A NGSs based WFS for the E-ELT and the VLT

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ABSTRACT

In the framework of the European ELT design, partially open-loop MCAO systems, coupled with virtual DMs, have been proposed to achieve AO correction using solely NGSs, to be selected in a FoV as wide as allowed by the Telescope optical design. The conceptual design of a very compact wavefront sensor, exploiting the just mentioned concept and characterized by a dynamic range limited by the stroke of the Deformable Mirror and by a limiting magnitude performance typical of a closed loop coherent wavefront sensor, have been presented in the past. This concept was based on the usage of a very linear wavefront sensor, like a YAW sensor, but a DM having the actual shape known “a-priori” could simplify a lot the design of such a compact WFS.

We investigate here the realm of possible opto-mechanical realization of a probe, capable to co-exist with the currently foreseen E-ELT LGS probes and giving the possibility to exploit the open loop wavefront sensing operation with the aim of reaching a preliminary design of such a system.

Furthermore, we devise a conceptual opto-mechanical design of a precursor of such a system, which could exploit at the VLT Global MCAO correction on the lower part of the atmosphere.

Keywords: ELT, VLT, Global MCAO, Adaptive Optics, Very Linear WFS, Natural Guide Star, Optical Design, Mechanical Design

1. INTRODUCTION

Adaptive Optics is a crucial component in the view of the construction of Extremely Large Telescopes (ELT) (see [7], [10] and [11]). In fact, it will be included as part of the telescope system itself, since all the ELT which are going to be built will have an adaptive mirror in the main telescope optical train, that will give the possibility to have partially corrected images to all the instruments that will be installed.

Only recently artificial references created with lasers have obtained decent performances and an acceptable level of reliability, and anyways are affected by some fundamental problems not easy to be overcome, like the un-sensitivity to the very low order aberrations, which obliges to use anyways Natural Guide Stars (NGS), or the cone effect, which makes necessary to use much more references to cover the same Field of View (FoV). Furthermore, the sky coverage achievable with laser assisted Multi Conjugate Adaptive Optics (MCAO) system are not as high as it was predicted a few years ago (both in term of sky coverage [18] and in term of system performance [2]). For all these reasons, the possibility to use Natural Guide Stars as references for the MCAO wavefront sensors is still a very sensitive item, above all considering some advantages which are intrinsic to the ELTs. New concepts of wavefront sensing, like the Global MCAO approach, have been recently presented (see [14]), and possible opto-mechanical layouts for the E-ELT case have also been proposed (like the Very Linear ELT WaveFront Sensor – see [4] and [9]), showing that Global MCAO is possible on ELTs with current available technology and also emphasizing that very good sky coverage can be achieved and very uniform strehl along the scientific FoV can be obtained too.

In the following, we will review these concepts, also showing that they might be applied to a 10m class telescope simply scaling the maximum altitude of correction that could be achieved, realizing in this way an instrument which is a precursor of the E-ELT system which could correct, on the VLT-UTs, only the lower atmospheric turbulent layers, realizing in this way what we call a Low Layer MCAO (LL-MCAO) system.
2. THE GLOBAL MCAO TECHNIQUE CONCEPT

The most important advantage that ELTs have, when looking at the possibility to use NGS references for the AO system, is that the overlap of the pupil images at the altitudes of the high turbulent layers is still very high, given a certain scientific FoV, as it can be seen in Figure 1. In this way, one could think to use a much bigger FoV for the selection of the MCAO system references, in a very similar manner to what has been proposed in the last years for the correction of the Ground Layer even on a 10m class telescope, where the perfect overlap of the pupils at the level of the ground allows for very big field of view used by the FWS conjugated to it. This concept is the basic one for the Multiple Field of View Layer Oriented technique (see [13]), introduced several years ago and utilized in the NIRVANA instrument (see [16]), which will be installed in the next years at the Large Binocular Telescope (LBT) in Arizona.

There has been a study (see [17]) showing that, considering a scientific FoV of 2′, a WFS FoV of 10′, a conjugation altitude for the high DM of 10km and a 40m telescope entrance pupil, the scientific meta-pupil coverage at 10km height is always higher than 70% by using only 3 stars, and it becomes higher than 90% when using 6 stars. This probability has to be of course coupled with the probability to find 3 (or 6) suitable stars in the 10′ FoV, which has also been computed and it is of the order of 87% (45% in the case of 6 stars) in the very conservative assumptions of having a limiting magnitude for the WFS of about 15 (we recall here that the recent results obtained at LBT with the Pyramid sensor are pushing instead this limit toward magnitude 17.5, see [3]) and looking at the galactic pole.

These numbers are of course very attractive, but there is a price to pay for the increased FoV of the WFS conjugated to the high altitude DM, which is the very small depth of focus that this sensor will have, translating into a very low sensitivity to turbulent layers not far from the sensor (and DM) conjugation altitude.

The Global MCAO overcomes this problem in the way that we describe in the following, considering a MCAO system with two Deformable Mirrors (DMs), conjugated at 0 and 8Km. In LO mode with optical co-add, the solution would be straightforward: there should be additional WFS conjugated to the turbulent layers far away from the DMs conjugation altitude. In this way, we can reconstruct how the atmosphere is at different altitudes, say 2, 4 and 6 Km, in addition to the reconstruction at the DM conjugation altitudes, which are 0 and 8Km in this example. At this point, if we have real DMs conjugated at 2, 4 and 6 Km, and if the correction is very good, they will remove completely the layers to which they are...
conjugated. Since they are not there, we can consider them as “virtual DMs” and remove numerically their effect from the signal seen by the two real DMs as if they were present, taking in this way into account the signal corresponding to that altitude.

In this way, even if the WFS FoV is very large, one will be able anyway to take into account the contribution of turbulent layers at intermediate altitudes, of course smoothed in a way which depends on the distance between the real DM and the virtual one (see Figure 2).

![Five virtual DMs and Two real DMs](image)

Figure 2 Left side: to drive the DM conjugated to 10Km we use the signal coming from each virtual DM conjugated to the selected altitudes (5 in this example, ranging from 0 to 8Km equally spaced) smoothed of a quantity which is depending on the distance of the virtual DM from the conjugation altitude and on the FoV; the same on the right side to drive the DM conjugated to 0; note that, in this particular example, the layer at 4Km is giving the same contribution to the signal to be applied at the DM conjugated to 0Km and to 10Km, for the symmetry of the system.

Due to the very high FoV in which the references for the WFS can be searched, and due to the small number of stars which are needed to obtain a very good metapupil coverage (from 3 to 6), instead of using the optical co-add, the numerical LO could be used instead, also considering that nowadays detectors with a level of RON close to zero are available (see [1]). In this way, if the WFS is operating in Layer-Oriented (L-O) fashion with numerical co-addition of the light, this means that there is a detector coupled to each considered WFS reference, but the reconstruction of the wavefront at different height is performed numerically in a way that the “virtual DMs” can still be driven, with a clear advantage in term of opto-mechanical complexity.

There is no change in mind with respect to what stated in previous publications (see [13]), where the optical co-add was always preferred with respect to the numerical one in the Layer Oriented technique.

In fact, when considering a 10m class telescope, the FoV where the references shall be found on WFSs conjugated to high altitude layers is small (of the order of a couple of arc-minutes), which means that the probability of finding bright stars is of course not so high, and the optical LO ensures in this case the most efficient usage of the light if the detectors have a not negligible RON. Otherwise, Numerical LO is preferable because of its simpler opto-mechanical implementation.
Another important thing to be noticed is the fact that, since we look at stars in a 10’ FoV but we correct the central 2’, and since we drive the real DMs present in the system also with the signal reconstructed at different heights with respect to the DMs conjugation altitudes, the WFS is essentially working in open loop and the correction implemented by the DMs cannot be monitored optically in the MCAO system. The concept (already introduced in the past, see [4] and [9]) explained in the following of the Very Linear WFS (VL-WFS) solves the problem on the WFS side, while the DMs shape can be monitored with dedicated WFS (like the YAW for example, shining laser light on them and retrieving in this way their shape) and can be taken in this way into account numerically inside the MCAO loop.

3. THE VERY LINEAR WAVEFRONT SENSOR CONCEPT STUDIED FOR E-ELT

As a consequence of what has been explained in Sec. 2, the WFSs which have to be used for picking up the light of the reference stars have to work in open loop. This fact means that the linearity range of the selected WFS shall be as high as possible, which is normally the opposite situation of the normal WFSs used for AO purposes (Pyramid, S-H, Curvature), that have to work around the zero signal with a small linear range but with a sensitivity which is as high as possible.

A solution to this problem is what we call the Very Linear WFS (VL-WFS), and it has been presented in the recent past (see [4] and [9]), where a very sensitive WFS, the Pyramid ([15]), is used in a local close loop (using a small DM) to take advantage of its sensitivity, and the open loop signal to be recovered is obtained summing the residual of the correction measured by the Pyramid and the shape of the DM, which is monitored using a Yet Another Wavefront sensor (YAW, see [5]). The latter is characterized by a very high linear range, and it is a sensor working in monochromatic light; therefore, the trick is to send on the DM a monochromatic light (for example, a laser beam at 633nm wavelength) which is then separated from the star light using a dichroic and sent to the YAW to be analyzed.

This concept is shown in Figure 3, in which the light picked-up from the star through a folding mirror and the monochromatic light injected through a fiber are sent (through a collimator) to the DM, and the split through a dichroic is done after a re-focusing lens.

Figure 3: the open loop measurement of the wavefront performed using two “co-operating” wavefront sensors, the Pyramid and the YAW, used respectively in close and open loop.

The general idea, explained in Figure 3, is to collect the light from an annular area much bigger than the one we want to correct, and thus there should be a certain number of movable arms (based on the concept described in the Figure) which can enter in the telescope FoV, select and fold the light coming from a reference (which we consider a star in the concept shown here, but it could be as well an artificial reference) and analyze the wavefront giving an open loop measurement of the aberrations.
The purpose of the previous studies was to show that such an arm is feasible with off-the-shelf components today available, and moreover that a possible opto-mechanical layout for this arm can co-exist with the current design of the E-ELT Nasmith interface.

We recall here the most recent study (see [9]), in which the preliminary opto-mechanical was optimized and a complete study of the two channels (Pyramid and YAW) was devised (see Figure 4). It has to be noticed that, even though the 2 sensors are completely different, they are both “pupil plane WFSs” (the detector is on the pupil plane), and both of them are working with four images of the pupil; thus, choosing in a proper way the optical components of the two sensors, we can obtain identical sized pupils, meaning also identical detectors. In this way, the combination of the residual signal seen by the Pyramid WFS with the turbulent wavefront seen by the YAW can be done very easily (summing directly the signal obtained in the corresponding pupils of the two sensors).

![Figure 4: On the left side the optical design of the Pyramid channel, while on the right side the optical design of the YAW channel.](image)

We also recall the mechanical concept already presented (see Figure 5), in which the main drivers followed have been a compact and light-weighted structure minimizing its obstruction in the focal plane (to allow close positioning on the references), where particular care has been given to the CCD positioning, trying to simplify as much as possible the cabling issue.

![Figure 5: the mechanical concept of one of the moving arm carrying the WFS](image)

We emphasize again that all the elements utilized are absolutely standard components, most of them commonly commercially available or, anyway, doable with technology existing nowadays: the detectors considered in this design are in fact E2V CCD 220, 240×240 pixels, and a suitable DM could be an ADAPTICA product having a diameter of 76 mm with 28×28 actuators. In alternative to the latter, commercial DMs from Boston Micromachines could also be used.
A note has to be done on the number of arms which are required to ensure the maximum sky-coverage and, at the same
time, a good overlap of the pupils at the level of the higher conjugation altitude. Previous studies (see [17]) have shown
that, considering a 2’ scientific FoV at a Galactic Latitude $b = 90\text{deg}$ (conservative case), observed with a 40m-class
telescope, if 3 suitable stars are found in the technical 10’ FoV, the metapupil coverage at 10Km of altitude is always
higher than 70%, so the probability to cover such a fraction of the metapupil only depends on the probability to find 3
stars in the technical FoV (which is 87%). If other cases, in which more references are considered, the probability to
cover a high fraction of the metapupil decreases, since it always has to be weighted with the probability to find a higher
number of suitable reference stars. Of course, for lower latitude fields, it becomes more likely to find a high number of
suitable references, and observing at the galactic plane, even the probability to find 6 NGSs (which would allow to have
a better coverage of the metapupil at high altitude turbulent layers) brighter than magnitude 15 is close to 1.

Therefore, to maximize both the metapupil coverage at the highest altitude (10km in our study) and the probability to
find a reasonable number of references, observing at the galactic pole most likely 3 references would be observed at the
same time, while observing at the galactic plane a higher number of NGSs can be utilized.

We thus decided to consider, in this conceptual design, a maximum of 6 arms which can be used to span the 10’ FoV.
We want to stress that the performance of FLAO at LBT (see [3]) is pushing the limit for the brightness of the reference
stars toward magnitude 17 and further, but we decided to make the conservative choice of limiting the magnitude to 15,
also to maintain anyway a reasonable level of correction.

4. THE VLT CASE, A REAL INSTRUMENT AND A PRECURSOR OF THE E-ELT: LOW
LAYER ADAPTIVE OPTICS

An interesting fact is that, considering fixed to 10’ the FoV where the stars shall be looked for, the same pupils overlap
that we have on a 40m telescope at 10km height is obtainable with an 8m telescope at 2km altitude. Thus, we might think
to an instrument designed for one UT at the VLT, which could both be used to make science and to demonstrate the
Global MCAO concept in the view of a possible future instrument to be implemented on the E-ELT.

In fact, such an instrument could be designed to have 2 DMs, one conjugated to the ground and one conjugated to 2Km
of height, correcting the atmosphere in the range between zero and about three kilometers, which would exploit in this
way a kind of super ground layer correction or, alternatively, what we call Low Layer MCAO. Moreover, it would scale
down to the 8m class telescope the concept of Global MCAO, introduced for the 40m class telescopes, without
compromises.

We made a conceptual design of the VL-WFS for such an instrument, again completely based on off the shelf
components, including the detectors and the CCD. It is basically a scaled down version of the WFS arms introduced for
the E-ELTs case, which is presented in Figure 6.
The final structure has the same characteristics of the arm designed for the E-ELT case, i.e. it is a light-weighted structure of about 15 Kg, very compact and with the obstruction minimized as much as possible, to facilitate the pointing also of references quite close to each other (the minimum distance between the references is of the order of 20"").

Scaling down the E-ELT arm, smaller CCDs and DMs can of course be used, and in the current design a commercial CCD39 is foreseen for both the Pyramid and the YAW arm, while the DM has been selected from a commercial one produced by ALPAO, which is the DM277-15, characterized by 277 voice coil actuators over an optical diameter of 24.5mm, with a stroke which is the highest available on this mirror sizes (±60µm for Tip-Tilt, ±45µm for defocus and astigmatism and about 3µm of inter-actuator stroke) at a working frequency of 1KHz.

The final dimensions of the arm presented in Figure 6 is perfectly fitting in the UT Nasmyth interface, as it can be seen in Figure 7, where a possible setup with 6 arms have been considered.

![Figure 7: an hypothetic VL-WFS setup for the UT Nasmyth interface at the VLT (photo taken from the ESO website)](image)

In fact, all the considerations made in Section 3 concerning the number of arms required by such an instrument are totally applicable to the VLT case, being the latter completely equivalent to the E-ELT case scaled only in the height of the DM to accomplish LL-MCAO on the same FoV and with the same sky coverage.

5. CONCLUSION

The recent results of the FLAO system (see [3]) at LBT are showing that the Pyramid sensor is obtaining on sky performance never achieved earlier, with Strehl Ratio greater than 90% in H Band, as it was already foreseen theoretically (see [12]) and proven on sky (see [6]). The operative on-sky limiting magnitude of the Pyramid sensor has been shown to be of the order of 17.5 in R Band. The VL-WFS has to operate in open loop, but the presented setup allows to use the Pyramid working locally in close loop, taking in this way advantage of its very good sensitivity. This is
achieved using, in combination with the Pyramid, a YAW sensor, working in its best possible configuration (monochromatic light and open loop). Even considering a more conservative number for the limiting magnitude equivalent to 15, recent computation (see [17]) are showing that a very good sky coverage can be obtained using solely NGSs, ranging from a minimum of 50% at the galactic pole to 100% when looking at the galactic plane. The fact of having such a large telescope aperture is the reason for which there is a very good superposition of the pupils even at 10Km of altitude, considering a science FoV of 2'; as a result of this, the uniformity of the PSF along the FoV will benefit quite a lot.

The proposed concept of an instrument for E-ELT based on the VL-WFS arms has the advantage that can share the available space with other sub-systems on the Nasmyth interface of the E-ELT, such as the LGS arms, and thus they might be used together or instead of them, with several possible configurations:

- Initially the telescope could start the operations using solely NGSs, adding only in a second time the LGS option; this would reduce quite a lot the money initially required for the telescope construction, being the laser construction and maintenance a significant fraction of the overall cost
- When the LGS option will be installed and working, the NGS arm might be used for the low order correction which is anyway requested to be done on 3 NGs in the current design
- In case of any failure of the LGS facility (their reliability and maintenance is still today an open issue, at Keck the scientific productivity with the LGS is half of the one using NGS), there will be always a backup solution ready to take over

The E-ELT may thus only take advantage implementing such a solution since, in the worst case, there will a good back-up solution in case of late development and/or performance problems of the artificial laser beacons.

Additionally, such an instrument can be completely scaled down to be installed and tested at the VLT, performing in this way the LL-MCAO correction and, depending on the kind of implementation and setup that this instrument might have, it might be both an instrument and a pathfinder for the E-ELT or just a demonstrator of the Global MCAO concept in the view of a future implementation on the E-ELT.

REFERENCES