AO for ELTs. How much margin for innovation?

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ABSTRACT

Adaptive Optics for Extremely Large Telescopes could need to be frozen, at conceptual level, within a few years. This requires to identify the directions of innovation which can have some chance to give improvement by a large factor. I try to outline some examples of such possible developments, in order to get an idea of how much margin can still be available for innovating concepts in this recently growing field.

Keywords: Multi-Conjugate Adaptive Optics systems, Extremely Large Telescopes, Wavefront Sensors.

1. INTRODUCTION

Adaptive Optics for Extremely Large Telescopes[1,2] is a necessity and not just an additional gadget for a lot of reasons that I will not report here a further time. For this reason AO for ELTs is expected to work smoothly giving an almost full sky coverage with a stable and a constant Point Spread Function over the FoV. All of these features are exactly the opposite of what today any AO system[3] is able to deliver. Multi Conjugated Adaptive Optics[4,5,6] (MCAO), the usual answer to such a problem, is expected to behave much better, provided enough reference sources are available. In these days, and especially at this Conference, there is great expectations that an ELT can see its first light with a reasonable time scale and that very soon an AO system should be frozen at the conceptual level and engineering of such formidably complex system should take place. This means that it is very important to understand if, at a conceptual level, there is still room for significant improvement in the outline of the AO for ELTs. In other words, today it seems that there could be margin for innovation in AO for ELTs, only if these would potentially promise a large improvement with respect to the current concepts. I still think that the key point behind AO for ELTs is to try to accomplish the target of achieving almost full sky coverage with solely Natural Guide Stars. It is worthwhile to point out that such a target, although not completely reached, will possibly lead, as a by-product, to the possibility to use Laser Guide Stars with a much improved efficiency. This latter is a matter we are not going to attack here, however.

2. HOW FAR IS THE DREAM?

At the turn of the millennium there have been works depicting a scenario where the usage of solely NGSs was enough to provide full sky coverage for MCAO[7,8], especially for ELTs. The basic idea was to collect stars from an enough large Field of View and to use them to compensate for atmospheric perturbation in a three dimensional way. The newly introduced concept of Layer-Oriented wavefront sensor seems to provide an excellent hardware realization of such a vision. Soon after, however, it has been pointed out that there is some limits to such an achievement. These limits are of technical and fundamental nature (although the word fundamental is here misleading to some extent, as it will be clear in a while). An example of technical nature is that, due to the limited size of fast readout, low noise CCDs, some optical

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systems called stars enlarger are to be used to feed the light coming from a significant Field of View onto existing CCDs used in AO. These devices, although simple in concepts, require special care as they are very sensitive to the tilt, while moving on the focal plane to search for the stars to be used as reference for MCAO. Such a sensitivity, moreover, scales with the diameter of the telescope and, as a by-product, can become prohibitive to be moved in a passive way in an ELT. This would require some active control of these. All of these needs are of course feasible in principle and proper engineering could surely achieve the goal to perform layer-oriented over a significant Field of View of a few arcminutes. On the other hand they would require some additional hardware and the original dream of having a system where an easily positionable array of pyramids[9,10] can be scattered over then focal plane of the telescope, becomes slightly more distant than expected. The fundamental limit we are mostly speaking here, then, is given by the smoothing effect in the thickness of the atmosphere. The larger the covered Field of View, the thinner the sampled slab of atmosphere. This is an effect that, once co-adding wavefront information in a linear fashion, is unavoidable. That means, in other words, that enlarging the Field of View to collect more starlight, a larger number of DMs would be required, growing rapidly to an unacceptably huge number (a situation, by the way, that could dramatically change if refractive correctors would become available, an option that seems far from reality today, but where, maybe, not enough efforts are being currently spent).
We think that both the drawbacks mentioned here can be overcome in some way. For instance in the first case designs does exists that allow, at the first order, a large tilt of the so-called stars enlarger, without any displacement of the re-imaged pupils. These systems, depicted in Fig.1, are based upon the idea to fold the beam such that the two lenses building up a star enlarger are actually centered one over the other, making the concept of decentering of one lens with respect to the other inherently impossible.

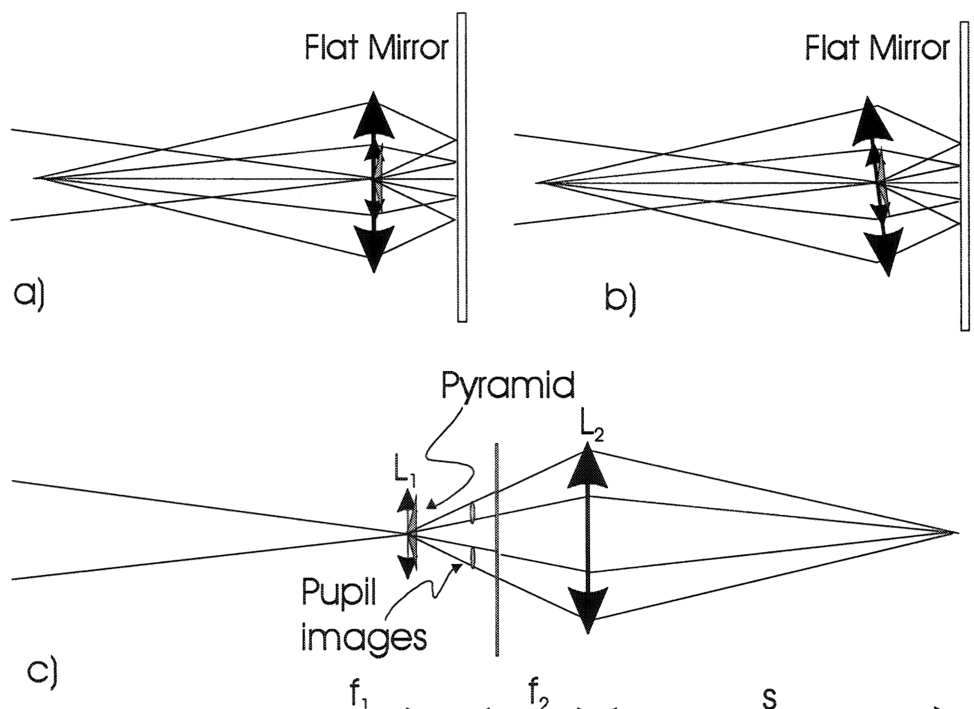

Figure 1 A star enlarger is essentially a small device build up with a couple of doublets able to locally augment the focal ratio on the pin of a pyramid. As the plate scale on the pyramid surface is augmented and this device is used to probe single stars we called it star enlarger. In a) the two lenses are physically concentric one to each other and thanks to a flat folding mirror on the right side the beam can be enlarged after a folding. A rotation of the group of two lenses and of the refractive pyramid, as in b) will not produce any displacement or bending of the rays. The unfolded design is shown in c) where are also annotated the two different focal lengths of the two lenses. The enlargement of the focal beam is roughly given by the ratio of these two figures.

Although there is still work to do in this direction, also the limit given by the Field of View could be, probably, overcome, just by overriding one of the assumptions made in the tracing out of the limitations for such a kind of MCAO system. It has been already shown that a quadratic signal can be used to compensate aberrations in MCAO, escaping the limits imposed by the linear superposition of wavefront signal. This can be done, for instance, in the way depicted in Fig.2. Further details are beyond the limits of this paper and are the subject of an ongoing study. However it is important to recall here that any quadratic approach will lead to the lack of knowledge of the sign of the measured aberration. This requires a control system that is, to some extent, unusual as it has to continuously learn which is the direction in which to apply the correction. Recently, a very simple trial and error approach has been implemented in a simulation of a layer-oriented MCAO system[11] leadings to the result that a shortage of the temporal bandwidth of the order of a factor two turns out to be required to achieve the same performances. It is noticeable that, provided the approach works fine as it is depicted here and does not encounter further limitations that are still to be uncovered, the loss of a factor two in bandwidth can be easily paid back by an increase in Field of View that could have no limits other than the ones of practical nature due to the optical design of the telescope. For instance vignetting will define a strong upper limit on the usable Field of View.

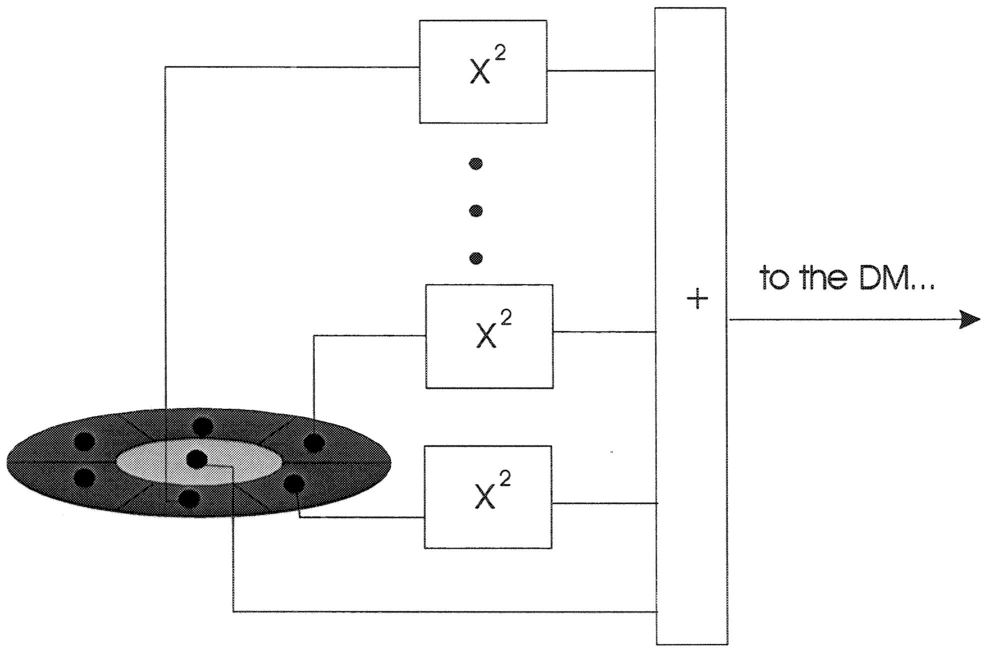

Figure 2 The Field of View of the telescope (in the lower left part of the picture above) is divided into a few regions of approximately the same size (for instance of the order of 2 arcmin). The wavefront data sensed in the annular region is then treated in a quadratic manner forming a quantity that, if properly used, can overcome the limitation due to the relationship between the used Field of View and the number of DMs required to achieve a certain correction.

It is not the first time that there is a consideration to be carried out about what often is considered a fundamental limitation. In this case, for example, the implicit assumption of linear superposition is taken for granted and it is probably enough to overcome this to enter into a realm (the one of non-linear control, in this case) that is vastly unexplored by the AO community. The indication that this could turn out to achieve the breakage of the link between coverable Field of View and the required number of Deformable Mirrors is a huge boost to push more efforts in such a direction.

3.TOWARD MORE EFFICIENT WAVEFRONT SENSING

Extension of sky coverage for ELTs leads naturally to the question if we have reached the ultimate in wavefront sensing sensitivity, especially at the faint end. I show hereafter at least a couple of examples where provisions for an augmented efficiency in wavefront sensing should be secured, especially for ELTs. As usual, these are just descriptive examples so, on one hand they deserve much deeper studies and analysis of the possible variations in order to be validated and, secondly, the existence of a couple of approaches does not exclude the existence of further ones, at least pointing out that simply we have not yet reached the ultimate limits and that some efforts to push that can be worthwhile.

3.1 HIERARCHICAL WAVEFRONT SENSING

The debate of Shack-Hartmann versus Pyramid wavefront sensing is still open, to some extent, so it is sad to use Shack-Hartmann in the following example but let's recall here that the size of the spot to be centered in this kind of wavefront sensor is of the order of the seeing limited spot size. This is a few times larger than the diffraction limit for a current ground based telescope but it will become a much and much larger ratio for ELTs. This means that, from a Shack-Hartmann perspective, the lowest order modes, requiring a coarse sampling of the pupil, could benefit by the smaller size of the spots to be centered, with respect to the finest sampling required for the highest order modes. The change in sensitivity is, at least in closed loop, huge. In fact the accuracy in centroiding a spot with a given amount of photons, affected by Poissonian shot noise, is proportional to the inverse of the square of the spot size. So, if one imagine a Shack-Hartmann wavefront sensor with a large number of sub-apertures across the diameter of the telescope pupil, the gain by just picking up a tiny fraction of the light and feeding with this an auxiliary Shack-Hartmann wavefront sensor with a coarser pupil sampling will lead to a marginal reduction of accuracy in the high order modes (because the light stolen to the fine sampling Shack-Hartmann lenslet array is a marginal fraction of the total) but a huge increase in the sensing of the low order modes. The above statement is correct only when the ratio in terms of sub-apertures across the telescope pupil is large. Assuming that such a ratio should be of the order of one order of magnitude it turns out that current AO systems should benefit, from the qualitative considerations we carry out here, by the addition of a channel sensing the tip-tilt only. It is not by chance that this is already what, in general, occurs in the existing AO systems. In fact the idea of split the light into several Shack-Hartmann wavefront sensors with different sampling of the pupil is simply just a generalization of the engineering approach to divide the light between tip-tilt and high-order modes.

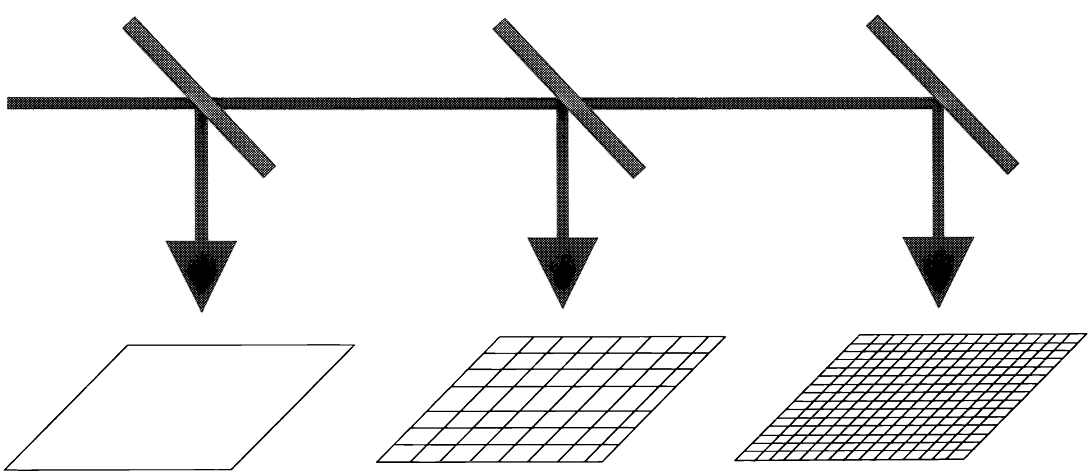

Figure 3 In a hierarchical wavefront sensor light from the reference star is split into a number of wavefront sensors with different pupil sampling. The number of sensors, the various sampling and the fractions of light split by the beam splitter depicted here are part of an optimization process that can also take advantage of the relative weight of the various sensed modes in the atmospheric turbulence.

We called this hierarchical wavefront sensing and it is clear by making simple numerical examples we are not going to report here, that in the case of Shack-Hartmann wavefront sensing, once in closed loop (the issue of bootstrapping being just mentioned here), the gain can be large. This will also depends upon the relative weight of low order modes and the effect of outer scale can be a relevant one. A detailed analysis of the problem is reported elsewhere[12]. In case of pyramid wavefront sensing the hierarchical approach is of some effectiveness only when RON of detector is relevant. Again, in the case of a large number of sub-apertures across the telescope pupil, as it will be in any ELT, this last point can be of some interest, at least assuming conventional state of the art CCDs, with RON of the order of a few units, in the faint-end regime.

3.2 CORONOGRAPHY AND WAVEFRONT SENSING

Several kind of coronographs work fine assuming the wavefront is perfectly flat. Failure of the coronograph to work is, hence, a sign of a not perfectly flat of the incoming wavefront. This simple observations leads to the speculation that an undisclosed class of wavefront sensors can be obtained by the coupling of a coronograph with some pupil viewer or other kind of parts of a conventional wavefront sensor. Let us take the simplest example of coronograph: a simple occulting mask in the focal plane. In geometrical approximation, once the wavefront is flat to a certain extent, no light will spill after the occulting mask. As soon as the wavefront will depart from a certain degree of flatness some light will overcome the occulting mask. If now a pupil reimager is properly in place a map of the region of the pupil where the wavefront is no longer flat can be obtained. It is easy to recognize that switching to a wavelike description of light such an "on-off" effect will translate into a smoother transition in the amount of transmitted light. As this is a sort of inverse Smartt wavefront sensor, and it is the most basic approach to this kind of detector, we would like to name this a Dumbb wavefront sensor. The basic advantage of this kind of wavefront sensor is that it will detect departures from flatness of a wavefront against a background of, essentially, no photons, leading to a net advantage in sensitivity.

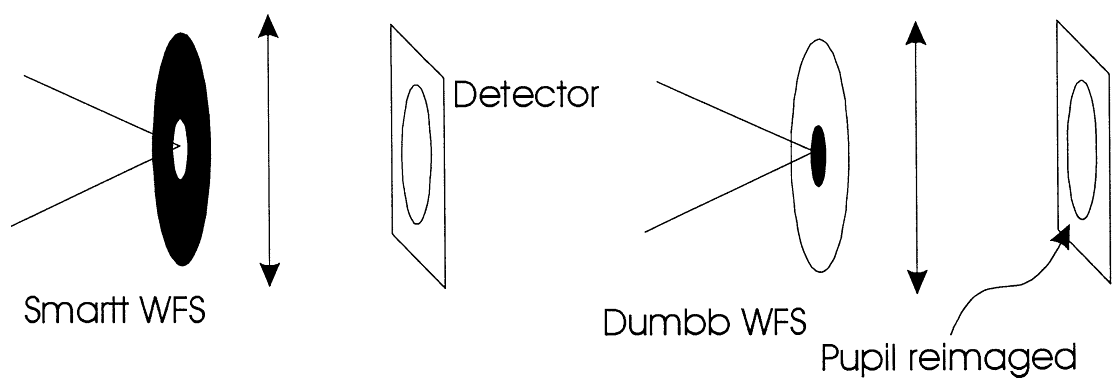

Figure 4. A Smartt wavefront sensor (left) produces an interferometric wave by light passing through a pin-hole, that interfere with the rest of the beam producing a signal, in a image of the pupil conveniently located over a suitable detector, proportional to the phase departure. In the right side a hypothetical Dumbb wavefront sensor will sense the light that is not properly blocked by the central occulting disk, a sort of primitive coronograph. The pupil image will exhibit a brightness depending upon the parts of the pupil that mostly depart form the perfect flatness.

This concept requires a better explanation. In general almost any kind of wavefront sensor is based upon some optical techniques to split the light into two or more channels. When these channels contain the same amount of light the wavefront is, at least locally, flat. This is the case of a Shack-Hartmann where the light is split into four quadrants and the wavefront is flat when the spots lie in the center of their four quadrant detectors. Once a perturbation of the wavefront is introduced some light is spilled from one channel to another. The detection of the perturbation is achieved when one is able to detect such a spilled light on the background of the usual amount of splitted light. Let us now suppose that in a conventional wavefront sensor a certain perturbation will lead to a transfer of the light channels (usually collecting, let us say, 100 photons each) of about 10 photons. As the Poissonian photon shot noise of the background (the 100 photons usually detected when the wavefront is flat) is of the order of the amount of spilled light the SNR of such a measurement will be of the order of unity, leading to a barely detectable event. Assuming that the same perturbation will lead in the case of the Dumbb wavefront sensor to the same amount of photons passing through the occulting mask, as these are to be detected against no background, the SNR of the measurement will be just the one of the Poissonian photon shot noise of the spilled photon, leading to SNR~3, a remarkable increase in sensitivity, indeed!

It is interesting that there are some hidden assumptions in the estimations I have carried out here. For example it is implicitly assumed that the amount of light coming from the source does not change with time, that is an important a-priori information in terms of optical knowledge of the source, but, in astrophysical terms is not a substantial one, with the exception of scintillation effects, that play a role in other kinds of wavefront sensors, by the way. Another important point is that unless you make a special arrangement (and this is not the case of the Dumbb wavefront sensor) you know which parts of the pupil are out of flatness and, maybe, to some extent, it is also possible to estimate the amount of deviation from flatness. However there is no clue on which is the direction one has to act to flat the wavefront. In other words the sign of the perturbation is lost in this kind of measurement. Just splitting the light into two channels and placing different kind of coronographs one can see that such a sign can be recovered, maybe at the expense of some sensitivity. A detailed work on this subject is, currently, missing.

4. CONCLUSIONS

In this paper I tried to figure out which could be some innovations in AO for ELTs that could be worthwhile to explore with some details. The examples described here are still at a rough and crude level and hence some work is needed to understand if they can maintain the promises of improving the sky coverage by an order of magnitude or so. I believe this, and other works, notably the ones from the Durham group, are depicting a scenario where still a significant margin for innovation in AO for ELTs does exists and that it is worthwhile to push research efforts in such directions in the coming years. These efforts can only make ELTs closer to reality with respect to what they are already now.

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