Mem. S.A.It. Vol. 75, 245

Memorie della

Adaptive Optics for Large Telescopes

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Abstract. At the turn of this new millennium several projects for 100m–class telescopes received special attention. If these will turn into giants of glass and metals, or will remain in the realm of the unfullfilled dream will depends upon a number of facts. One of these is, at least on the technical side, to outline and demostrate a credible road–map for the development of adaptive optics for these telescopes. I show here my personal one along with some considerations specific for the Canary site.

1. Introduction

Adaptive Optics (AO) is a difficult technique that offers almost diffraction–limited imaging at a certain *price*. Part of the price does not depends upon the dimension of the telescope at which the AO system is installed. Examples for such a kind of issues are the augmented emissivity, the limited sky coverage and, at least to some extent, the diminuished reliability of the observations. This means that, as the gain switching from seeing–limited to diffraction–limited is clearly scaling with the diameter of the telescope (and sometimes quadratically, for instance for the case of detection of background limited, point–like objects), an AO for a 4m–class telescope is on the edge of fruibility and, in fact, sometimes it can be surpassed by lucky nights at a telescope located on very good sites. ON the other hand, AO can clearly overcome any other current system, including HST, when used on an 8m–class telescope, like NAOS–CONICA, I believe, is starting to show in these days (Schodel et al. 2002).

As a result it is clear that AO for future, Extremely Large Telescopes (ELTs, Gilmozzi 2000, Nelson 2000,Ardeberg, Torben & Espinosa, 2001), is more than an additional gadget but it will boost its performance to figures that can substantially change its scientific capabilities, and hence will dominate the choice to invest a large amount of funds and manpower to turn into glass and metal such tools.

As far as sky coverage is concerned there is little doubt that the breakthrough in this direction is given by means to enlarge the corrected Field of View (FoV) of these telescopes.

2. Multi–Conjugated Adaptive Optics

Multi–Conjugated Adaptive Optics (MCAO hereafter) is the obvious answer to the enlargement of the compensated Field of View as it overcomes the problem of the limited size of the isoplanatic patch size (see also Fig.1).

MCAO can also be seen as a sort of closed–loop tomography: the technique to disentangle the contribution to the starlight deterioration by the atmosphere from the various layers. Today there are several projects running to perform MCAO on the sky: among these is surely the project under design at the GEMINI

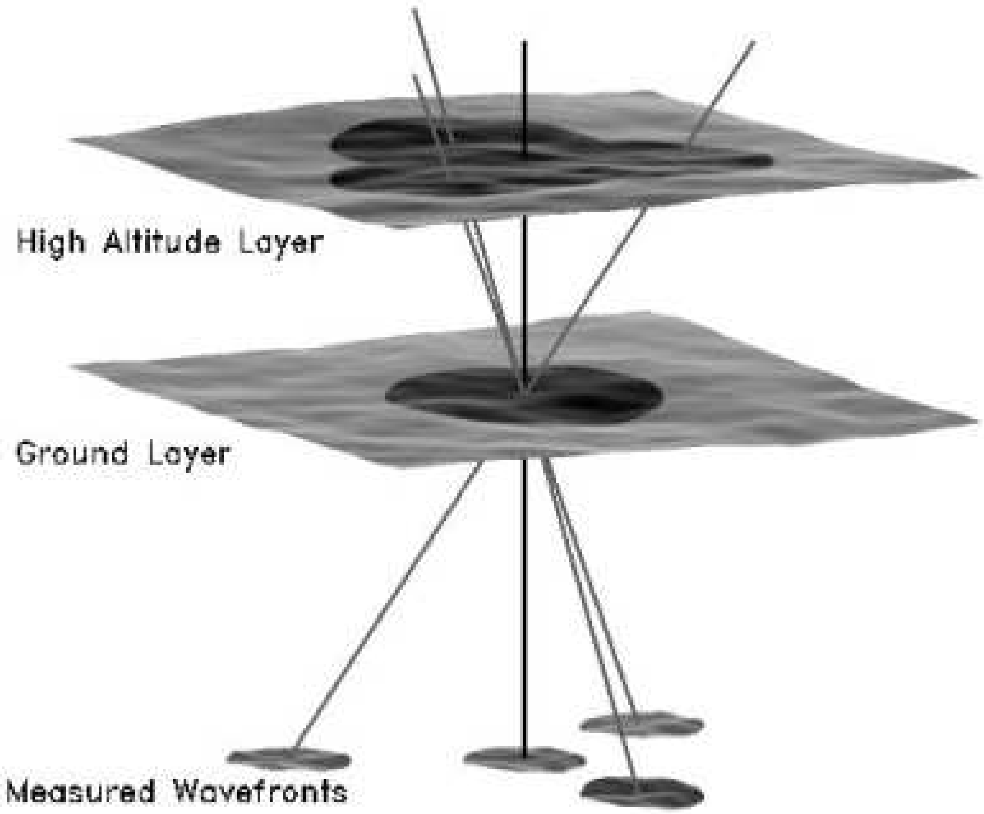

Fig. 1. Anisoplanatism is a consequence of the deployement in three dimensions of the atmospheric turbulence. In this pictorial view two turbulent layers are outlined in the regions where the footprints of the beam of a telescope looks into four different directions. The distortion of the coming wavefront experienced by such four directions is common for the contribution coming from the lower, ground–based, turbulence layer, and it is strongly different for the high–latitude contribution. Tomography is the open loop technique to retrieve, for instance, the central line–of–sight wavefront deformation starting from the three outer measurements. To date only open–loop experiments have been succesfully attempted, the first actually from the Canarian sky.

where an ambitious system with 5 Laser Guide Stars (LGSs) should accomplish the goal of uniform Strehl on a large FoV over one of the two 8m-class telescopes (Rigaut, Ellerbroek & Flicker 2000). As this is clearly the project with the most strong scientific drive at least two other are noticeable here: the MCAO Demonstrator (MAD) by ESO and the project NIRVANA (Herbst et al. 2003) aboard LBT (Hill & Salinari 2000). The first is mostly run by ESO with two collaborations by our group for the delivery of a Layer–Oriented WFS (see also Fig.2) and by a Portugal group to deliver the cryogenic and optomechanical side of the Near InfraRed camera: a 1 by 1 arcmin FoV, Nyquist sampling at K band, movable on an X-Y stage in order to cover the whole 2 arcmin in diameter FoV.

NIRVANA stands for Near InfraRed and Visible Adaptive iNterferometer for Astronomy (Carbillet et al. 2002) and it is equipped with a couple of Multiple FoV

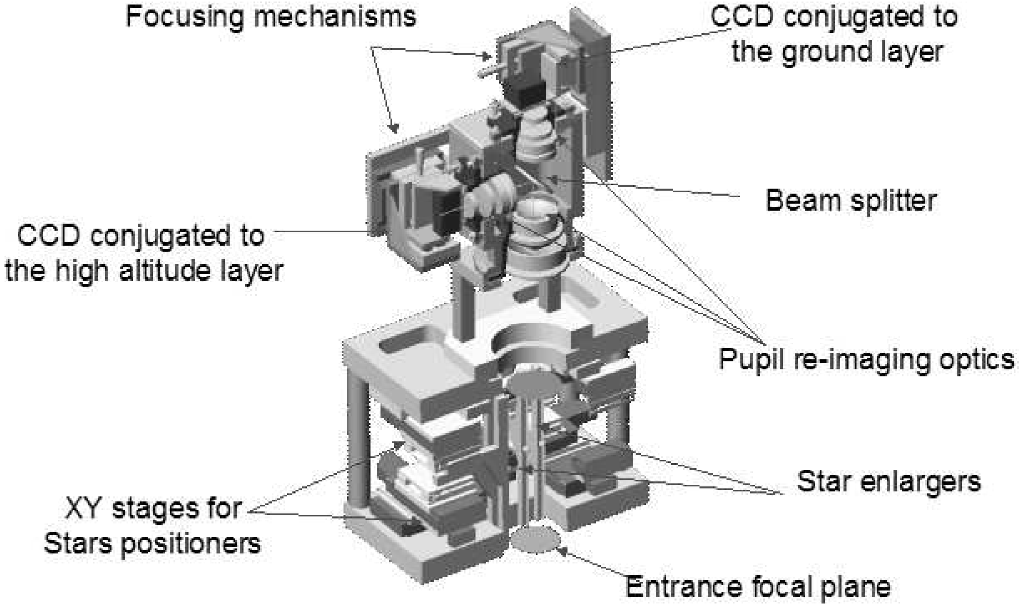

Fig. 2. The layer–oriented WaveFront sensor for the MultiConjugated Adaptive Optics Demonstrator of ESO is shown here in a CAD cut–through. The sensor is able to feed two detectors conjugated to two different layers, from a maximum of 8 reference stars spanning a circular area of 2 arcmin in diameter.

MCAO systems (Ragazzoni et al. 2001, 2002a). These can search for natural reference stars over a FoV of 6 arcmin in diameter for the correction of the ground turbulence (see also Fig.3) and to the central 2 arcmin in diameter (also the maximum achievable FoV in the scientific train) for the correction of the second and eventually for a third layer.

Layer–oriented approach, it is maybe interesting to recall here, is a technology that, essentially, would provide in an optical way, the reconstruction of the shape to be applied to a DM conjugated to a certain layer altitude (Ragazzoni 1999, Ragazzoni, Farinato & Marchetti 2000, Diolaiti, Ragazzoni & Tordi 2001). It is also a real closed–loop system, as several other possible kinds of MCAO exhibits to some extent some non–closed–loop behaviour and hence rely, for instance, on the linearity of the WFS, an issue not discussed here.

There is no doubt that these, together with other similar projects, maybe on a smaller scale, currently envisioned in the coming time, will make clearer direction on which are the realistic options for adaptive optics on ELTs in the near future. Such a technique is currently pushed by using a combination of several pyramid WFSs (Ragazzoni 1996, Ragazzoni & Farinato 1999, Esposito, Feeney & Riccardi 2000).

MCAO, in fact, is a strict requirement for an ELT from several points of views. First of all, the limiting magnitude of a telescope range with the fourth power of the diameter, when this is background limited and the image is diffraction limited (or at least the Strehl is significantly larger than, let say, 10%, and it is uniformly used through the comparison) making almost full sky coverage for ELTs a mandatory scientific driver. Secondly, instruments are close to unfeasibility when a seeing–limited telescope is considered. Although probably a size of the order of $D = 30$m is still the maximum limit at which one can consider to build a seeing–limited instrument, to convince the

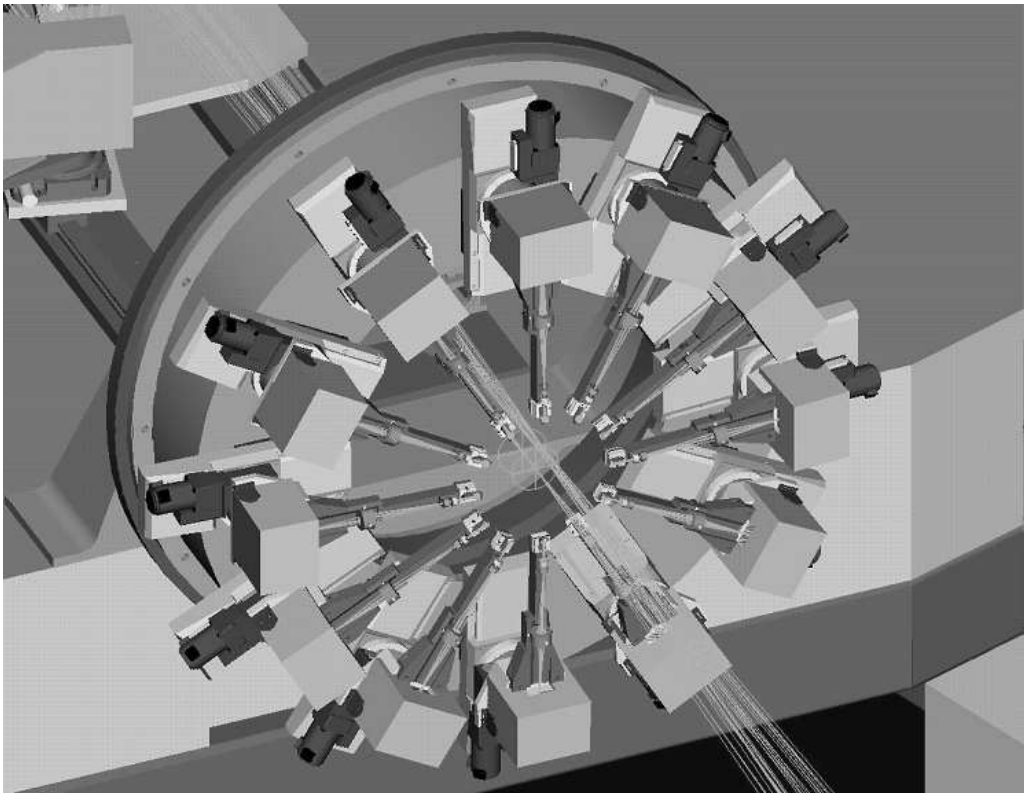

Fig. 3. In this preliminary design for the ground layer WaveFront Sensor for NIRVANA aboard LBT, a number of independent WFSs are employed, each with its own detector. The success of this approach would be linked to the availability of a number of very–low–noise CCDs, like the new L^{3}CCDs (Mackay et al. 2001, Tubbs et al. 2002). At the moment of writing this option has been dropped in favour of an optical coaddition scheme for funding reasons, as the costs of the CCD would dominate the related budget.

reader of such a statement let us think to the more trivial example of an imager. In this case, in fact, the PSF size is roughly equal to $F\lambda$ in the case of a diffraction limited telescope, while such a value is to be multiplied by D/r_0 for a seeing limited telescope. Here r_0 is the Fried parameter, describing the atmospheric turbulence, or in other words the *seeing*, and even in the best cases it is of the order of 0.5m, making the multiplicative factor not smaller than something of the order of $D/r_0 \approx 100$. The result is that in order to match a Nyquist sampling with a pixel size p, one needs a focal ratio of the order of:

$$F_{\mathrm{diff-limit}} = \frac{2p}{\lambda} \approx 14 \tag{1}$$

for the diffraction–limited case and:

$$F_{\mathrm{seeing-limit}} = \frac{2pr_0}{\lambda D} \approx 0.14 \tag{2}$$

where for the numerical example we used the previous mentioned figures for D/r_0, $\lambda = 1\mu$m and a pixel of $p = 7\mu$m, equivalent to the smaller today available on the market. While we note that the figures reported here are somehow optimistic, even assuming a twofold decrease in the pixel size (but one have to recall that the physical limit of $p \approx \lambda$ cannot be reached) it is easy to realize that a simple imager would require so fast optics that are simply unfeasible to design.

3. A road–map for a 100m class adaptive optics system

We can synthethyze the questions one has to answer in order to trace out a road–map for turning into reality the AO for an ELT, in the following list:

- Can we build an Adaptive Optics for a 30..100m class telescope now?
- Which kind of development we have to pursue in order to (better) accomplish such a task?
- What can we do now to demonstrate the feasibility of such an adaptive optics?
- Does Canary deserve some special care/attention/benefits with respect to adaptive optics for these kind of telescopes?

And we have also to distinguish the research and development required for different areas, for each of these I list below at least one example:

- Components:
  - Deformable Mirrors reliable and cheap
  - Detectors sensitive, large and fast enough
  - WaveFront Computers powerful enough
- Concepts:
  - WaveFront sensing technique proven, efficient and effective
  - Sky coverage and achievable performances capable of deliver the promised science
- Complexity:
  - Capability to handle the large numbers of data flow and the expected rate of failure of subsystems

Components, concepts and complexity are three distinct items, but they are clearly correlated one to the other. To a some extent they are interchangeable. For instance one can conceive the realization of a full MCAO system, now, by using a WFS where the light is being splitted into a number of existing small format, fast readout CCDs. This is an obvious example where the lack of new components (large format, low noise and fast readout CCDs) is compensated by an increase in complexity (optomechanics, electronics, and synchronization of several controllers).

This raise an interesting fact: we could design an MCAO for ELTs, today, with existing and proven components, with existing concepts (not yet proven on the sky, although this is close by a few years) and with an increase in the overall complexity that appears marginal with respect to the one that in any case one is faced to.

This can be accomplished, in my opinion, with a combination of Multiple–FoV, only natural references, approach (Ragazzoni 1999), feeding an array of existing detectors, and driving an array of piezo–stack, or secondary–adaptive mirror technology–based, Deformable Mirrors (Brusa & del Vecchio 1998, Riccardi et al. 2001). This can be done today and in a few years ne can have a ready–to–built design based upon these, somehow conservative, assumptions. The research and development efforts should be spent into the exploration of concepts aiming to an even further sky coverage, likely employing LGSs, but not limited to these, as some novel approaches and related technologies could unveil in the near future (Ragazzoni et al. 2002b).

4. Perspectives on La Palma

La Palma is clearly one of the top sites where an ELT, soon or later, could takes place. Of course most of the decision chain is driven by political, economical, logistic and practical arguments, so that from an AO perspective we can only work into the characterization of the site, to understand if there are particular reasons to build the MCAO in one way or in another. This translates into two realms of

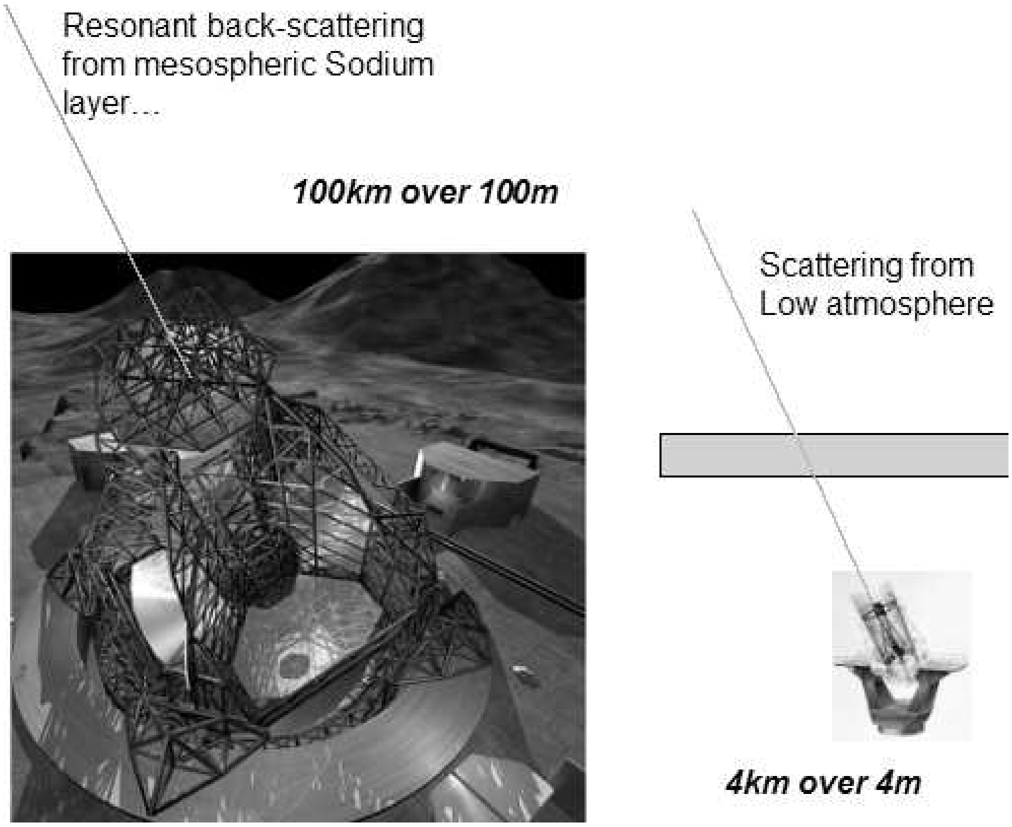

Fig. 4. To mimic a 100m telescope with a Sodium LGS an experiment at the WHT, a 4.2m class telescope, is scheduled to occour down the Canarian sky. A Rayleigh beacon with an optical gating at roughly 4km of range will simulate the same geometry, although turbulence deploying over the beacon altitude will be, unavoidably, lost.

measurements: $C_N^2(h)$ (turbulence profile) and maximum wavefront deformation for groups of layer at a certain altitude. The first parameter translates almost directly into number, positioning, and density of actuators, on the various DMs; the second in their maximum stroke. The usage of concepts like Taylor frozen hypothesys for prediction are likely to be so varying from time to time that I do not believe that, at this stage of the development, a through study specific for Canary at this level would be of strong impact. An important point often missed is the correlation of the two quantities mentioned before with weather, season and overall seeing quality. This would give a clearer perspective of the performances attainable for such an ELT.

Finally we cannot avoid to mention that Canary has been and will continue to be one of the preferred test–bench for technological developments in an ELT perspective. In fact under the Canarian sky the first tomogrpahy has been achieved (Ragazzoni, Marchetti & Valente 2000), the world largest segmented mirror is in construction (the GranTeCan project), and an experimento to probe several unconventional approaches to sense LGSs is going to be carried out at the WHT (see also Fig.4). There is no doubt that such a continuous pushing of the technology to their limits in the area could make easier the installment of an ELT on the island.

5. Conclusions

We are living a boiling moment for 8..10m-class telescopes and their instrumentation: several groups are studying detailed engineering plans for ELTs and 4m-class telescopes are looking for a role in this new scenario Wide-field, large sky coverage, user friendly AO are on their way (maybe not all these in the same group, however). Specifically for Italy it is worth to mention that we have, or we are going to have, access to TNG, VLT, LBT, VLTI, LBTI; all tools with resolving powers similar to ELTs with AO although with limited performances in terms of limiting magnitudes, easiness of data recovery and FoV. Unique science is already possible, today, and the situation will improve in the near future.

As instrument makers should recall that the value of their instrument is in the science these effectively do, the astrophysical community should recall that they could have unique opportunities at their hands.

Acknowledgements. This work would not has been possible without the contribution of a number of persons, including: David Andersen, Carmelo Arcidiacono, Heinz-Harald Baumeister, Peter Bizenberger, Emiliano Diolaiti, Jacopo Farinato, Wolfgang Gaessler, Adriano Ghedina, Tom Herbst, Stefan Hippler, Stefan Kellner, Ralf Rainer Rohloff, Roberto Soci, Elise Vernet, Robert Weiss and Wenli Xu.

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