MCAO for ELTs

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ABSTRACT

The current status of the Layer–Oriented approach for the MultiConjugated Adaptive Optics techniques in the Extremely Large Telescopes case is reviewed. This includes a brief analysis of the variations of the concept as they have been conceived up to now, and which could be the developements one should expect (and hope for) in the near future, in the perspective of becoming MCAO for ELTs a reality. Then the concept of Multiple Inverse Bessel Beams, or Pseudo Infinite Guide Stars is given, along with some guidelines about what could be precursor experiments to be performed in order to validate and/or to gain experience in the field.

Keywords: Adaptive Optics, multi–conjugation, Extremely Large Telescopes

1. INTRODUCTION

MultiConjugated Adaptive Optics (MCAO[1,2] hereafter) for Extremely Large Telescopes (ELT[3,4] hereafter) is, for a number of reasons, mandatory in order to achieve most of the scientific goals that ELTs are supposed to deal with. From this point of view MCAO for ELTs can be seen as a potential *show–stopper*. This is the reason why not only a concept, but also precursor experiments on much smaller telescopes (the current generation up to 8..10m class telescopes) are going to be foreseen. In the following I will try to summarize the current situation on what can be done with the Layer–Oriented approach[5,6] for ELTs, by using solely Natural Guide Stars, and then I will introduce in some detail the concept of Multiple Inverse Bessel Beam (MIBB hereafter). In the first part I will try to show how a relatively moderate research in the field is going to take to several important results. As at least one layer–oriented based MCAO system is going to see its first-light in the close future[7,8], I will assume the developments will further continue. In the second part I would like to introduce a second step in the exploitation of MCAO for ELTs, as effectively using LGSs but in a complete different manner with respect to the traditional approach. The concept of angular gating, in particular, is not new and in fact something on MIBB reflects some previous proposal conceived[9] with the same aim. Although some precursor experiment on this subject starts to become conceivable, I would like to stress that we are living early days on this field and that in the near future for whatever reasons, the scenario could be as populated by several different concepts, as several of these maybe will remain in the realm of the dreams that will never became true.

2. LAYER–ORIENTED BEYOND THE EDGE OF AN 8..10M MIRROR

Layer–oriented MCAO is a technique to disentangle optically the correction specific for the turbulence arising in the volume around the Deformable Mirrors. In its basic form it is essentially an optical device that produces a three–dimensional, anamorphic copy of the atmosphere, with some pupil–plane wavefront sensor[10] as a detector placed in the proper plane. On this 3D copy it's possible get the signal proportional to some relationship with the wavefront perturbation (for example to the first derivatives, or to the Laplacian). As it is built LO–MCAO is by definition a subset of what is called *global reconstruction*[11,12] or sometimes *star*–oriented approach: where every (conventional) WFS looks at a single star and where the correction to the DMs is devised by a somewhat powerful WaveFront Computer.

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Before to enter into the realm of the exploited or sketched variations to the LO–MCAO scheme I would like to point out that is surely not by chance that today, to the best of my knowledge, the only two detailed simulations of MCAO for ELTs has been done[13,14] by two different groups (we didn't made any attempt in such a direction), both using variations around the LO–MCAO scheme. In fact the computational demand to perform LO–MCAO is by far smaller than the one for global reconstruction. In the original form of LO–MCAO, in fact, the computational requirements are a duplication (in case of two DMs) of a single, rather conventional, AO loop.

It is noticeable that some of the conclusions obtained by studying the LO–MCAO approach[15] has been done by more general approaches published so far[16], in particular about the effect of smoothing, or about the compensation, as far as a certain spatial resolution, for turbulence located at a distance relatively to where the DM is placed.

Another important misconception is that LO–MCAO is a complicated device. In fact carrying around on the focal plane small pyramids is by far less complex than carrying around some complete WFS so that, from a purely mechanical point of view, the LO–MCAO is surely a simpler approach. The major complexity of e optical layout is a reality, although this translates into a much simpler electronic and software arrangement.

The last word in all this business is given to our real target: the sky, it is interesting to look around for the MCAO systems being actually built. On this side the scenario is rather clear: the GEMINI system[17] is a very well shaped classical MCAO pursued with big efforts from the GEMINI AO group. Clearly, as LO–MCAO is a subset of classical MCAO (performed in a numerical fashion) there will be some possibility to test on the sky the LO–MCAO approach, but this is clearly not the target of a project explicitely designed to be an end–user for astronomical purposes. ESO is building at the VLT visitor foci (in a fast–track manner, with much less constraints than the ones usually imposed to VLT instruments) an MCAO Demonstrator[7] (MAD) incorporating both the star and the layer–oriented concepts as two different WFS with most of the other hardware in common. This is by far the most interesting approach in order to get an idea on the real field how the two techniques performs. For LBT, finally, we are building the LO–MCAO system NIRVANA[8] incorporating the varation with the multiplicity of the FoV used by sensing different turbulence volumes (the Multiple Field of View, or M–FoV variation[18,19]). The LBT is a telescope still in its erection phase, a phase with a single–conjugated secondary adaptive mirror[20,21] has to be implemented on the sky. Moreover, NIRVANA aims to get interferometric images by combining the light coming from the two telescopes. It is clear that, although such an instrument will have unique observational capabilities, there is some chance that its results will come in a timeline where likely most of the knowledge we are lacking now about MCAO will be already filled by other discoveries.

Other groups are working considering MCAO experiments/instruments on the sky. The conference where this paper is being printed is wide enough to give an overview about such topic but my feeling is that one or two years are still needed to clarify the directions where AO groups are moving forward.

It has been just mentioned the question about to perform LO–MCAO in a purely numerical or purely optical fashion (excluding, for the moment, tree–structured ways to perform such an approach optically and numerically, together), essentially raised up from the novel, almost noise–free, photon counting–like, CCDs[22] introduced by Marconi and Texas Instruments, recently. Although the debate is still in development, and much of the final outcome also will depends upon how much fortune such detectors will have in the real astronomical field. Some initial analysis has been performed[24], making the optical co–addition still superior, at least under a certain extent. About this point it is also to be noted that a fair comparison between numerical co–addition using almost noise–free detectors and optical coaddition using again this type of detectors should be made.

About M–FoV LO–MCAO we still have to note how some assessment on the sky coverages[25], the range of expected magnitudes and the number of stars collectable[26] has been pursued, although a very detailed analysis is still missing. Also the issue of the variation of Strehl across the FoV is not still being adressed with detail for this approach. However we should note that this effect will tend to be much smaller in importance for ELTs, as because the number of pixels required to sample at least at Nyquist level the PSF will imposes smaller scientific FoV. In fact, conceiving a 100m class ELT whose central FoV of 30x30arcsec (requiring a 60k x 60k detector to exploit) the variation of Strehl in such small area with the usual choice for M–FoV of 2 and 6 arcmin diameter for the high– nad ground–turbulence correction, usually leads to Strehl variations not larger than a few percent.

Surely this is an area where the choice of the asterism and the optimization of the gain of each individual star can provide further relaxation, although no particular efforts has been spent in this direction up to now.

We take this opportunity to mention that in the M–FoV the ground layer correction is performed with stars scattered in an annular rather than uniformly filled disk, region. This translates into a correction more concentrated along the range direction toward the conjugated layer (the ground one) as it is already known in confocal microscopy[27], whose LO–MCAO is a gigantic replica on kilometric scales.

As the telescope pupil overlap on the high altitude layers becomes larger and larger with ELTs typical apertures, it is reasonable to expect that novel concepts can be applicable to ELTs but not to 8..10m class telescopes. One example of these, but there is no evidence this is the only one, is given by the multi–resolution variation on the M–FoV theme, described elsewhere. Finally, keep little attention to non–linear variations of MCAO in general is needed. A second–order approach has been described in the past to get a signal proportional to additional DMs to be introduced in the optical beam[29]. The expense of a faster (of a factor two) detector reading and by imposing modulation in the pyramid wavefront sensing applied to LO–MCAO. Recent efforts seem to indicate the small relevance[30]. The practical disadvantages of this technique are likely to make it just an example of overcoming the simple linear approach. We are still missing, however, novel variations on MCAO based upon second order effects. As these could be, under a wide range of conditions, small ones, there is some chance that, maybe with the noticeable expection of system using LGSs as references, any concept will translates into something providing improvement of a big factor.

3. DOES LASER GUIDE STARS LOOKS LIKE STARS?

As someone said that the best approximation in the physical world of the mathematical concept of a point is a star, there is little doubt that the meaning of the last letter in the acronym LGS is a misleading one. This turn out to be true especially for ELTs where the elongation effect at the edge of a $D = 100$m telescope will be of the order of 10arcsec for a Sodium beacon. There are a number of effects on the design of an MCAO system for ELTs when one consider in detail the limited range of the Sodium beacon. The first interesting point is that, whenever one would like to use LGSs as references for exploting an even rather small FoV of the order of one arcmin, over an ELT, the off–axis angle of rays entering the pupil from these sources does exceeds significantly the typical number quoted for NGSs–based LO–MCAO. This does not only means that the complexity and the additional constraints imposed to the optical design by MCAO are larger for LGSs than for NGSs–based LO–MCAO, but that also the smoothing effect on turbulence located away from where the DMs are placed will be more severe. In other words, the depth of focus of such correcting devices will be shorter, and hence the correction capabilities will be proportionally diminished. The list of drawbacks of using LGSs in MCAO, at least in the *conventional* way does not end here. The optical properties of the optical system is different from an infinite source with respect to a finite. In fact, this sort of macrophotography required to ELTs in order to perform LGSs WFS translates into a number of calibration issues. The mentioned problems (and other technical ones, like for instance the huge difference in the location of the focal plane where LGSs form into the telescope structure) can be, of course, counter–attacked in a variety of ways, each leading, in the best case, more complexity and less reliability onto a system whose complexity is already beyond any ground–based instrument never done.

On the other hand, sky–coverage with NGSs soley, although it can probably be improved with respect to what is currently believed, by some technicalities we still have to exploit, will turn out to be unsatisfactory when one will consider the science opportunities of an high Strehl, pushed into the shorter wavelegnth, ELT ready operate in almost any point in the sky. The weak point in LGSs is, essentially, linked to their finite range. In other words most of the trouble linked with LGSs are due to the technical problems arising when *reimaging* of a source at $H \approx 92$km should be done. Moreover, because of these problems one is actually tempted to gate a Sodium beacon. Imposing on the LGS and on the detector, requirements/capabilities that will further add other complexity and operation difficulties and degraded reliability, at the further expense of a smaller efficiency of the fired power.

As often happens when the source of several problems is common, instead of trying to solve each of these, a much more effective way is to change the way the LGSs are sensed, such to avoid to make a real reimaging of the beacon and using instead the back–scattered light into a completely different manner.

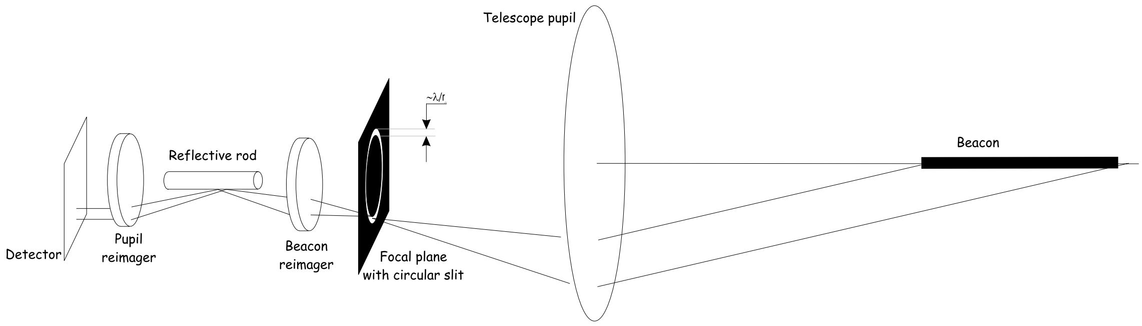

Figure 1. The overall conceptual layout of the inverse Bessel beam concept applied to an Extremely Large Telescope. A subaperture on the telescope pupil will be interested by a short segment out of the whole beacon. Curvature of the wavefront will imply a different length of the segment and hence a different illumination on the conjugated portion of the pupil.

The concept I'm going to describe is an example where LGSs are not used as sources but rather as lamps illuminating some region of the pupil and of the focal plane, a concept that leads to the nice acronym of Pseudo Infinite Guide Stars (PIGS, hereafter).

The basic idea is to isolate from the light emitted from LGSs portions of beams that are coming from virtual sources at infinity or, in other words, by selecting some parallel beams coming from the Sodium beacon. This can be made in a circular symmetric fashion by placing some circular slits into the normal focal plane, conjugated at infinity. The expert reader will note at this point, a strong similarity with the so–called Bessel beams [31](recently popped up to the media also because of a claimed super–luminal behaviour[32] that, as correctly reported by several auhtors[33], is just a geometrical effect and was well known from years) but with the inversed direction of light propagation, leading me to name the described approach an inverse Bessel beam. Of course such light, although it is originating from a circular source located at infinity, does illuminate only partially the pupil (interesting just a limited annular zone). Multiple slits can produce an uniform illumination of the pupil or, at least, to avoid regions of the pupil where no rays are projected. As this pupil filling is clearly more difficult (i.e. there is need of more slits) toward the center of the pupil rather than on its edge (because now the elongation perspective is treated as a positive resource) the larger central obstruction are, in a certain sense, favoured for this configuration. Taking typical figures for the range of the Sodium beacon[34] ($H \approx$ 92km) and a conservative estimate of the effective thickness of the Sodium layer (a full thickness for instance of $\Delta H \approx$10km) a number of about 11 slits are required to cover a D = 100m ELT with a linear obstruction ratio $\epsilon = 0.3$ as the OWL design.

The efficiency of the described approach, in term of light throughput, depends upon the density and the width of the circular slits. It is beyond the limits of this paper to show that a slit width of the order of λ/r_0 is equivalent to a time–gating giving a spot elongation smaller than the same amount. Because each slits does not cover the whole pupil, each slit is unefficent with respect to the usage of the whole LGS beacon beam, with the proper time–gating, just of the inverse number of required slits. Hence this turns out to be of the order of 10%. However, as soon as the way the wavefront is sensed (an issue that will be described in a few lines) has a linear behaviour, in terms of collected signal and a large amount of circular slits can be placed. For instance, for the above mentioned OWL case it turns out that the outer ring has a diameter of the order of $\approx$ 200arcsec while the innermost one is of the order of $\approx$ 66 arcsec in diameter (that naturally leads to a FoV usable for scientific purposes of the order of one arcmin in diameter, a generous one indeed). As using a spacing of 2arcsec between a slit and the subsequent one, a total number of the order of 33 slits, that is a factor of 3 *more* efficient than the usual time gating described so far. Actually, in fact, the way the rays are selected can be seen as a *angular* gating rather than a *temporal*. Although a concept, not completely new, it has been proposed in a more rough way in the recent past[9].

The numbers quoted above, however are meaningless if they are not coupled to perform wavefront sensing in a efficient way. For efficient we means some optical way to translates distortion of the wavelength fraction

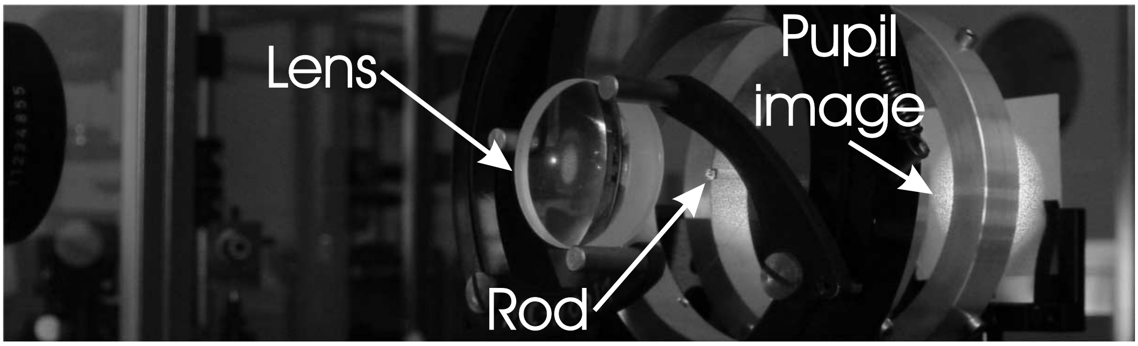

Figure 2. A preliminary setup of a z–invariant WaveFront Sensor to be implemented in order to perform scaled down simulation of the inverse Bessel beam concept.

order of the incoming wavefront to a large variation in the measured flux into some type of detectors. We have now to distinguish the radial and the angular part of the wavefront variation. In fact it turns out that the measurement of the pupil illumination, reimaged after passing through the set of circular slit, is proportional to the Laplacian measured along the radial direction. In order to be convinced about this (also see to Fig.1) one have to conceive that a different curvature in the wavefront passing through turbulence close to the telescope aperture (where the term *close* has to refer to the range of the LGS, that we suppose now to be a Sodium one, so that turbulence located at 10km of range are one order of magnitude closer than the beacon range) will make the light going through the slit coming from a portion of the beacon whose length will change accordingly to the curvature of the wavefront as measured along the radial direction. The remaining component of the wavefront, that is its variations along the angular direction, can be obtained by using a z–invariant wavefront sensor[36], originally conceived for Rayleigh beacon. The interested reader should give a look to the cited reference where she/he will note that the sensing of perturbations measured along the angular directions are by far more efficient than the one measrued along the radial one. But in this case one can easily see that a perturbation of the order of a wavelength fraction over a subaperture of the order of r_0 are such to change even more than 50% of the light collected in the pupil. In other words the system can be made extremely sensitive (probably one has to conceive some tools to bootstrap the loop when the aberrations are by far too large).

A small prototype of this type of wavefront sensor has seen the light in the lab recently and we are going to perform scaled down tests onto an optical system simulating an extended beacon (see Fig.2).

As this type of WFS will measure the Laplacian of the wavefront as described in polar rather than rectangular coordinates, over a single image of the pupil, it can be used directly in a Layer–Oriented fashion, as splitting the light into two or more channels and by refocussing different detectors where the DM is located. More than one LGSs can fill completely the volume of atmosphere over the telescope aperture. It is interesting to note that circular slits in the focal plane will be shifted with respect to the optical axis of the system, depending upon how much the beacons are fired into a tilted direction with respect to the telescope axis. The filling of the pupil, on the other hand, will take place around the intersection of the firing location with the pupil plane itself. This will privilege multiple launching of LGSs from the cage of the secondary mirror unit, but of course a much more detailed study is needed.

4. CONCLUSIONS

The LGSs–based (or, better, the PIGS–based) concept described so far as an extension of the NGS–based LO–MCAO: does not require further constraints onto the basic optical design of the telescope, as it concern beams coming from sources (although virtual ones) located at infinite range from the telescope aperture. A development program can consider to use as much NGS–based technology as possible. This will also make the PIGS–based approach more robust and/or requiring less firing power. The efficiency of the system can likely be much more than the factor 3 described in the text because the efficiency for the sensing technique can be made significantly larger than the conventional ones. This probably translates into power needs already in the range of the currently developed Sodium–line laser[37,38], without making any constraint because of the pulse format[39] (actually a CW laser will works fine as well, with a better exploitation of the Sodium population in the mesospheric atmosphere). After laboratory demonstration, which we are actively pursuing, an on–sky demonstration would be essential to push forward this development (and maybe to point out toward variations on the theme or much more interesting novel concepts still to be unveiled). The latter can be, at least in principle, performed, on a smaller scale, with a Rayleigh beacon over a current top–class telescope, aiming to perfomr WF sensing of the lowest layers of the turbulence. Both a detailed, althouh conceptual, description of the layout of the WFS in its final configuration for an ELT and for a Rayleigh demonstrator are beyond the limits of this paper. It is evident, however, that the coming years can make the vision of MCAO for ELTs much more clearer than what is today, and it could happens that approaches that now are beyond our immagination, will soon be disclosed.

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