DEALING WITH TURBULENCE: MCAO EXPERIENCE AND BEYOND

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Multi Conjugated Adaptive Optics, thanks to the Multi Conjugated Adaptive optics Demonstrator, MAD, of European Southern Observatory, entered in the realm of producing astronomical science after more than a decade. I review our experience with the Layer Oriented Wavefront Sensor paying special attention to the practical influence of the encountered atmospheric turbulence on the achieved science. An outcome, maybe very personal, of the perspective in the near and not so near future are outlined.

Keywords: Multi Conjugated Adaptive Optics; Extremely Large Telescope.

1. Introduction

Multi Conjugated Adaptive Optics (MCAO hereafter) is a technique for achieving correction of astronomical images distorted by the atmosphere turbulence over an “extended” Field of View.[1] The concept of “extended” here means significantly (by a factor of a few to several...) better than the isoplanatic patch size. This is accomplished by optically conjugating more than a Deformable Mirror (DM) to different heights of conjugation along the line of sight of the telescope. With a little oversimplify this means that the correction of the turbulence does no longer happens on the flat realm of the telescope pupil, just characterized by two dimensions, but it deploys also along the line of sight of the telescope, in the volume of turbulence that lies in the path of the telescope. The turbulence occurring in the conoidal shaped region on top of a large telescope acquires, in this light, a new relevance. To make a meteorological example MCAO "changes" the way one have to look in to turbulence. The same way as different problems make a different view of the same meteorological conditions. The same judgment of the meteorological conditions can be extremely different if you are looking for a leisure walking, driving or for flying, just to make an example. A combination of low ceiling with no precipitation can make flying unsafe and prohibitive, but still acceptable for both walking and driving, while a very thin fog can make vertical visibility acceptable for flying and unsafe for driving or unpleasant for walking. Adding a third dimension can makes our judgment of a situation completely different. This is true also for turbulence. A strong turbulence almost concentrated on the ground layer can make MCAO extremely easy, in spite of the total integral of the image deterioration being worse than a situation in which the degradation of the image is caused by a large number of distributed thin layers all scattered over the whole column in the line of sight with not, or little, concentration toward the ground layer. Switching to MCAO, it can pos completely new problems, so that, for example, it is irrelevant in conventional Adaptive Optics if the ground layer thickness is 10m, 100m, or 1km, while this would makes huge differences and poses strong limitations or imposed different technical approaches if the same imaging problem is attacked through MCAO. Also, MCAO is somehow generic as statement, although it clearly indicates that we care much more how is the vertical distribution of the turbulence, on top of the bi-dimensional one on the pupil surface, making the integral of the turbulence, what is generally called "seeing" to make a step back in terms of importance. If MCAO is developed at a point that the volume of the atmosphere sampled by a certain DM has, or it can be assumed to have, the same horizontal speed, the accuracy of a wavefront prediction based upon the Taylor's hypothesis (the one of "frozen layers") can makes a huge difference in the limiting magnitude, or in the Signal to Noise Ratio attainable with a certain Laser Guide Star, in the MCAO correction. Dealing with turbulence using MCAO, in other words, open a completely new realm and it is obvious to me we are just starting to scratch the surface and interesting news are awaiting us. In the following I will try to give a short background to the problem and to express my impressions on our experience with MCAO, and my initial views on what can going to happen in the near future.

2. A Brief History of MCAO

The "father" of MCAO is, without any doubt, Jacques Beckers. In a couple of short, little, probably kept for too-futuristic for some time, conference papers[1,2] wrote around the end of the 80s encompass most of the concepts that will be revisited in the decade occurring about ten years later his work. The most relevant one, that I would like to recall here, is that, in principle, and with the proper knowledge of the turbulence, and assuming that the turbulence power is uniformly distributed along the vertical axis, the introduction of a DM can account for the same volume of turbulence individuated by a certain distance for the conjugation of it. In other words, in an MCAO with a certain Field of View, each DM can compensate turbulence up to, say, a certain distance from the DM. If this distance is, just to make an example, 5km, one DM can only compensate for this turbulence, and the residual one will deteriorate the whole image. This is the concept of Ground Layer Adaptive Optics. If you place two DMs and one is conjugated to the ground, while the other is conjugated to 10km, under the same assumptions of the previous example, you can achieve compensation till 15km. Also, this makes clear that the larger the number of DMs, the larger Field of View you can provide is (almost linearly, if you are forced to place one DM conjugated to the ground). It is interesting to see a theory of a complicated thing like MCAO not using one of that odious power like 6/5, or 11/3 so much common in this field. The rest of the development of MCAO involves so much people and it is impossible for me to make a fair review of all the persons that made a development into this realm, also because of mine and mine co-workers involvement. So, I will stitch to the concept of Layer Oriented (LO) for a while. The reader interested to the technical details of course should read the related[3–5] but the important thing I would like to make clear here is that, as in MCAO the new thing is to make more than one DMs coupled optically with different "heights" in the atmosphere, Layer Oriented is the one that physically (optically) makes this also for the WaveFront Sensing part. Conventional WaveFront Sensing of several stars and "fusion" of these signals into a computer makes, virtually, the same approach, but this is achieved inside a WaveFront computer, with the advantages of flexibility and the disadvantages of Signal to Noise Ratios (just to mention a couple of things, and not the less controversial, or at least the ones for which, depending upon the type of sensing, coupling, or algorithm, things can dramatically change). In my poor and maybe isolated opinion, moreover, simulations, in the realm of MCAO, becomes more and more difficult or, better, the results from simulations are increasingly more difficult to interpret, just because of the massively augmented degree of freedom of the problem. This means, just to be a little more explicit, that the number of assumptions one have to make are much more, and that, as for a journalist writing a piece on politics, choosing this or that assumption, model, distribution, number and/or position of stars, explicit or implicit assumptions, the results can be made to vary in a rather large span of figures. It can happen that, based on a (detailed) couples of simulations based on a long chain of (realistic) assumptions, a result is obtained and that, also for some sociological behavior of the Astronomical community, a certain result is given for granted or for "typical" while, maybe this is not the case. As this paper is dealing with "my" experience on dealing with turbulence in MCAO I can say we spent a lot of time and efforts into developing a simulation code using real stars distribution as actually observed in the sky using input catalogues as we were interested into assessing the sky coverage of this and that technique. Then all of these figures can be varied by factors of "several" just because of assumptions on turbulence, or on the spectral sensitivity of detectors, and a lot of other factors, making the efforts to refine the "second digit" almost useless. Anyway, given I was outlining my personal view on the development of MCAO I think a good series of event happens at the turn of the century (wow... I always wanted to write a phrase like that...) with basically two projects taking place: namely MAD at European Southern Observatory (ESO) and the MCAO at GEMINI. It is remarkable, in that time, the first open-loop measurements on the sky,[6] made with the TNG telescope from the Canary Island sky, using an asterism suggested as a nice gem to observe in an eyepiece of an amateur astronomer's telescope in the magazine "Sky and Telescope". This piece, have shown for the first time with direct hand-on measurement in the sky, that MCAO was possible. Not that really anyone working into it doubted, but still it has been an useful thing to push toward the situation of today. The two projects I mention developed under completely different paths. ESO developed a MCAO Demonstrator (that explain the MAD acronym) that turned to reality through the efforts of Enrico Marchetti and co-workers,[7] while the GEMINI system[8] run under the visions of Francois

Rigaut and, at least for most of its initial phase, Brent Ellerbroek. MAD was supposed to be without any specific dedication to achieving this or that limiting magnitude or sky coverage, and was supposed to be used for purely technical purpose with no science in mind at all. I vividly recall a discussion in which I was the only one claiming we should focus, at least partially on making science with it. As usually happens in life, then it turned out that science becomes the main focus of ESO on MAD and in fact most of its impact on the Astronomical community is surely depending upon this. So, in fact, I made an implicit step in my narration and we arrived to nowadays where MAD has been successfully used on the sky several times.[9] The Layer-Oriented wavefront sensing has been operated on the sky as well, although in a completely independent run.[10] I still think Layer Oriented is a more efficient and "cheaper" (for example in terms of number of pixels to be used in the wavefront sensor) that the conventional sensing of individual stars, but I do not want to take this opportunity to stress this even more here.

3. MCAO (LO), Finally on the Sky

And so, after almost twenty years after the "vision" of Jacques Beckers and seven years after having got proof that MCAO was doable on a night telescope we had a run of nine contiguous night with the Layer oriented (LO) wavefront sensor onboard MAD. The first three nights were devoted to technical assessment of the performance on the sky. Efforts to make this useful to science as well as by product failed as it was required to use narrow-band filters only in order to avoid troubles in the determination of the Strehl in the observed field. So, the total number of useful night for science purposes is actually six. We observed targets ranging from pulsars around isolated stars,[11] to Globular Clusters,[12] to extragalactic objects like nearby dwarf galaxies,[13] BL-Lac, high-z galaxies, QSOs and their jets. In most of these cases we get data useful enough to produce a peer-reviewed scientific paper. No one wants to compare these efforts, produced by a handful of volunteer, with respect to the European-wide efforts made in three runs by ESO to furthermore exploit the capabilities of MAD. The important point here, is just one, and common: MCAO works, and it can produce science at the forefront of knowledge. It offers an unprecedent quality over a relatively large Field of View and, given that at NIR wavelength the diffraction limited size matches the one of HST, I have finally see combined images HST (visible) with MAD (NIR) in which the comparison between the two is not clearly in favor of the space telescope. It is remarkable that the ratio in size of HST with the VLT is so close of the one of JWST with next generation ELTs. Instead, I would like to focus on different aspects. For example, again, as in the beginning of this paper I just mention that adding a further variable the judgment and assessment of an MCAO system becomes more depending upon different assumptions, the same can be said for science capability. There has been endless discussions and an uncountable number of documents in which it is stressed that one imperative for MCAO is uniformity of the quality. In spite of this, I have seen exceptional, outstanding published results obtained with PSFs whose Strehl varies of a large factor over the Field of View of the camera. Also, the quality of the results are still very depending upon the initial turbulence conditions. And, finally, and maybe the most important thing, I still believe it is questionable if the results of the run, or of any run, of MAD in the sky can be used to make a definitive assessment of the sky coverage attainable with solely Natural Guide Stars. Any answer, in fact, will be plagues upon the assumption of the condition of the turbulence in the nights when the run actually took place. Why such a crude statement??? If the result of an Adaptive Optics system would solely depends upon, say, the seeing, you could "place" the result of the MCAO-MAD run in the context of the (well) known statistic of achievable seeing. So that if you get tantalizing results into night of exceptionally good seeing you could question its usefulness, while if the same results are obtained into night of poor or average, in statistical sense, seeing, you can place a big crown on such a technique. However, as I mentioned earlier, this is not so simple for MCAO as the number of variables in the game are much larger. Some of them are simply not known, and some are not used in that particular MCAO experiment. I mention sometime the Taylor hypothesis and clearly if one would be in the position to use it to "integrate" for a much longer exposure time the wavefront sensing measurement (please note that there is no mention of the word "prediction" in such a statement) the limiting magnitude can be conveniently augmented. In principle, the only limit to this is given, eventually, by the ratio of the size of the telescope diameter with the Frieds parameter of the focused layer, a number that could easily exceeds one order of magnitude. MAD uses solely Natural Guide Stars (NGS), so that all the technical and fundamental troubles affecting Laser Guide Stars (LGS) are ignored implicitly. However the other MCAO instrument that is going to see the light in the sky soon, the MCAO system at GEMINI, heavily rely on these artificial references. In this moment I can only states that it will be extremely interesting to see the classes of results and of performances that will be obtained. For the moment, as I have been generally optimist about the usability of NGSs instead of LGSs, it can only be seen as suspicious the statement I am doing, that among the three 8m class telescopes where LGSs are routinely usable, the results and the efficiency have been widely different. A subtle indication that, furthermore, the realm of variables playing in this difficult game is even more large, in spite of the common thought that LGSs will make the use of MCAO more uniform and seamless. It is worthless to say that we are all looking forward to see the outcome of the GEMINI system in the very near future.

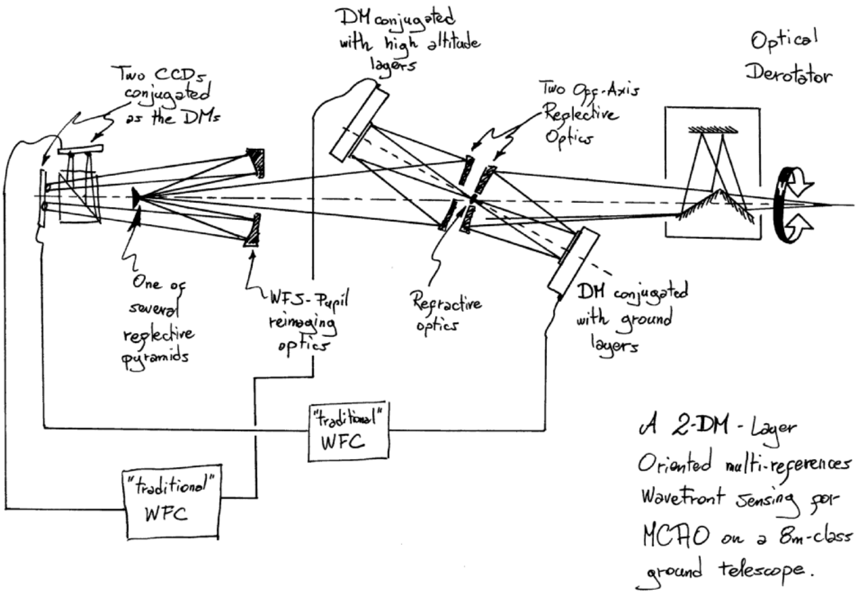

Fig. 1. A sketch of the MAD-LO "optical design", about 1999.

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