Adaptive optics with solely natural guide stars for an Extremely Large Telescope

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ABSTRACT

In the past decade the ingredients for making real an Extremely Large Telescope with an Adaptive Optics system driven solely by Natural Guide Stars have been conceived, developed, built and proven on the sky. Still, the straightforward merging of these concepts is not enough to fulfill such an ambitious goal. We show here that a combination of the layer-oriented approach, the virtual deformable mirrors concept, and a combined use of different kind of wavefront sensors, some taking advantage of working in Closed Loop and some other characterized by an extremely high dynamic range, make the goal a reachable one. It is remarkable that such an approach requires, on a telescope of ELT class, including a common Deformable Mirror conjugated to the entrance pupil or close-by, a minimum impact on the guide probe units. The last involves the adoption of small Closed Loop AO system with an extremely high dynamic range wavefront sensor looking at the detailed shape of a small Deformable Mirror that allows the use of sensors taking advantage of the Closed Loop conditions. A pyramid wavefront sensor, fed by the Natural Guide Stars light and closing the loop with the mirror, and a YAW wavefront sensor looking at the mirror itself, allow for a natural and efficient combination of the data. The limits in the Field of View covered by such an approach are given by pure meta-pupils superimposition rather than to the spatial frequency of the achievable correction, breaking the limits previously thought for this kind of systems. The overall combination leads to a significant sky coverage, with performances comparable to the ones under discussion for some Laser Guide Stars approaches, without the related hurdle. The small technical impact on the telescope makes this approach not directly in-conflict with a Laser Guide Stars one allowing the designer to keep all the options on the table up to a very late stage.

Keywords: Adaptive Optics, Extremely Large Telescopes

1. INTRODUCTION

In these days Extremely Large Telescopes (ELTs) are turning from conceptual ideas to detailed drawings and are expected to become soon giants of metal and glass. Adaptive Optics concepts turned into reality in the last few years and even Multi Conjugate Adaptive Optics (MCAO) systems, thanks to MAD (even though its initial purpose was to be just a MCAO demonstrator), have obtained good on-sky performance and remarkable scientific results, using two different concepts of wavefront sensing: Star Oriented (SO) and Layer Oriented (LO). In the early days of MCAO it was speculated that these big telescopes, for several reasons, might benefit in an unprecedented way of solely Natural Guide Stars (NGSs) wavefront sensor driven systems, and that the adoption of artificially generated Laser Guide Stars (LGSs) could become an obsolescence from the past.

It has in fact to be recalled that in order for such a system to be effective, the layer under scrutiny must be “filled” by photons coming from a certain patch on the sky, able to finally reach the entrance pupil of the telescope. This fact gives a limit to the utility of a larger Field of View for a given telescope diameter and for a given height of the layer under scrutiny (in normal MCAO, also the one to which a DM is conjugated). For typical altitude values of 10km, such a limited FoV (imposed by the fact that you have to reach a minimum number of photons) is of the order of a couple of arc-minutes for a D=8m telescope, but it would reach half a degree for the majestic D=100m telescopes, as it would have been for the OWL project, envisaged a few years ago.

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There is indeed a price to pay in enlarging the FoV of the WFS, as pointed out in several occasions in the recent past, since a larger FoV also limits the equivalent thickness of the turbulence that can be sensed or corrected. In order to enlarge the FoV for a given degree of correction, there is need of more and more DMs that would become rapidly an unpractical and very expensive option. While this leads to focus on ways to optimize MCAO systems (like in MCAO systems based on Multiple Field of View – MFoV) or to increase the efficiency of wavefront sensing, a general sense that all these techniques would, at their best, increase the sky coverage by a mere factor of a single digit figure pushes toward the assumption that LGSs are necessary.

It has to be pointed out that, in several observing sites, the powerful layers close to the ground one (i.e. the ones which, increasing the WFS FoV, would be seen very smooth) are either absent or far enough from the ground that even with a much smaller WFS FoV they would be barely visible.

Is has also to be noticed that in the MFoV technique, when using two DMs in a ten meter class telescope (common compromise adopted in some instrument under construction), the reasonable FoV of the WFS conjugated to the high altitude layer would be of the order of 2', i.e. pretty much similar to the FoV of a LGS based system, thus being the two cases identical in term of depth of focus and sensitivity to the turbulent layers close to the DM conjugation altitude.

But indeed finding a way to increase the WFS FoV to maximize the probability to find several reference stars maintaining the possibility to correct for layers not far from the DM conjugation altitude would go in the direction to overturn what has been till now another barrier.

We are going to show in this article that there are ways to overcome this barrier, increasing the system performance by one or even more orders of magnitude and making, we believe, solely NGSs MCAO a re-born concept in the ELTs framework.

We will assume in the following that the detectors RON is negligible, and thus only LO with numerical co-addition of the light is considered.

2. THE VIRTUAL CORRECTION CONCEPT

Let us take a rude approach and assume we are able to build and operate a system with several DMs, for example let us assume 5 DMs in the following. Apart from tuning the numbers, there should be no discussion that, conceptually speaking, a wider FoV wavefront sensing system with a larger enough number of DMs is equivalent to a relatively small FoV WFS driving few DMs. To use the numbers mentioned before, we can easily guess that a 10armin FoV with five DMs MCAO should operate correctly with a performance comparable to the one of a 2arcmin FoV with two DMs MCAO system (the case of MAD on VLT). While the statement before does not depend upon the telescope diameter the relative effectiveness in terms of collecting starlight is actually very different. In fact the 10arcmin, 5 DMs option would still perfectly take advantage in terms of NGSs sky coverage for a D=42m telescope while it would be slightly on the limit for a D=30m one. We will come back later to point out that a MFoV MCAO could use as much as one degree FoV for a layer in the first km and almost half a degree for an intermediate layer at, say, 4km of height, making the potential for a further enhancement of the sky coverage a paramount one.

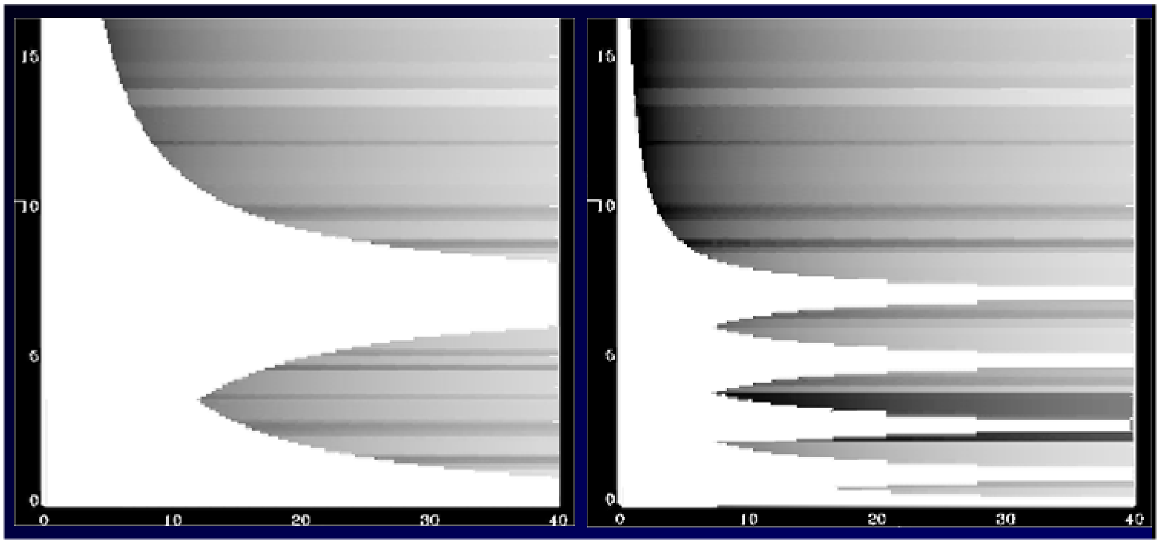

Figura 1 In the diagram of spatial frequency vs. height above the Observatory a DM aiming to correct for a certain FoV will erase a portion of the turbulence. Left: two DMs with a limited FoV; Right: five DMs with a much larger FoV achieving approzimately the same performance.

This hypothetical MCAO system, although probably very demanding from several practical viewpoints (the optical design must conceive all the FoV into several DMs conjugated to altitudes not so distant one from each other, leading probably to the need of a reimaging system for each DM, with an expected total of reflections and powerful surfaces in the ballpark of 20 or more, with consequences in terms of emissivity and overall optical quality budget), should perfectly work from the viewpoint of Adaptive Optics correction and, in such a sense, it may uses NGSs in the whole 10 arcmin Field of View.

You can now imagine to have a perfect DM in action with a perfect WFS looking to a certain bright star. For "perfect" WFS we mean here that it is absolutely linear and that for any incoming WF, within a wide range, it will give a perfect measurement of the WF itself. This is somehow in contrast with, basically, all of the existing wavefront sensors, as they usually operates around zero, in Closed Loop operation, or in the neighborhoods of such a region. For the moment, however, let us assume we have, at least, such a "perfect" WFS. Once we just know the exact direction of the reference star (an information that nowadays can be known a-priori given we are here speaking of NGSs likely to be individually brighter than, say 15 or 16 magnitude) the effect of the actuators of the DM on the WFS is perfectly predictable. In other words if one knows the actual movement of the DM surface one can straightforwardly compute with extremely high accuracy the signal coming out from the WFS. Please note that we wrote "actual movement" and not the signal given to the DM, so in other words hystheresis or non-linearity in the DM play a role in the difference between the signal and the actual movement but not here. Given this degree of knowledge one can imagine to remove (physically or, better, optically) the DM and simply to add its effects on the WFS signal just on the stream of data coming out from it. We are turning, in other words, the optical DM into a virtual one. In the past the concept of "virtual DM" has been introduced in the framework of producing better interaction matrices, but that was a sort of "static" concept once the loop is being closed while here we think to a sort of "virtual DM" where there is a continuous region of memory where the actual displacement of the DM are stored and continuously updated. In this configuration it is clear that the loop would have no way to "feel" if the DM is a true physical one or a virtual DM lying somewhere in the memory of the WFC. You can extend this in a drastic way as well, removing all the DMs and leaving the WFS completely in Open Loop looking at the several NGSs and updating continuously into five (in this specific example) virtual DMs their actual movements. Of course in this extreme case no correction will ever be applied to any starlight. There is nothing of conceptually strange into all this other than the WFS have to work with an high degree of linearity.

It has also to be noted that, at least at this level, the non linearity of the (non existing) DMs do not play a role at all.

It is worthwhile to point out that this approach is not the first to pretend to works in Open Loop fashion, as MOAO system works in a very similar way, but we do not further speculate onto this point, other than pointing out that the concepts and limitations that apply to MCAO will do also for MOAO so the latter have to take into account these behaviours.

3. A VERY LINEAR WFS

Further to require extremely linearity, these WFS working in Open Loop will not benefit from the gain occurring when they work in Closed Loop. This is noticeable for both Curvature and Pyramid WFS for instance, while it basically do not affect a Shack-Hartmann one. A simple way to make a WFS both linear and working with the gain proper of Closed Loop operations at the same time is simply to make it working in a local Closed Loop. This is done by replacing the WFS unit with a Single Conjugated Adaptive Optics (SCAO) system with a DM and a WFS closing the loop on each individual NGS. The quality of the correction should be good enough to guarantee both a certain linearity regime of the WFS and a significant gain in the WFS quality operating in Closed Loop. Please note that the two points are somehow balancing each other. For example a perfectly Closed Loop will make the WFS looking basically zero, so from the latter no information would be retrieved, while all the information on the WF will be given by the actual shape of the DM. A poorly Closed Loop with a WFS linear enough will give a residual information from the WFS that will have to be combined with the information coming from the DM. Since the problems of non-linearity of the DMs are known, a simple solution for retrieving the actual WF information is to illuminate the DM with a reference monochromatic light and to sense the DM with a very linear WFS. The YAW by Eric Gendron is the obvious candidate for such a device, it also having the conceptual advantage to give information in the same format as the Pyramid WFS.

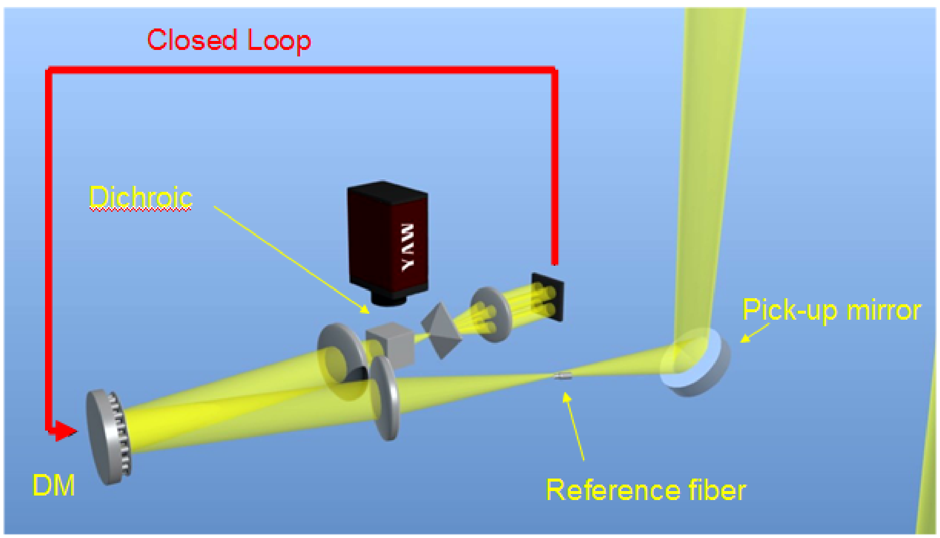

Figura 2 A conceptual scheme for a Very Linear WFS. A loop is closed on the reference star while, through a dedicated reference, the DM shape is measured by a YAW sensor.

Such a linear WFS requires a tiny FoV so several optical solutions that would be unpractical for a true SCAO system can be used. In particular there is no need of a separate collimator and camera as the splitting of the input and output from the DM can be made with distances equivalent to a few arcsec.

Summarizing, the WFS will be made of a collimator/camera that both illuminates the DM and makes the light back reflected by the DM itself converge. The DM has a very small tilt angle (in contrast with the larger one in any SCAO system) and the light is then reflected out thanks to a slightly off-axis small mirror. In input both the NGS light and a reference source are used. The light is then splitted by a notch type filter dichroic so that the light from the artificial reference is not sent to the NGS WFS (here a Pyramid one) and the light removed from the starlight is just an extremely tiny fraction. The Pyramid WFS is closing the loop through the DM and the residual are summed up with the measurement of the YAW of the actual shape of the DM.

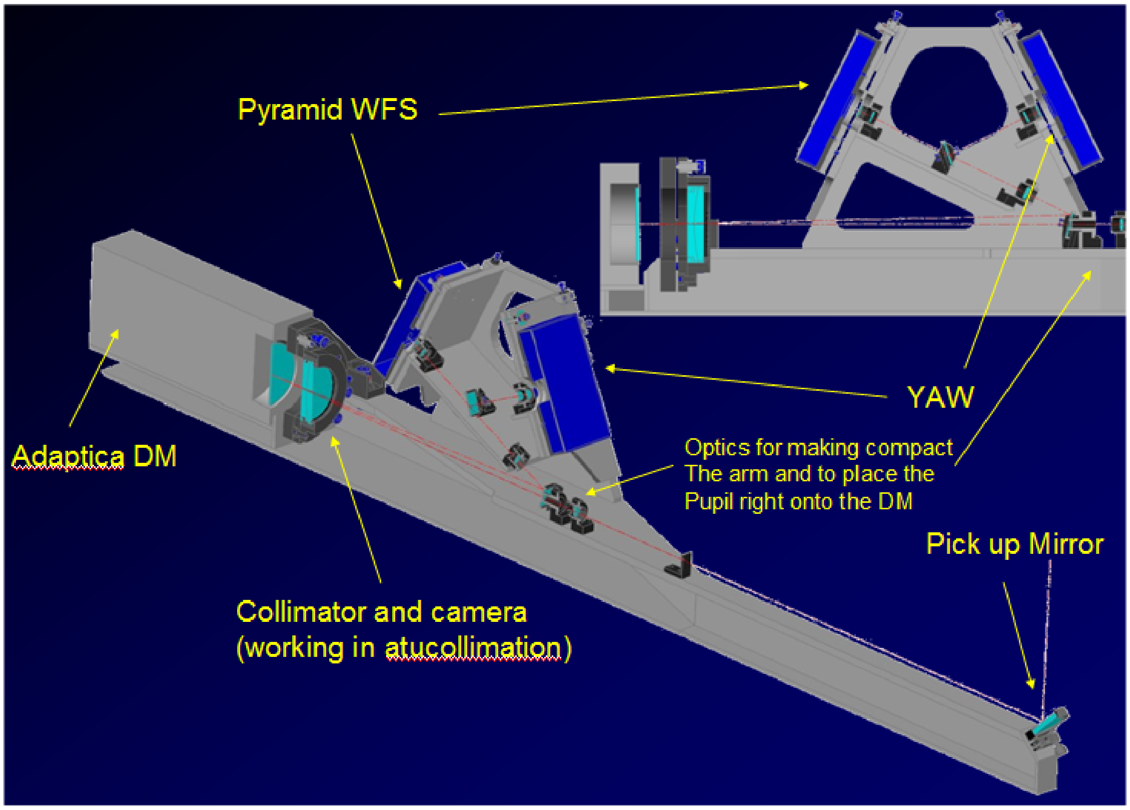

Figura 3 A possible optomechanical layout for a Very Linear WFS. In this case the collimator and the camera are the same group of optics and the DM is slightly tilted and used almost in autocollimation.

This WFS retains the advantages of a Closed Loop Pyramid WFS but offers the linearity of the YAW too, basically only limited by the dynamic range of the DM. The corresponding extension of the dynamic range of the YAW can be made at the expense of a brighter reference source, that has no other drawback in the described layout.

4. CLOSING THE LOOP

With the Very Linear WFS in action a sort of five virtual DMs are in operation. From these one can figure out the correction for any given direction (simply piling up with the proper geometry the corresponding WF) or to drive a – for instance – two DMs system like MAD. To make the latter true one has to retrieve the virtual DM information at the same altitude of the real one, and to co-add the others with a smoothing proportional to the footprint of the light beam pivoting on the existing DM and with an aperture given by the Field of View of the MCAO system.

Still this information is Open Loop and, in other words, the effects of non-linearity, hystheresys, saturation and so on of the DMs will be unseen and hence will unavoidably affect the quality of the resulting correction. However the same way applied to sense the DM in the WFS scheme can be applied as well here. Let us suppose for example to have a MAD-like two DMs MCAO. This is established after the WFSs so it would be apparently unavoidably in Open Loop. Now let us assume to have, at the edges of the science FoV a small number (like 3) other references that will mimics three reference stars illuminating the two DMs with such an angular displacement to basically cover all of their optical surfaces. Looking at these references after the MCAO module with three YAWs, extremely linear WFSs is equivalent to know in detail the shape of the two DMs. In fact one has to have a sort of tomographic reconstructor that will give in real time the actual shape of the two DMs. Please note that this is paramountly simpler than the real tomographic problem on the sky as it is known in advance, by construction, that the wavefront deformation occurs only at the two DMs locations. In this way one has on one side the five virtual DMs maps and the two actual DMs maps reconstructed. The commands to the DMs are now given by difference between the actual DMs shape and the projected one using the technique mentioned in the previous paragraph. Although this relies on a difference between two virtual layers they reflect the actual DMs on one side and the actual shape of the DMs that would compensate for a full 10 arcmin FoV correction.

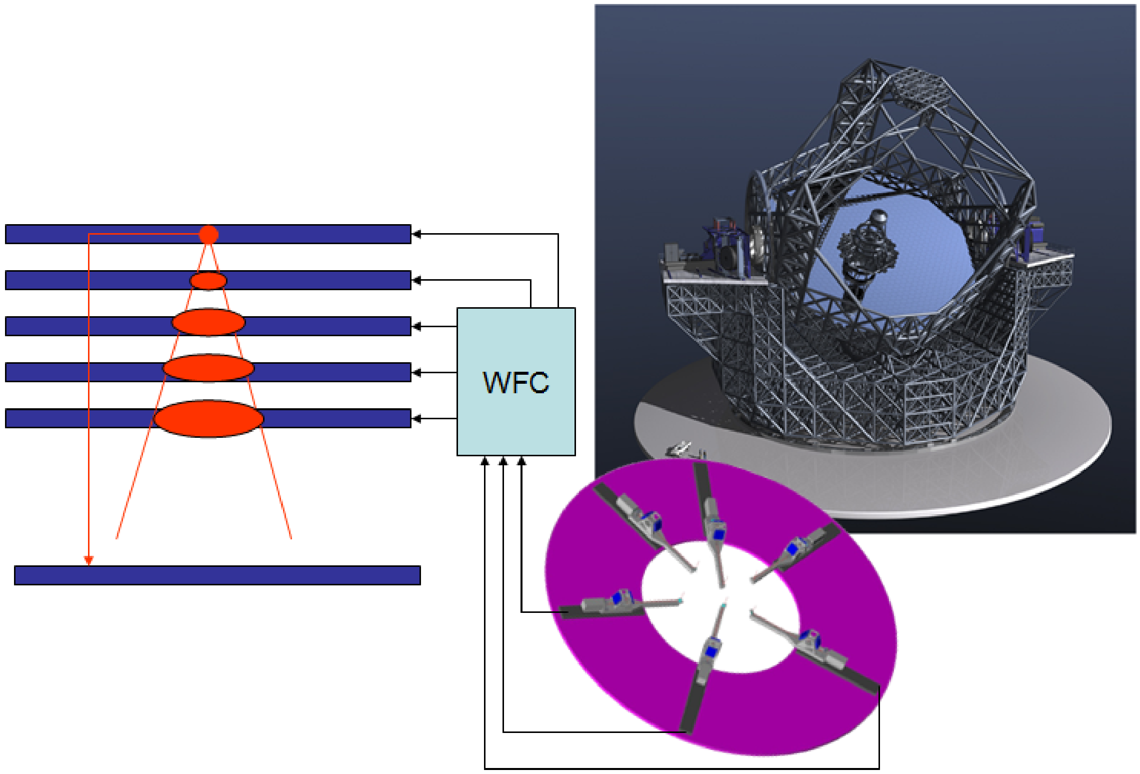

Figura 4 Once the five virtual DMs described in the text are build up in the WFC one can retrieve the signal to given to a certain DM at a certain altitude by coadding the virtual DMs with a proper smoothing given by the footprint of the FoV to be used for the scientific observations.

In this way the loop is, actually, definitively closed!

5. CONCLUSIONS

There is a number of details that goes beyond the limits of this paper. The sky coverage calculation, an error budget assessment, and a number of technical details are here just traced down. However one should realize that the FoV where to look for NGSs is now of the order of 25 times the one covered by MAD and, in principle, for a D=30m telescope whose optical design can be adapted from scratch this would translates into a MFoV MCAO with searchable areas that range from 8arcmin for the highest altitude layer to more than half a degree for the ground layer correction. A technique to assess the achieved SNR can be easily based upon the equivalent way of making the calculation for the full MCAO system and then deprojected. These results could also be tuned upon the actual results by MAD in order to be reliable enough to make a firm prediction on their performance.

Finally it is to be noted that this approach is only mildly invasive of a current telescope design as basically requires to add a few Very Linear WFSs in the acquisition arm and to add reference fibers and small YAWs on the instrumentation side. The existence of one or more adaptive mirrors in the optical train before the WFSs not only can be easily handled in the correction scheme but it would greatly reduce the requirements in terms of dynamic range in the local DMs.