PYRAMIDS, LAYERS AND NO LGSs!

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Abstract. A decade after the first achievement into the improved capabilities in sensing by the pyramid wavefront sensor and from the outlining of novel classes of Multi Conjugated Adaptive Optics experimental verification of such approaches has been vastly proved by results from MAD onboard VLT and from FLAO onboard LBT. Refinement and extensions of these techniques promises to achieve similar goals within references scattered in a Field of View much larger than the one being compensated, an approach only marginally exploited in the so-called Multiple Field of View approach while the adoption of virtual DMs would allow a much deeper exploitation of such possibilities. As in the meantime the diameter of the largest project shortened somehow it is time to gather all these concept, to assemble -possibly- in an efficient way in order to continue to pursue the goal of achieving diffraction limited imagery at a level concorrential with what is being promised by artificial references, by the usage of solely natural guide stars. The resulting approach is a robust one (as it is not incompatible with Laser generated beacons) and can be implemented into existing optical design of the current extremely large telescopes under development.

1. Introduction

In the last decade the Adaptive Optics arena populated by several novel achievements. Pyramids wavefront sensors working in closed loop proven to be particularly effective exploring the theme of efficient use of photons. Multi Conjugated Adaptive Optics turned from the realm of theoretical and numerical analysis to the astronomical results one, and the extension of the concept from « measuring » the wavefront in some direction and « applying » in some other ones, like in Multi Object Adaptive Optics, is moving its first steps in the steel, glass and true starlight world. I try to assemble these along with some ideas that circulated in the past together with some new ones in order to convince the reader that through the use of pyramids and the smart use of the concept of layers, it is likely that one can achieve the long standing vision of Adaptive Optics to the whole sky with solely Natural Guide Stars.

2. Pyramids

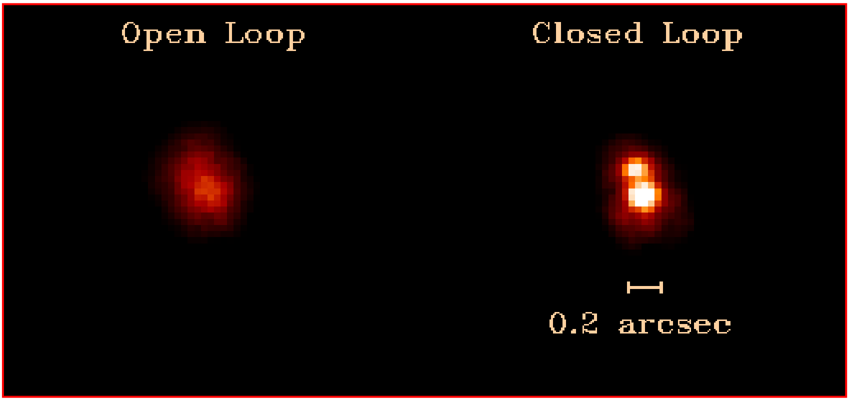
The pyramid Wavefront Sensor has been introduced more than a decade ago [1] with the initial aim to mimic the Shack-Hartmann (SH) one but with an arrangement of light onto the detector such that rebinning » of the latter would automatically translates into rebinning of subapertures without loosing in SNR because of the augmented effects of RON in case the same action would be performed with the conventional SH. This result was obtained at the expense of a continuous mechanical movement that allowed to change the dynamic range of the sensor, an opportunity that could be achieved anyway with the SH with the defocus of the spots onto the detector. The differences between the Pyramid and the SH were supposed to stay, at the time, just in the realm of practicalities. However, some time later, it has been realized [2] that, in analogy with the curvature wavefront sensor [3], the Pyramid exhibits a potential advantage in terms of sensitivity to the SH one. Although the Pyramid WFS has been actually implemented [4] in closed loop on the TNG (a 4m class telescope), a rough measurement of such a gain has been achieved on the sky in earlier times [5], and in identical conditions in laboratory at ESO in the framework of MAD a comparative measurements [6] of single reference AO has been actually performed (all giving results consistent with a prediction of a gain of about 2 magnitudes) it is only recently with the outstanding results obtained at LBT [7], that there is wide consensus that (following ref. [8]) « the high sensitivity and flexibility advocate the Pyramid WFS as the best choice for modern AO systems ». It is noticeable, however, that the basys for the augmented gain of the Pyramid were extremely simple assumptions for the low order modes (a small spots making a larger signal than a large one for the same amount of absolute displacement) and that its extension to high order modes was obtained through solid physics concepts like Heisenberg uncertainty principles. It should turn out not to be so surprising the striking matching of the prediction with actual measurements [9] obtained by the group working on Pyramir, another AO system for a 4m class telescope, whose sensor works in the NIR. Maybe a lesson learn is that any result from 4m class telescope is nowadays, in an era in which ELTs are coming on their way, appears not to be convincing at all.

The pyramid Wavefront sensor goes beyond expectations not only in the faint-end regime but also in the bright end one. It has been shown, in fact, that because of its much smaller sensitivity to aliasing with respect to the SH and the curvature one it is able to achieve, at high Strehl ratios, in both high and low photon fluxes, better performances than the SH, even with proper spatial filtering [10]. In an hypothetical comparison with a SH under similar conditions in a Strehl vs. Magnitude plot the pyramid WFS would outperform the SH in any area of the diagram! This, combined with its pupil-plane nature made of it as an ideal ingredient for the next stage in the AO development…

3. Layers

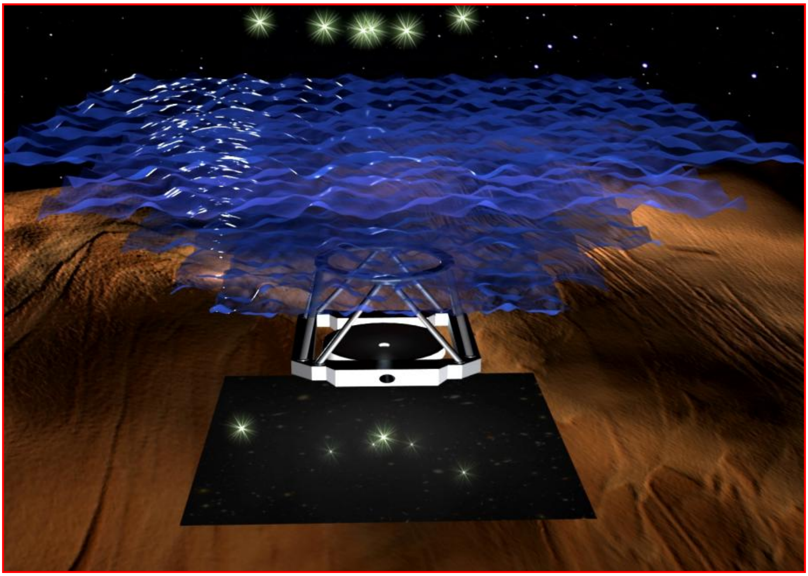
The naive picture of the atmosphere in the early times of Multi Conjugated Adaptive Optics was the one of just a few strong layers surrounded by a negligible amount of turbulence. With the exception of the outstanding intuition by Beckers [11,12] this concept leads to the early concept of MCAO to focus on correcting this or that turbulence layer.

Fig. 1 About ten years ago at the time of the Conference the first ever pyramid closed loop system onboard at TNG produced this non-dramatic picture of an anonymous double star.



The actual performance of a system, it turned out with the development of the matter, lie in the ability of the system to compensate for the "turbulence between the layers choosen for the correction". This are related to the Field of View covered, in the case that a fully closed loop approach is followed. This led to the wrong conclusion that the combination of practicalities (transparent correctors, after the promises of the first Liquid Crystal devices, turned out to be unuseful for their chromaticity and speed) and of fundamental reasoning made these system limited to a few arcminutes and with a sky coverage that, although can be very interesting, would lead anyway to a limited amount. These concepts [13] are behind the MCAO Demonstrator by ESO, MAD [14]. In its layer-oriented version [15], a technique depicted at the turn of the century, fully closed loop approach with a limited Field of View would allow for unprecedent science. And this has been the case. While the MAD with the three SH produced outstanding science, the layer-oriented Wavefront Sensor focused deliberately onto extragalactic science. Taking care of each single photon collected in an often poor of bright references Field of View we demonstrated that an amount of scientific results in the extragalactic arena, otherwise not obtainable from ground based instrumentation, was possible [16]. This, however, was already pushing on the edge of the technique. The Adaptive Optics system onboard NIRVANA on LBT is just the extreme stretching of this approach [17,18]. But the time to revive the vision depicted when just using geometrical superposition of starlight footprints was taken into consideration [19] has come from a few years and the key point here is to make dropping one of the assumptions that limited the Field of View to the realm of a few arcminutes. This assumption was to work in closed loop. Or maybe not...!!! In fact the idea behind the novel approach already outlined elsewhere is to use loop closure just where this leads to a huge advantage (the Pyramid gain in performance, the famous 2 magnitude for an 8m that can scales up to 3 magnitudes when an ELT is being considered). The basic concept behind is to makes a novel class of WaveFront sensors that actually are small closed loop AO systems. As they need to cover just a few arcsec (the dynamic range imposed by the seeing and a few other practical considerations) their optics can be simple and optimized along the wavelength used for the sensing itself (conventional AO system have to allow for both the optical and the NIR side of the spectrum to be correctly managed). The accurate measurement of the wavefront in open loop is achieved by monitoring the closed loop correction (i.e. the shape of the Deformable Mirror) combined with the residual. The degree of correction required here depends upon which is the residual non linearity of the WFSensor in closed loop (of course a Pyramid one is likely to be an optimum choice) and has to be traded off with the limiting magnitude at which it has to operate. Also, in the mean time, the development of low or close to zero Read Out Noise detectors allowed for an extra gain to be piled up into the scheme.

Fig. 2. Looking for stars over a rather large (i.e. 10 arcmin) Field of View and compensating it through five (real or virtual) Deformable Mirrors would achieve similar performances than the ones achieved through MAD..



Once a number of reference stars are being measured in order to establish what a significant number of DMs could leads to the virtual correction of a Field of View limited by geometrical consideration and practical ones (both limits converge toward around 10 arcmin in diameter for a 40m class ELT) this information can now be retrieved to actually close locally a conventional AO system (i.e. with just one DM) or any sort of MCAO system (like a central patch of 2 arcmin in diameter). It is to be pointed out that there are a number of variations on this theme that are possible and that, for practical reasons, are already available with the current ELT projects. In particular the E-ELT does employ a quaternary mirror with adaptive capabilities. This means that the turbulence optically removed by this DM is “gone” as seen from all the WFSs behind it. The dynamic range requirements and the degree of non-linearirty that is acceptable would be heavily relaxed.

Furthermore, the global knowledge of the turbulence details in real time in a truncated conical shape above the observatory would allow to a number of techniques (recalling here just the adoption of the Taylor hypothesys as a first guess of prediction for the incoming wavefront at any direction) to further improve the performance and are neither listed or speculated here.

4. Conclusions i.e. No Laser Guide Stars

Let's take MAD as a reference system. This is a 2arcmin Field of View MCAO system working fully in closed loop. That means that the reference stars and the scientific compensated area lies within the same region. In the Star-Oriented mode SH are envisaged while in the layer oriented one Pyramids are employed, however, often they worked in poor condition in terms of achieved Strehl. Also, we expect, as the prediction has been strikingly confirmed by the measurements, that the prediction into gain in the faint end should augment of about another magnitude. Looking for 1 to 2 magnitude fainter stars in an area that is 25 times larger (a 10 arcmin patch in the sky) would lead a 1% sky coverage approaching the full sky using just these simple arguments and "back of the envelope calculations. This leads to the speculation that this approach, with some optimization (now the degrees of freedom are becoming much more…) could be achieved on almost the whole sky with performances much better than the MAD one, although probably intermediate with respect to the ultimate ones obtained by the LBT system in its bright end regime. Laser Guide Stars can still be envisaged, of course, and in layer oriented fashion (numerical as well as optical) their conical feature is not a real drawback other than the geometrical coverage one. This is particularly unpleasant for an ELT, such that with LGSs one cannot probably expect very high performances and the gauge of the required performances could be adjusted accordingly. While the detailed calculation is well beyond this little paper it is noticeable that any decent sky coverage obtained with reference stars over a much larger patch on the sky size as we were used by current MCAO systems can remove the selection effects that mades AO working on the fields where other instruemtns would never be pointed at because of the bright references too close.

Finally on the YouTube channel PadovAdOpt you can find several illustrative movies to explain some of the concepts outlined above.

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