Due to the fast evolving daytime seeing conditions and the fact that most science is done at visible wavelengths, a very high closed-loop bandwidth is required to achieve solar AO correction. The high temporal frequency content of the wavefront fluctuations leads to required sampling rates of 2 kHz or more. This, along with the fact that solar AO systems need a large number of corrective elements in spite of the relatively small, compared to night-time telescopes, apertures of solar telescopes, gives systems that approach the complexity of what is referred to as extreme AO[2]. The optical layout of the EST features two main adaptive optics

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modes: the conventional AO (CAO) and the Multi-Conjugate AO mode (MCAO) [1]. The CAO mode uses the ground layer DM and a high order correlating Shack-Hartmann wavefront sensor (HOWFS). The MCAO mode uses five DMs at conjugate heights of 0 km (ground layer DM) and 1.6, 6.6, 10 and 23 km. It uses the high order sensor for the center of the FoV and one wide field low order sensor (LOWFS), with less sub-apertures but wide FoV, that senses the field-dependent and weaker aberrations of the high altitude turbulence. The pupil and focus geometry of both Wavefront Sensors, with a reduced number of subapertures, is shown in Figure 1. The main parameters of the system are displayed in Table 1. A similar approach was proposed for the German Vacuum Tower Telescope [3] and GREGOR MCAO systems [4].

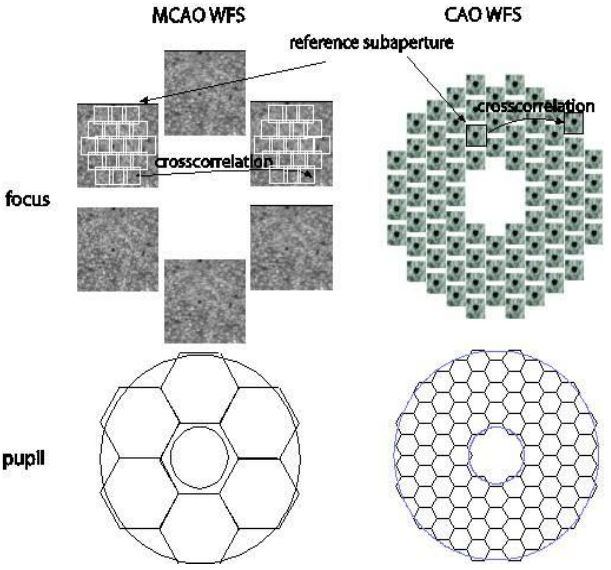


Fig. 1. High-order narrow-field SH WFS and low-order wide-field SH WFS concept

Table 1. EST AO system parameters

Parameter	CAO	MCAO
DM heights [km]	0	0,1.6,6.6,10.6,23
Spatial sampling [cm]	8	8,30,30,30,30
Sensing field points	1	19
FOV(arcsec)	8	60
Subaps/metapupil diameter	50	50,15,20,23,36

2 THE PROBLEM OF THE INTRINSIC ANISOPLANATISM ASSOCIATED TO THE SOLAR WAVEFRONT SENSOR

One of the challenges of solar AO is that the wavefront sensor has to work on extended and low-contrast objects such as sunspots or solar granulation. A correlating Shack-Hartmann is used to sense the wavefront. The FOV has to be large enough to contain structure for the correlation algorithm to work robustly, but not too large, to avoid averaging of wavefront information from the upper layers of the atmosphere. Usually a FOV of 8-10 arcsec is used. With such FOV, the anisoplanatism affects the measurements of the correlating SHWFS, averaging the wavefront information over the field of view 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. Therefore, the contribution of this anisoplanatism to the AO measurements must be taken into account in solar AO performance evaluation. This was never done before the starting of AO studies for the 4-m class solar telescopes. So far no analytical formulas include the wavefront sensor anisoplanatism error in the error budget and in the error model used to perform the simulation. Therefore, the only way to estimate its effect is numerically, by including an end-to-end model of the wide field cross-correlation WFS in the simulations. A similar approach has been developed by Marino [5].

3 PERFORMANCE ANALYSIS

We performed open-loop simulations for different telescope elevations with the Fractal Iterative Method (FrIM3D) [6], a fast algorithm for tomographic wavefront reconstruction developed at CRAL. In this case we have reconstructed layers at the altitude of the DMs. The simulations featured 10 realizations of a turbulent atmosphere with r_0=10 cm at 550 nm. The atmosphere includes 19 frozen layers distributed in altitude, representative of typical atmospheric conditions during solar observations. This r_0 is maintained for all the elevations, and the reason is that solar telescopes observe at low elevation during the first hours of the day, and at that moment the atmosphere is less turbulent. Therefore, we use the same value for 15° elevation than for the zenith. The atmospheric profile is the combined C_n^2 profile from Rimmele [7]. 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-ofview, in order to include the anisoplanatism effect [8]. 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 2. These simulations show the homogeneous correction over the 1 arcmin FOV that FrIM3D is able to give and confirm the results obtained by Marino [5]. The reduction in the Strehl for low elevations is an effect of the intrinsic anisoplanatism associated to wide field WFSs and the generalized fitting error.

We have also estimated the temporal delay, WFS measuring and bandwidth errors, calculated according to Rimmele [2]. The temporal delay error, in case no temporal prediction is made, can be estimated using the following expression:

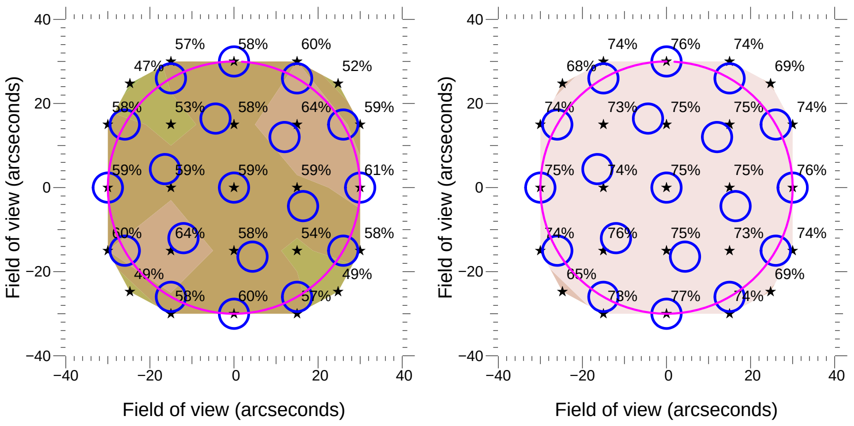
$$\sigma_{delay}^2 = 0.962\,(\tau/\tau_0)^{5/3} \tag{1}$$

where τ is the delay and τ_0 the coherence time of the atmospheric turbulence.

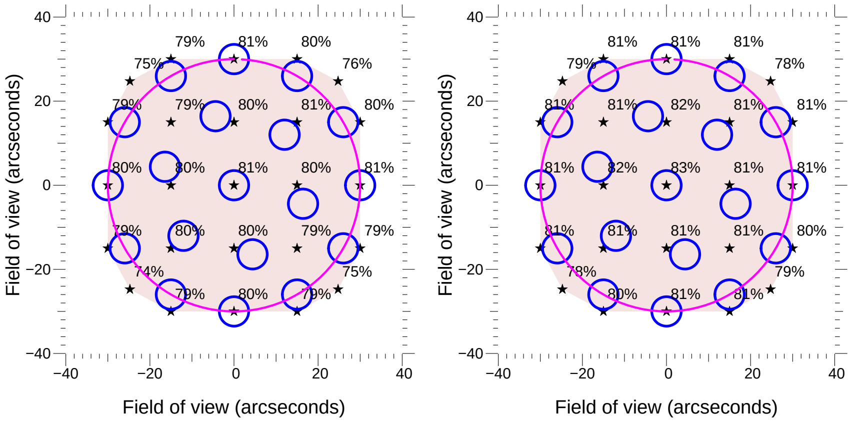
The WFS measuring error can be estimated with the following equation:

$$\sigma_{WFS}^2 = \frac{5m^2}{4n_r^2 \cdot contrast^2 \cdot SNR^2} \tag{2}$$

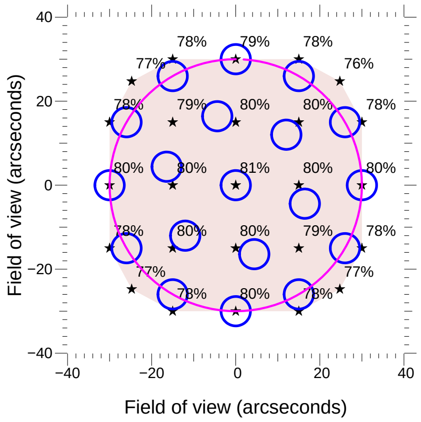
where m is the width of the reference subimage autocorrelation function in pixels, n_r is the subimage size in pixels, SNR is the signal-to-noise ratio, and the contrast is the is the measured contrast of the observed solar scene.



(a) strehl at 15° elevation (b) strehl at 30° elevation



(c) strehl at 45° elevation (d) strehl at 60° elevation



(e) strehl at 90° elevation

Fig. 2. Strehl ratio for different elevation angles. The blue circles are the centers of the WFWFS subfields. The pink circle is the 1 arcmin FOV. The stars are used to probe the Strehl.

The bandwidth error is due to the limited correcting bandwidth of the AO system. The bandwidth error is proportional to the ratio between the frequency of the turbulence, quantified by the Greenwood frequency f_G, and the bandwidth f_S of the AO system:

$$\sigma^2_{BW} = \left(\frac{f_G}{f_S}\right)^{5/3} \tag{3}$$

In the special case of a single turbulent layer moving at a speed v, the Greenwood frequency f_G can be written:

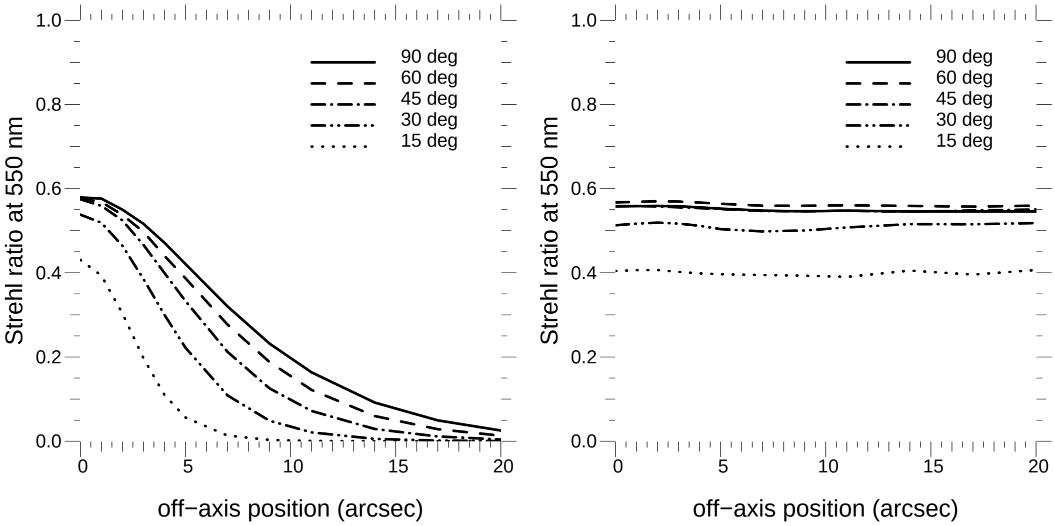
$$f_G = 0.427 \frac{v}{r_0} \tag{4}$$

In general, closed loop bandwidths in excess of 100 Hz are required for solar AO systems.

In Table 2 we show the values used to estimate the Strehl ratio including the estimation of these 4 error sources. In Figure 2 we have plotted the Strehl in function of the field for different elevations. In Figure 3(a) we show the results of a CAO simulation for the EST and in Figure 3(b) the MCAO results. We see that in spite of the effect of the anisoplanatism of the 10 arcsec correlating SH still an homogeneous correction is obtained at 15° elevation with an Strehl of 40% using an MCAO system.

Table 2. MCAO simulations parameters

λ	τ_0	Frequency	SNR	Contrast	f_S	f_G
550 nm	2 ms	2 kHz	223	3%	1kHz	213 Hz



(a) AO

(b) MCAO

Fig. 3. Estimated performance including the fitting, temporal delay, WFS measuring and bandwidth errors

4 CONCLUSIONS

In this paper we present open-loop preliminary reconstruction results to study the impact of the intrinsic anisoplanatism of the correlating SHWFS on the performance of MCAO systems. The decrease in the Strehl going to lower elevations is observed to be very similar to the SCAO case, meaning that the anisoplanatism error dominates the performance. But in closed-loop MCAO, the anisoplanatism effect on measurement is expected to decrease and it is required to pursue this study in order to understand if MCAO closed-loop correction could mitigate the anisoplanatism effect. Nevertheless, an homogeneous 40% Strehl over the 1 arcmin FoV was obtained with FrIM3D.

An interesting discussion is open regarding the low order and high order WFSs schemes. In the preliminary design of the EST MCAO the altitude DMs were after the HOWFS, like in the German VTT at the Observatorio del Teide, but the VTT only managed to close the loop at low order with such an arrangement [3]. The Dunn Solar Telescope at Sac Peak also has the HOWFS before the high altitude DMs in the optical train, but it has two independent loops: one for the pupil DM and the HOWFS and another for the high altitude DMs and the LOWFS [9]. But an optimal system should have all the WFSs behind the DMs, because if the HOWFS is placed before the high altitude DMs it will be blind to the changes they introduce in the wavefront. Therefore it would be interesting to study the impact of MCAO system components position on the control of the full MCAO loop. We also plan to study new wide field WFSs or new approaches with the existing WFSH.

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