Ground-Conjugate Wide Field Adaptive Optics for the ELTs

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Beyond Conventional Adaptive Optics

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ABSTRACT

Ground-conjugate wide field AO is presented and preliminary performance results are given, which show that significant seeing improvement can be achieved over 10-20 arcmin field of view. A proposal for an ELT AO system is sketched.

1. INTRODUCTION

After many years dedicated to single deformable mirror (DM), pupil conjugated Adaptive Optics (AO) systems, new ideas are floating around for innovative concepts. Multi-conjugate adaptive optics systems are now in the making (e.g. Gemini South). Layer oriented MCAO schemes look promising. The Extremely Large Telescopes (ELT) efforts fostered concepts like wide field of view partial compensation, developped in this paper. New concepts like "button AO", as in the proposed instrument FALCON (see Gendron, this conference) are a whole new kind of AO altogether. This paper presents the concept of boundary layer, wide field of view compensation together with first performance evaluations. A concrete proposal is made for a 30-m ELT AO system, which we think conciliate most or all of the science and technical demands of an ELT.

2. BOUNDARY LAYER COMPENSATION FOR WIDE FIELD AO

2.1. Introduction and principles

The goal of this study is to compute the "compensated seeing" resulting from the compensation of a unique turbulence layer, or to be more precise the compensation using a unique deformable mirror, conjugated to a given altitude. This is done within the frame of the Giant Segmented Mirror Telescope (GSMT) study, for which the field of active and adaptive optics are overlapping largely, given how high the resonnance frequencies of the structures and how large the amplitude of deformation of the same structures and of the primary mirror are likely to be.

Because the boundary layer is the dominant layer in most astronomical sites, even the best ones, one idea that has been around for some time is to use a deformable mirror to do ground layer compensation. This is especially relevant for ELTs, as most likely some precautions will have to be taken to at least partially screen the telescope from the wind, which is contrary to free air flushing, the current prefered method to get rid of local seeing effects.

Ground layer compensation is not much different than multi-conjugate adaptive optics, except that only one mirror is used, instead of several mirrors. The field considered is also much larger than for MCAO. However, the requirements in terms of number of actuators, althought slightly less stringent, are comparable as we will see later.

In classical adaptive optics, the goal is to compensate a phase in a given direction (i.e. integrated along a given line of sight). The 3D turbulence volume is collapsed to give the integrated phase along the line of sight and the deformable mirror is shaped to compensate this phase. One can see that as soon as one looks away from this particular direction, the compensation is degrading: this is the anisoplanatism of the phase compensation, because what we correct for is effectively occuring in a volume, and not a single plane. Conversely, in ground conjugation, only the layers which are common to all points in a finite field of view are compensated. Ideally,

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a true "ground layer", located at the telescope pupil, would be completely isoplanatic, that is all points in an infinite field of view would see this layer in the same fashion. In this ideal world, a high order AO system could potentially remove almost entirely the contribution of this ground layer, and its contribution only. Such a compensation would be valid for a infinite field of view. Its effect would be to effectively suppress one of the main layer of turbulence, hence increasing r_0 and therefore improving the FWHM. Of course, nothing is never ideal, and in fact the ground / boundary layer is distributed between the real ground and somewhere between a few tens and a few hundred meters. It has been demonstrated elsewhere (Rigaut et al 2000) that under the condition that any points in the field of view have equal weight in the compensation scheme, a layer not exactly conjugated with a deformable mirror can not be compensated entirely. Effectively, the spatial scales smaller than $\theta * \delta_h$ are projected out of the command pace (i.e. not compensated), θ being the field of view diameter and δ_h the difference of altitude between the deformable mirror and the layer. In turn, this means that the larger the field of view one wants to correct, the thiner the effective layer that will be compensated. In fact, an approximation of the thickness of the atmospheric volume compensated by a single mirror is given by $2 * r_0/\theta$. This effect is quite serious as for field of view of 5 arcmin, and for relatively good seeing conditions (20 cm at 500nm), the equivalent "thickness" is 1.6 km for a compensation at K band and only 275 m for a compensation in the visible.

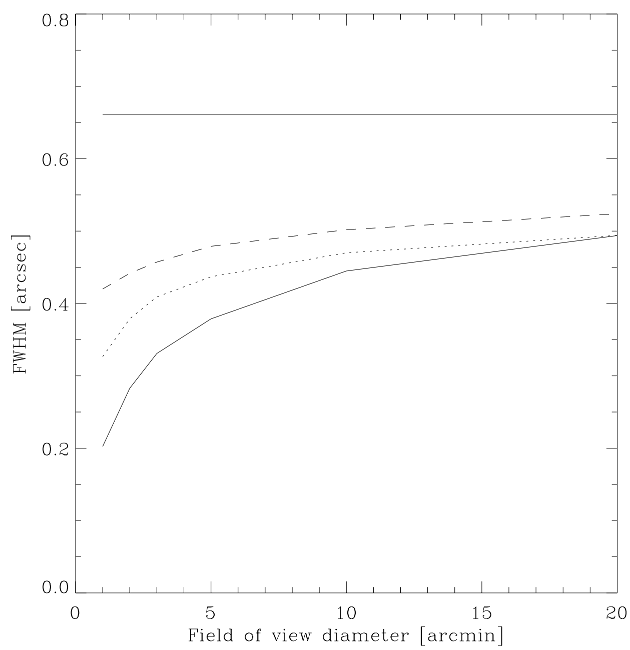

Figure 1. Median Natural seeing (upper solid line) and median compensated seeing from the Cerro Pachon ballon profiles at V band for a DM with an actuator picth of 25cm (solid), 50cm (dotted) and 1-m (dashed).

2.2. SNR considerations

The advantage of this scheme is, of course, a very wide compensated field of view and a nice, uniform and well-behaved PSF, in the sense that it does not show the bi-modal profile (core+halo), characteristic of classical AO image, but shows basically an improved seeing profile. This goal of this type of system is not to deliver diffraction limited performance, but to simply improve the seeing, which is of interest for a range of wide field applications. A gain of a factor of 2 in the seeing translates into a gain of a factor of 4 in light concentration for point sources ($z \geq 1$ galaxies can almost be considered as point sources in this case, as the spatial extend of their core is typically 0.2", independant of the redshift), therefore a factor of 4 in integration time for background limited observations. Conversely, it translates into a 0.75 magnitude gain in sensitivity. This is the same gain that one would gets, at constant seeing, by increasing the telescope diameter by 2 !

2.3. Performance evaluation

The effect on the PSF is in fact rather complex and can not be computed simply. Getting the PSF involves estimating how the phase is affected by the compensation at each altitude. A code was written to this effect, based on an analitical formulation that was proposed in Rigaut et al (2000) that uses the power spectral density of the phase. A full description of this code is beyond the scope of this paper. Very briefly, the phase power spectral density was computed as follow:

$$PSD_n =< \tilde{\varphi}^2(h_n,\mathbf{f}) >= \frac{0.023 \times 1.46}{2.1^{5/3}} Cn^2(h_n).\delta h_n. \begin{cases} [1-\mathrm{sinc}(\theta(h_n - h_{\mathrm{DM}})\mathbf{f})].(f^2+\frac{1}{L_0^2})^{-11/6} & \text{if } f < f_c \\ (f^2+\frac{1}{L_0^2})^{-11/6} & \text{if } f \geq f_c \end{cases} \quad (1)$$

where h_n is the altitude of "layer" n, h_{DM} is the altitude of conjugation of the DM (here chosen as 100m above ground), f the multi dimensionnal frequency vector (f its norm), δh_n the thickness of layer n, θ the field of view diameter, L_0 the outer scale (an infinite outer scale was used in the following) and f_c the system spatial cut-off frequency, $f_c = 1/2.d_{\mathrm{act}}$, d_{act} being the actuator picth. The overall phase PSD is then obtained by summation of PSD_n over the number of discrete layers. This is very similar to a formalism that was already proposed as a general formulation of the AO compensated PSF in a previous work (Rigaut, Véran, Lai, 1998). Once the total phase PSD is obtained, the phase structure function is computed (see e.g. Noll 1976, eq 19 for exact formulation). Under assumptions of gaussian statistics, the atmospheric optical transfer function can be expressed from the phase structure function by simple exponentiation. The PSF can then be computed from the the atmospheric and telescope transfer function, assuming centro-symmetry.

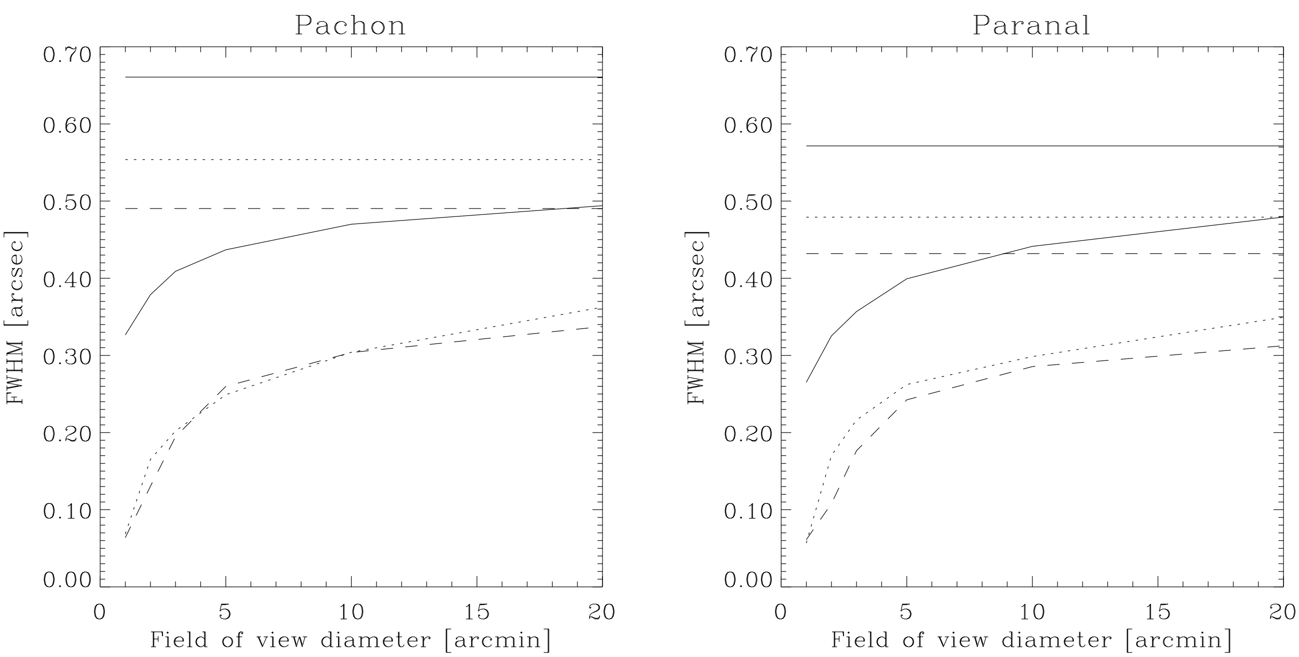

Figure 2. Natural (straight upper line) and compensated (lower curve) seeing at V (solid), J (dotted) and K (dashed) bands, for the Cerro Pachon and cerro Paranal for d_{act}=1 m.

The performance was parametrized versus the wavelength (V, J and K bands), the interactuator picth and the field of view (1, 2, 3, 5, 10 and 20 arcminutes).

Because in some case, the variation of performance with respect to the layer altitude is very fast, we used balloon atmospheric profiles provided by M.Sarazin (ESO) for Cerro Paranal (10 lauches) and by M.Chun (Gemini) for Cerro Pachon (over 35 lauches), with a typical vertical sampling of 3-5 meters. These balloon profiles were obtained over months or years by a team from Université de Nice led by Jean Vernin. The Pachon balloon data were integrated from only 30-m above ground, to avoid local effect due to the launch. Paranal lauches were made from the valley below the summit, and the profiles were integrated rather arbitrarily from 30-m below the summit, in an attempt to get rid of the same local lauch effects and turbulence in the valley, but to account for the unavoidable summit ground effects. This has no effect on the compensated seeing, as the very ground layer is almost perfectly compensated, but influence slightly the site natural seeing. The value obtained (median FWHM of 0.66" at 500nm at Pachon and 0.57" at Paranal) are in general agreement with the values given for these sites.

Figures 1 and 2 summarize the results obtained so far. These results are for a 10-m telescope, but should be mostly independant of the telescope diameter (except when close to the diffraction limit, which only occurs at K band for very small fields in the plots). Therefore the results are generally extendable to 30-m telescopes or larger. The FWHMs discussed below are temporal medians over the profile number. These FWHMs are uniform over the entire field of view.

Figure 1 shows the natural and compensated median FWHMs at Cerro Pachon for the V band versus the compensated field of view diameter (1 to 20 arcmin), for 3 values of the interactuator spacing $d_{\rm act}$. Several remarks: as expected, there is a rather strong dependance upon the field of view. Gains of over a factor 2.5 can be obtained over small field (1'), but quickly go down to much more moderate values (e.g. 1.3) for 20' fields. This figure shows also that performance depends on relatively high spatial sampling (small $d_{\rm act}$) only for the compensation of small field of view. For fields of 5-20', a sampling of a few r_0 degrades only marginally the performance.

Figure 2 displays the natural and compensated median FWHMs at Cerro Pachon and Cerro Paranal for the three bands V, J and K, versus the field of view. This figure shows that this compensation scheme, like any other phase compensation method, is very wavelength dependant. Apparently, a threshold is passed for the Pachon atmosphere at around 1 micron, for which the maximum gain is obtained. Median "seeing" of 0.3 arcsec can be obtained for fields of approximately 15 arcmins in the NIR (J and K), while it is possible only over fields of 1.5 arcmin in the visible.

Fig 2 shows boundary layer compensation results for both Cerro Pachon and Cerro Paranal. The initial seeing is better at Paranal, but the compensated seeing is very similar to Cerro Pachon. This was expected, as the altitude seeing can be expected to be the same (Chile sites). Paranal is known to be better than Pachon, and one reason for that is that there is less boundary layer at Paranal (therefore less to be corrected by ground layer compensation). Incidentally, this is interesting as it flattens differences between various sites and allows considerations of more practical sites for the construction of an ELT.

It has to be noted that during this discussion, the issue of how the turbulent volume is sensed was not addressed. The computations made here assume a perfect knowledge of the turbulence volume. This might seem restrictive, but in fact is quite tractable for boundary layer compensation, as in this case not the whole volume, but only the layers of interest have to be known. Simply averaging the wavefronts measured on guide stars scattered over the field of view of interest should average out the high altitude contribution -providing these sources are numerous enough, e.g. 10- , leaving exactly the “part” of the phase which is to be corrected by the ground conjugated mirror. In case of large fields of over 10' in diameter, the number of bright natural guide star (NGS) is usually large enough to allow using them with a high enough probability of success. For smaller fields, the use of laser guide stars (LGS) can be considered. These LGS can be either sodium or rayleigh, as the cone effect is negligible at the altitude of interest (remember we compensated only the few first hundreds meters at most). Smart sensing method -e.g. layer oriented pyramidic sensors- could also be of interest, as they possibly allow to average the sensing signal “on the chip”, therefore inproving the noise propagation properties, and allowing to use fainter NGS/LGS.

2.4. Conclusion and practical implementation

Ground compensation appears to be tractable for seeing improvement over field of view of up to 10-20 arcmin. It is especially interesting for the NIR domain, for wide field imaging or spectroscopy, where the highest gain are reached (2 or more). This technique could help alleviate in part the very challenging task of building seeing limited spectrographs for these giant telescopes.

However, such systems are at least as complex as classical AO systems, and therefore only make full sense in complement or conjunction to other kinds of AO (MCAO, high order-narrow field, low order thermal IR), for which a relatively high order ground conjugated deformable mirror is needed. Because of the targeted wide field application, it sounds ineffective to use another mirror than one of the telescope main mirror train. The advantage of this method would be largely reduced if one were to use a complement of mirrors to re-image the ground layer on a separate DM. Note however that this scheme is extremely sensitive to the conjugation of the DM. Therefore, although it is not a show-stopper, using the secondary mirror does not come without performance loss on Ritchey-Chretien design, the secondary being conjugated below ground level. This performance loss remains to be evaluated. The primary mirror, or a prime focus corrector, could be used for the purpose of ground layer compensation.

3. A CONCRETE PROPOSAL FOR AO ON AN ELT

3.1. New paradigm and ELT AO requirements

The main change of paradigm with this new generation of telescope is that they can not work without AO. This was debated at length during initial discussions on ELTs, in the various communities. The conclusion that AO was absolutely essential to ELTs is both science based and engineering based, but it is not our purpose to discuss it here. In turn, this means that AO is promoted from a still marginal -although growing fast- discipline of observational astronomy to a indispensable and integrated part of these future telescopes. AO will have to work in all conditions, on all parts of the sky and accomodate all kinds of astronomical programs. This is quite a giant leap and challenge. Preliminary work on the science case for these ELTs (at least the ones the author is aware of, e.g. Edimburgh 09/2000) shows that, even though narrow field / high angular resolution science constitute a good share of the programs, a very large interest remains for moderate field of view works (10-20 arcmin).

Below is a preliminary list of requirements/modes of observation :

- Very high Strehl ratio imaging over very small field of view (extra-solar planet detection),
- diffraction limited imaging and spectroscopy, with possibly moderate Strehl ratio, over 1-2 arcmin fields (remember that the pixel size to sample $\lambda = 1\mu$m diffraction spots on a 30-m telescope is 3.5 mas, thus require a 35000x35000 pixel array to cover 2'x2'),
- Low emisivity diffraction limited imaging and spectroscopy in the thermal infrared (above 4-5 μm). This can be achieved by cryogenic optical systems (cryogenic AO!) or simply by reducing the number of optical surfaces. Considering realistic advances in the thermal detector technology, and the need for sampling the diffraction limit, moderate field are a reasonable goal. For instance, 40"x40" Nyquist sampled at 10 μm is covered by a 1000x1000 detector array,
- 10-20 arcminutes field "seeing limited" (or improved seeing) imaging and spectroscopy. For 0.3" median "improved" seeing (see previous section), it will not be rare to have 0.15" occasional image quality, in which case 0.07" pixels are required. With this sampling, a field of 20'x20' can be covered with a 17000x17000 pixel array.

3.2. A Versatile Concept

Figure 3 presents an AO concept for an ELT. A Ritchey-Chretien design is considered in this representation, but this concept applies to other kinds of design (e.g. OWL). This proposal includes:

- A segmented active primary with moderate temporal bandwidth but large stroke, to compensate for gravity induced structural deformation of the structure and the low temporal frequencies of wind load on the primary mirror and telescope structure.
- A segmented adaptive secondary. The purpose of this central corrective element is five fold:
    1. It serves as a fine compensation stage for the mirror figure compensation (mostly wind load temporal frequencies not corrected by the active M1)
    2. It can be used as the single high order DM in the high Strehl ratio / small field of view / low scatter applications like extra-solar planet detection/imaging,
    3. It is the single DM in thermal infrared applications, avoiding the use of additional emissive mirrors,
    4. It serves as a first stage of the MCAO system (see below), and
    5. It can be used to compensate the ground/boundary layer, as detailled in the previous section.

Current deformable secondaries, developped for the new MMT and the LBT, are showing promising results. The current version already have an interactuator pitch close to what is needed for an ELT for all the applications mentionned above. A magnification ratio of 10 between secondary and primary is common, which will make the secondary 3 m in diameter for a 30 m ELT, thus requiring 7 segments of 1 m. An actuator pitch of 2 cm

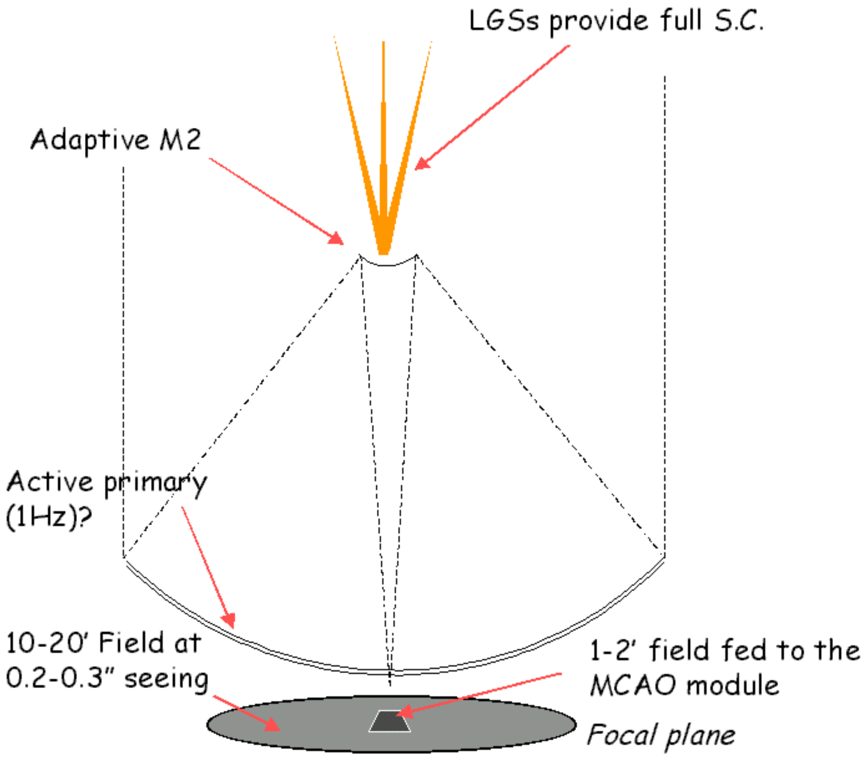

Figure 3. Proposed ELT AO concept

would map in 20 cm on the primary mirror, leading Strehl ratio of typically 70% at 500 nm and over 90% at 1 μm*, which are in the range of what is needed for planet search.

This will provide a 10-20 arcminutes field of "improved" seeing. The central 1-2 arcminutes are feeded to a separate MCAO system that uses 3-5 additional deformable mirrors to produce diffraction limited images over this entire 1-2 arcminutes field, or are directly feeded to a thermal IR instrument (M2 correction, no additional compensation required) or to a planet search type instrument (M2 correction, no additional compensation required).

This scheme provides an adequate answer to all the observing mode requirements listed in the previous subsection. In addition, it opens the possibility of multiplex observations, where the central part of the field can be observed simultaneously with the outer part of the field, with different instruments of course, but each benefiting from a certain level of AO compensation.

ACKNOWLEDGMENTS

The perspective of an era where ELTs are possible is producing a lot of excitation in the astronomical community. It fosters many exchanges on new ideas and new concepts. This paper has attempted to present some of them. These ideas are for most of them floating around –this design is very much inspired from the CELT design, with the notable difference of the ground conjugate wide field AO– and are not the author's only, but emerged during discussions with many of the community members as Brent Ellerbroek, Jerry Nelson, Roberto Ragazzoni, Roberto Gilmozzi, Matt Mountain, Philippe Dierickx, Eric Gendron, Andrei Tokovinin, and others.

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*Using a simple $\mathcal{S} = \exp[-0.4 * (d_{\rm act}/r_0(\lambda))^{5/3}]$ approximation, typical to include fitting and servo-lag errors.