Principles, Limitations and Performance of Multi-Conjugate Adaptive Optics

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ABSTRACT

Multi-Conjugate Adaptive Optics (MCAO) holds the promise of moderate to large adaptively compensated field of view with uniform image quality. This paper is a first effort to analyse the fundamental limitations of such systems, and that are mainly related to the finite number of deformable mirrors and guide stars. We demonstrate that the ultimate limitation is due to the vertical discretization of the correction. This effect becomes more severe quite rapidly with increasing compensated field of view or decreasing wavelength, but does not depend at first order on the telescope aperture. We also discuss limitations associated with the use of laser guide stars and ELT related issues.

Keywords: Multi-conjugate adaptive optics, wavefront reconstruction, AO implementation, AO performance

1. DRIVERS FOR MCAO

MCAO was proposed by Beckers[1] in 1988 as a mean to increase the compensated field of view of an adaptive optics system. There are other drivers, such as sky coverage, resolution of the cone effect for large telescopes and/or short wavelength when using Laser Guide Stars (LGSs).

In the early 1990s, when early astronomy oriented Natural Guide Star (NGS) systems began to see light, it was realized that their application was restricted to a very small fraction of the sky, due to the need for a very bright guide star (GS) next to the field of interest. It is well known and accepted that the sky coverage, with classical NGS AO system, is of the order of 5 to 10% at K band, and depends on the wavelength approximately as λ^6. LGS was proposed as a solution to this problem, providing an artificial star wherever it is necessary. Unfortunately, this solution (a) does not provide *full* sky coverage, because of the tip-tilt indetermination problem[12], but in addition (b) has limitations due to the finite range of the LGS, the so-called cone-effect or focal anisoplanatism, which induces a phase error that increases as $(D/r_0)^{5/3}$ for a given Cn^2 profile (typically 0.5 rd^2 of phase error at 1 μm on a 8-m telescope), rendering the compensation at visible wavelength on a 8-m telescope very inneffective -and therefore preventing any compensation on even larger telescopes.- Earlier studies of the performance of MCAO includes for instance Ellerbroek[4] and Berkefeld[2].

This paper proposes a first approach to the analysis of the performance and fundamental limitations of MCAO. Section 2 deals with the principles of this technique. Section 3 presents the first thought on its limitations, and section 4 discuss the aspects related to MCAO with laser guide stars. Section 5 reports examples of performance. Finally, section 6 briefly discuss application to Extremely Large Telescopes (ELTs).

2. PRINCIPLES

Various schemes were proposed to solve the cone effect: stiching and butting[6] and tomography[10,13], to cite the main ones. Stiching and butting have their own severe limitations, and turned out to be difficult to implement. Tomography is far from being trivial to implement either but was more promising: By relying on 2-D phase information along several directions (i.e. coming from several guide stars), it is possible to reconstruct the 3-D index of refraction contents. This scheme is *global*, in the sense that every GS is providing information on the whole pupil, and is therefore more economical that e.g. stiching, or any other scheme where each GS is only providing information very locally in the telescope pupil. Tomography therefore requires less GSs than other schemes. Tomography comes down

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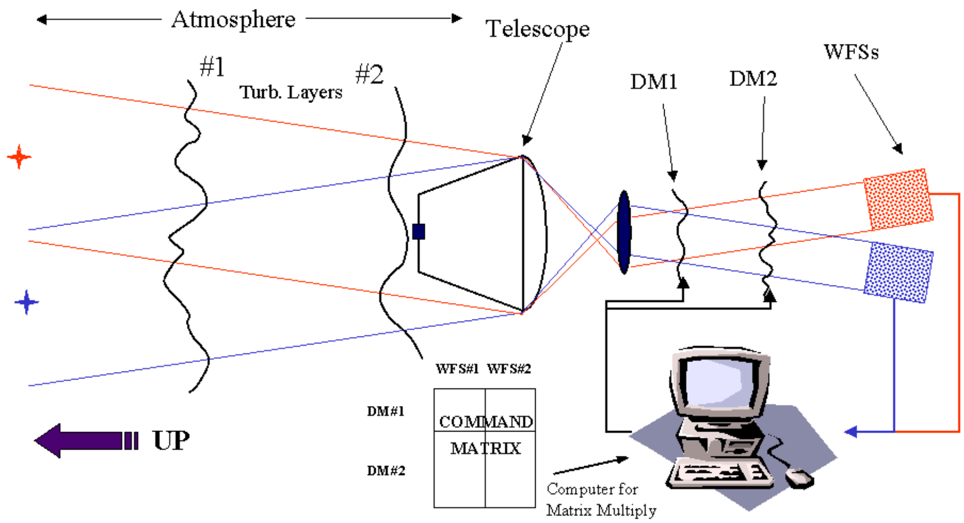

Figure 1. Sketch of the MCAO principle.

to an inversion process, and usual constraints apply, like for instance the number of GSs has to be larger than the number of layers to be reconstructed, to insure stability.

Tomography as such was first conceived as an open loop measurement scheme. One of the problem associated with open-loop tomography is that the GSs, significantly off axis, will not be compensated, and therefore the phase excursion in their directions will be quite large. As in the technique of deconvolution by wavefront sensing[8], a clean reconstruction process requires clean and accurate measurements, therefore wavefront sensors with large dynamic range, and good (or well calibrated) linearity. In general, this is impractical or means less sensibility. Indeed, for any known sensor schemes (Shack-Hartmann, Curvature, shearing interferometer, pyramidic), a larger dynamic range is at the expense of sensitivity: For Shack-Hartmann, it means more pixels in each subapertures (thus more noise if the detector is not noiseless), for curvature, it means using larger extra-focal distances, etc...

Tomographic MCAO provides a solution to the later point: By using several deformable mirrors (DMs), a MCAO system compensates for the phase distortion in a 3-D fashion, and therefore provides a uniform compensation over an extended field of view. This field of view may include the GSs, which means that the wavefront sensing will be done in close-loop. The goal of the close loop is now to null the wavefront sensor measurements, and tomographic MCAO becomes a straightforward extension of classical AO: An interaction matrix is done between the N sensors and the M mirrors, and this matrix is inverted -folding into the process whatever constraints are deemed necessary, for intance, one may use the expected Cn^2 profile and build a minimal variance or a MAP[7] estimator- and used for the system control.

Figure 1 presents a sketch of a MCAO system: Two wavefront sensors look at two GSs, and control two DMs through a control computer. It has to be underlined that the information from all the sensors are used to control any and each DM. In this sketch, one of the DM is optically conjugated close to the ground, and the other one is conjugated to altitude.

To summarize, MCAO has the following advantages:

- It extends the compensated field of view of the AO system. This by itself is a considerable advantage. The consequence of the enlargement of the FoV is not only that more field is available, but also that one of the main variable has been removed, that is the anisoplanatic degradation, and therefore the compensation will be more stable. If the PSF is spatially uniform, it will be in most cases possible to find a PSF calibrator in the field itself. This is of prime importance for a reliable extraction of the photometry, which has been one of the main limitations in the astronomical exploitation of AO images to date.

- It provides a solution to the cone effect, althought specific problems arise with the use of LGSs, see section 4. Compensation of Extra-Large Telescopes (ELTs) is potentially feasible (see Section 6).
- Other potential advantages are:
  - Slicing up the atmosphere into layers will probably, at least for the non-zero altitude layers, enable scheme that rely on the taylor hypothesis, such as predictive algorithms for the high order correction, etc...
  - Although it requires more than one NGS for the control of the low order modes in a LGS system (extension of the TT NGS in a LGS system, the sky coverage is increased with respect to a classical LGS AO system. This is because the NGS can be quite off-axis –in fact, it *has* to be– without damaging the on-axis performance.

However, MCAO does not come without problems and limitations, which are exposed in the next section.

3. LIMITATIONS

The MCAO problem is, as for classical AO, a linear problem: A set of unknown variables (the mirror commands) has to be determined using a set of measurements. This constitutes a set of linear equations that can be written in a matrix form, and inverted.[5] The full analysis of these errors therefore implies solving explicitely this set of equations. However, this may be very cumbesome and requires a lot of computing time, especially when scaling up to large systems. This full analysis is presented in separate papers.[5,3] Our goal here is to present a more qualitative approach of the actual physical process that limit MCAO performance.

MCAO suffers from the same main limitations than classical AO: fitting, servolag, noise and spatial aliasing. Anisoplanatism, as we noted above, is different in a MCAO system. In addition to these well known sources of error, additionnal errors arise from the 3-D treatment of the problem: We have called them *generalized fitting, generalized anisoplanatism and generalized aliasing errors.* In the next subsections, we expend on these errors and try to give an estimate of their magnitudes.

3.1. Generalized Fitting error

This error results from the discrete number of DMs. Let us assume to assess this error that we use a MCAO system with an infinite number of GS, i.e. a perfect tomographic information. The phase perturbations are known perfectly, but have to be compensated by a *finite* number of DMs. Consider the case of a layer at a distance Δh from one of the DM as in Figure 2. Because every points in the field is weigthed equally, the mirror will have to compensate equally* for all the points along $\theta.\Delta h$ in the layer. A perfect and general solution does not exist for all directions, and the system will only apply on the DM at this point the *average* phase over $\theta.\Delta h$ (think of a very local bump at the layer: it is impossible for the system to correct this bump *for any direction in the sky* unless the compensation is done at an altitude conjugated with the layer). In effect, the reconstructor will just project the phase distortions it can not correct out of the command space.

A first order approximation of this projection can be written:

$$\varphi_c(h,\mathbf{x}) = \varphi(h,\mathbf{x}) - \varphi(h,\mathbf{x}) \star \sqcap_{\theta.\Delta h} \tag{1}$$

where the subscript c stands for "compensated" and $\sqcap_{\theta.\Delta h}$ is a 2D gate function of width $\theta.\Delta h$. The phase power spectral density (PSD) is then:

$$|\tilde{\varphi}_c^2(h,\mathbf{f})| = |\tilde{\varphi}^2(h,\mathbf{f})|.(1-\mathrm{sinc}(\theta.\Delta \mathrm{h.f})) \tag{2}$$

In a real system, the number of actuator is limited and the compensation up to a given frequency $f_c = 2/d_{act}$ where d_{act} is the actuator pitch:

$$|\tilde{\varphi}_c^2(h)| = \frac{0.023}{r_0^{5/3}} \left[\int_{f=0}^{f=f_c} (1-\mathrm{sinc}(\theta.\Delta \mathrm{h.f})).\mathrm{f}^{-11/3} + \int_{\mathrm{f=f_c}}^{\infty} \mathrm{f}^{-11/3} \right] \tag{3}$$

*This is a basic assumption throughout this paper. Other schemes, that weighs unequally the field points or use a completely different wavefront sensing scheme, can be imagined, but may not provide as uniform a Strehl ratio.

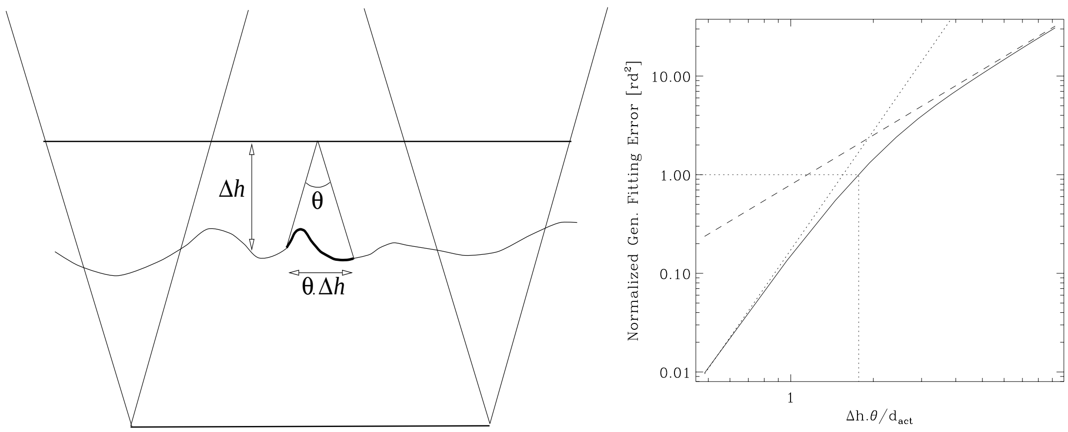

Figure 2. Left: Geometry for generalized fitting error (see section 3.1). Right: Normalized Generalized Fitting Error, i.e. Generalized fitting error (in rd^2) divided by the classical fitting error, versus the normalized parameter $\Delta h.\theta/d_{act}$. The dashed line show the asymptotic behavior in 5/3 for $\Delta_h.\theta > d_{act}$

where the first term is the generalized fitting error and the second term the classical fitting error –it has been demonstrated elsewhere[12] that this last term, for a perfect system, is equal to $0.23(d_{act}/r_0(\lambda))^{5/3}$.–

The right hand side of figure 2 shows the amplitude of the generalized fitting error : The ratio of this error to the fitting error is displayed versus the normalized parameter $\theta.\Delta h/d_{act}$. This figure illustrates the asymptotic behavior of this error in the expected 5/3 power law.

Figure 3 shows results from a Monte Carlo code described in [5] , for various mirror numbers and altitudes. This code is a full simulation written at Gemini for the purpose of studying/designing the proposed MCAO system for Gemini south. In this case, the reconstructor is a simple least square estimator. In this particular example, to reduce other MCAO error sources (Generalized anisoplanatism, see next section), a very large number of guide stars were used (25 NGSs). Several runs were then performed with the same phase screen successively at various altitudes between 0 and 17 km above ground. The average Strehl ratio at K band over the 90 arcsec field of view is plotted versus the layer altitude. Several remarks can be done:

- As expected, the Strehl ratio reach extremum values totally compatible with the classical fitting error when one DM is exactly conjugated with the phase screen. In between DMs, the Strehl ratio decreases due to the generalized fitting error.
- The addition of the 0 km DM from system "b" (dotted line) to system "a" (solid line) does not significantly improve the performance in the 4-13 km region.
- Increasing the separation between DMs makes the generalized fitting error goes up steeply (e.g. from system (b) to (c)).
- The very crude analytical approach proposed above seem to describe quite well the amplitude of the generalized fitting error, at least for this kind of systems.

An arbitrary limit to Δh when designing a MCAO system is to have both terms of Eq 3 balanced (classical fitting and generalized fitting errors). A 2D numerical evaluation of this integral (see right hand side of Figure 2) leads to $\theta.\Delta h_{\max} = 1.75\, d_{act}$ for this condition to be realized. Table 1 give some examples for various systems derived from this last condition. It also gives a estimate of the number of DMs to cover the 0-12 km range with spacing = $2 \times \Delta h_{\max}$. The first line is typical of compensation $\lambda \geq 1\mu$m, the next two lines of compensation in the visible at a fairly good site. An important consideration is that this approach shows that, at first order, *the number of DMs is independant of the telescope diameter, but depends only on the DM pitch (driven by r_0 at the wavelength at which one wants to correct) and the compensated field of view*. This dependance is actually quite serious, and the tractability of MCAO for compensation of field of view larger than 5' is questionable.

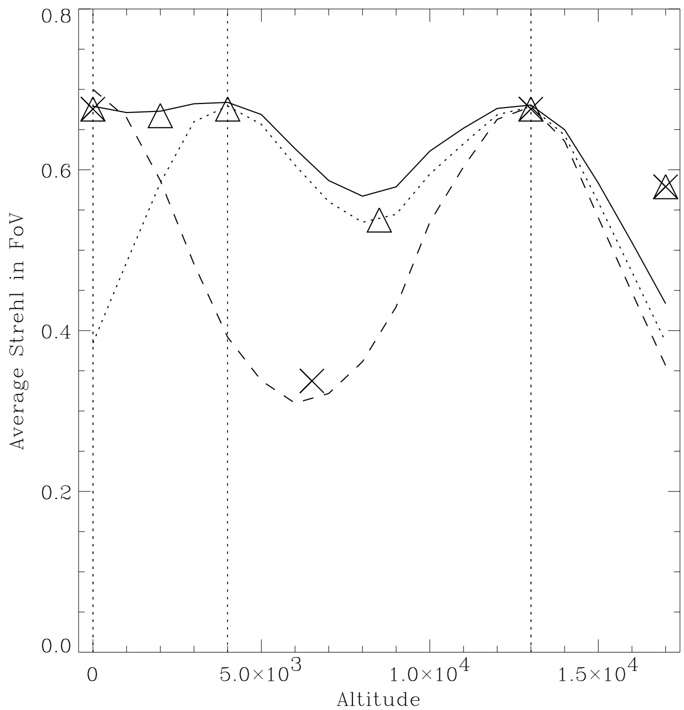

Figure 3. Average Strehl over field of view when compensating a single layer versus the layer altitude for various systems: (a) a 3 DM system with conjugation altitude of [0,4,13] km (solid line), (b) a 2 DM system with mirrors at [4,13] km (dotted line) and (c) [0,13] km (dashed line). All DM have pitches of 1.3 m on an 8-m telescope. The compensated field of view is 90 arcsec on a side. Triangles present Strehl evaluations computed from Eq 3 for the system (a), and crosses are for the system (c).

Table 1. Estimates of $\Delta h_{\max}$ and the number of DMs for various DM pitches and field of view (see text)

d_{act}[m]	FoV [arcmin]	$\Delta h_{\max}$ [m]	$N_{\rm DM}$
0.5	1	3000	3
0.2	1	1200	5-6
0.2	10	120	50

3.2. Generalized Anisoplanatism

Let us consider again the geometry presented in figure 2: In this particular configuration, some part of the turbulence volume is sampled by two beams, some by only one beam. One can easily see that tomographic information is not obtained in the outer, uniquely sampled turbulence volume. Therefore the system will have no clue on where to apply the correction, unless one uses a priori knowledge of the Cn^2 distribution (but even that will only make things better statistically speaking, not provide a solution to the problem under discussion). The reconstructor will still find a set of commands that minimize the error in the direction of the guide stars, but that does not necessarily imply that the compensation will be optimal in other points of the field. In the simulations carried out at Gemini, this effect produced more or less serious non uniformity in the image quality across the field. An example of it can be found in Flicker et al, figure 4. As could be expected, it proved to be more severe for higher order systems. A more thorough analysis of the exact limitations imposed by this effect is still to be done.

3.3. Generalized Aliazing

It is possible that turbulent layers combine to look the same in more than one GS direction, tricking the reconstructor into commanding the same phase correction all over this particular field, althought in between the GS the integrated phase may be different: Imagine that there are two turbulent layers at 0 and h km with identical sine wave aberrations of period l, and that there are two NGSs, one on-axis and one off-axis by some angle α. If the atmosphere was to produce sine waves with a period $l = h\alpha$, the pair of NGS would see exactly the same phase distortion in both directions and conclude that it was all produced in the ground layer, although at any other angle $\alpha \neq ml/h$ (m an integer) the integrated phase would be quite different. For a simple two-layer atmosphere, the total PSD of these degenerate combinations may be estimated by treating the specific frequencies at which they occur as delta functions in the turbulence power spectrum. Because of WFS noise, the delta functions are in reality somewhat smeared, giving more weight to these modes. For more than two layers it becomes difficult to imagine all the ways in which the atmosphere may conspire to deceive the sensors, and given that the atmosphere contains many layers, this may ultimately be an important contribution to the limitations of a MCAO system. A possible partial solution to this problem might be to have asymmetric configuration of high order GS, which might reduce the number of degenerate modes. Additional analysis/simulations are required to fully characterize this effect.

3.4. Static Plate Scale Issues

If an error is made in the initial positionning of the NGS sensors (high order or tip-tilt), it will directly translate into a static plate scale error for the science field (see also discussion of section 4.1). This problem is potentially damaging for any kind of application that require somewhat accurate astrometry. Calculations show that current DMs, with typically 10% hysteresis, will by themselves induce plate scale errors of the order of 1 part in 50000 (2 mas error on a 100 arcsec base).

If more accurate astrometry is required, several solutions can be considered. The ideal one would be to position the NGS sensors to the exact position of the guide stars. Unfortunately, it is not realistic to rely on accuracy of catalogues at the required level (depending on the application, but typically a fraction of the diffraction width). The most obvious solution, then, is to monitor the average positions of the NGSs, *before* closing the loop with the altitude conjugated DMs. One has of course to insure that the later DMs are *flat*, which may be done with (a) interferometers or any means to check and control the actual surface of these DMs or (b) possibly with calibration sources, as for instance a couple of point sources with accurately known separation introduced in the entrance focal plane of the MCAO system, preferably at the very edge of the field, and which positions would be monitored by dedicated sensors in the WFS focal plane.

3.5. Sky Coverage

One of the problem associated with MCAO, at least in the tomographic scheme used here, is that it requires a minimum of 3, preferably 4 to 5 or more guide stars. Because of the generalized fitting and anisoplanatism errors exposed above, these 3-5 GS have to be within a field of approximately 1 square arcminute. The probability of finding a suitable NGS configuration of adequate magnitude (< 14) is extremely small ($<< 0.01\%$). Therefore, NGS MCAO, in the current scheme for wavefront sensing, is not of wide enought application to be of real interest. As we will expand below (Sect. 6), enlarging the research field by increasing the telescope aperture,[9] does not solve the problem, as the generalized fitting and anisoplanatism errors get very large, requiring more DMs and more GSs.

A solution to increase sky coverage is to use LGSs. This alleviates problems related to variable geometric configuration of the GS, allowing more robust solutions for the practical opto-mechanical system implementation, and provide full sky coverage for the high order modes compensation. In the following section, we discuss the limitations imposed by the use of LGSs.

4. LGS RELATED ASPECTS

There are several limitations and implementation issues when using LGSs to drive a MCAO system.

4.1. Null modes: Tip, Tilt and quadratic modes

The major limitation is an extension of the Tip-Tilt indetermination problem encountered with Classical LGS AO systems. In these, the LGS position indetermination implies that the global wavefront tip-tilt is not known. In a MCAO system, several (say 4-5 for the purpose of this argument) LGSs are used, at different positions in the field. The indetermination in the position of these LGS means not only that the global wavefront tip-tilt, but also that the plate scale (determined only by the distance from one LGS to another) is not measurable.

Another way to understand this problem is to consider a defocus mode at a given altitude: It can easily be demonstrated that each of the guide star will see only (a) the same amount of defocus and (b) a tilt component, different at each guide star. The tilt components of this measurement is the only measure of the altitude at which this defocus is. Unfortunately it is not measureable with the LGSs. An error in the altitude at which this defocus is applied will results in a dynamic plate scale error, and a reduction of the Strehl in the long exposure image. This can be extended to other quadratic modes (the two astigmatisms). Here, we have called these modes “null modes” because they belong to the null space of the high order LGS reconstructor.

It can be demonstrated (Rigaut & Ellerbroek, in preparation) that a single set of five modes, applied as combination of quadratic modes at an arbitrary altitude and the ground conjugated mirror, suffice to compensate these null modes. Consequently, a minimum of 3 natural guide stars (6 measurements) are needed to control these five modes.

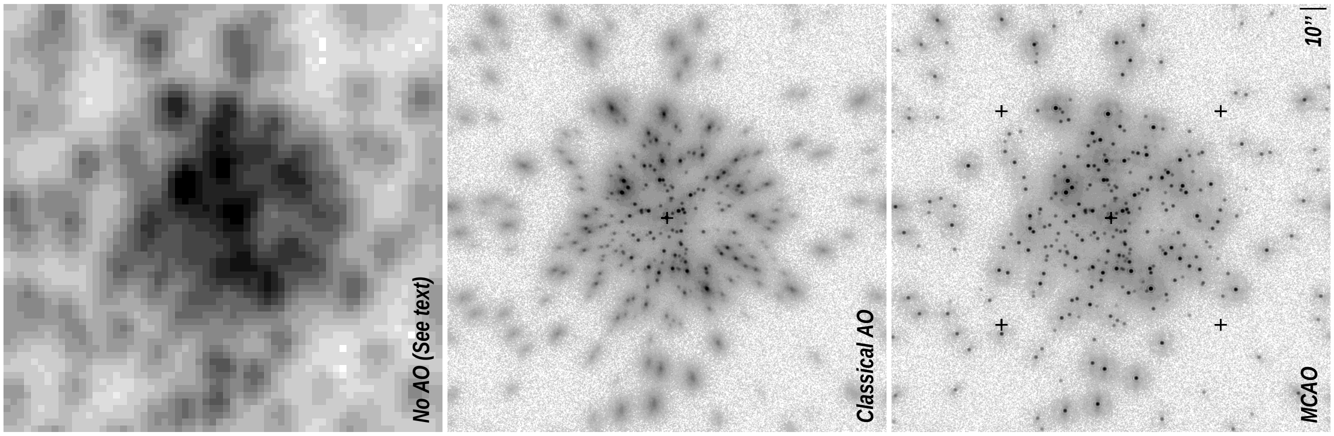

Figure 4. Simulated stellar field, containing 320 stars, and showed without AO, with a classical one-mirror pupil-conjugated AO and with a 2 DMs MCAO. Images at 2.1 μm on a 8-m telescope. The field of view is 165 arcsec on the side. Initial seeing is 0.7" at 550nm. Note that each star has been individually and locally blown up 15x to be able to better see the PSF variations. Because of this, the crowding looks worse than it actually is (especially on the No AO image). The guide stars are not shown on these images, but their positions are marked by crosses.

4.2. Sky Coverage

Fortunately, the NGSs required to compensate the null modes can be quite faint (a study at Gemini indicates a limiting magnitude of 19 for a 50% Strehl ratio loss at H band), and do not have to be close to the field center –in fact, as long as they are within the MCAO compensated field, the further apart the better, as one might expect.–

Sky coverage computations for the Gemini South MCAO system lead to values of approximately 15% at the galactic pole and 80% at 30 degrees galactic latitude. Folded in these numbers are conservative assumptions for the system throughtput and a 2 arcmin field of view to search the NGSs. Bahcall and Soneira star counts were used.

4.3. Minimum off-axis angle

Because of the finite range of the LGSs, they have to be positionned slightly more off-axis than the science field one wants to correct to cover effectively the whole turbulence volume crossed by the science beams. This additional angle is $D/(2.h_{\mathrm{Na}})$. It is small for an 8-m telescope (10 arcsec) but reach non-negligible values for a 100-m ELT (almost 2 arcmin radius). However, this problem should only translate for ELTs into requirements for larger field of view and not additional LGSs, as the generalized anisoplatism is constant with constant θ_{GS}/D.

5. PERFORMANCE EXAMPLES

This section only gives example of performance. For a more thorougth analysis of the performance, the reader in encouraged to read the paper from R.Flicker et al,[5] which present results of simulations done for the Gemini MCAO systems.

Extensive simulation and theoretical analysis has been done at Gemini during the past year. Two different codes are currently used to assess the performance of MCAO, written by the authors. The baseline for the Gemini MCAO system is: 5 LGS at each corners and in the center of a one arcminute field. 3 NGS to be picked up wherever available in a 2 arcminute diameter field. 3 DMs at 0,4 and 8 km, with 17, 19 and 13 actuators across the beam, respectively. The results of the optimization of the system parameters are presented in Flicker et al. Some notable conclusions from this study are:

- the phase reconstruction for up to 3 DM is remarkably robust. The actual performance degrades very smoothly with mismatch of the DM with the main layer altitudes.
- 3 guide stars are enought to ensure stability of the reconstruction, but the targeted PSF uniformity (3-4% relative Strehl ratio variations across the FoV at H band) is only achieved with 5 GS for a compensated field of 1 arcmin square.

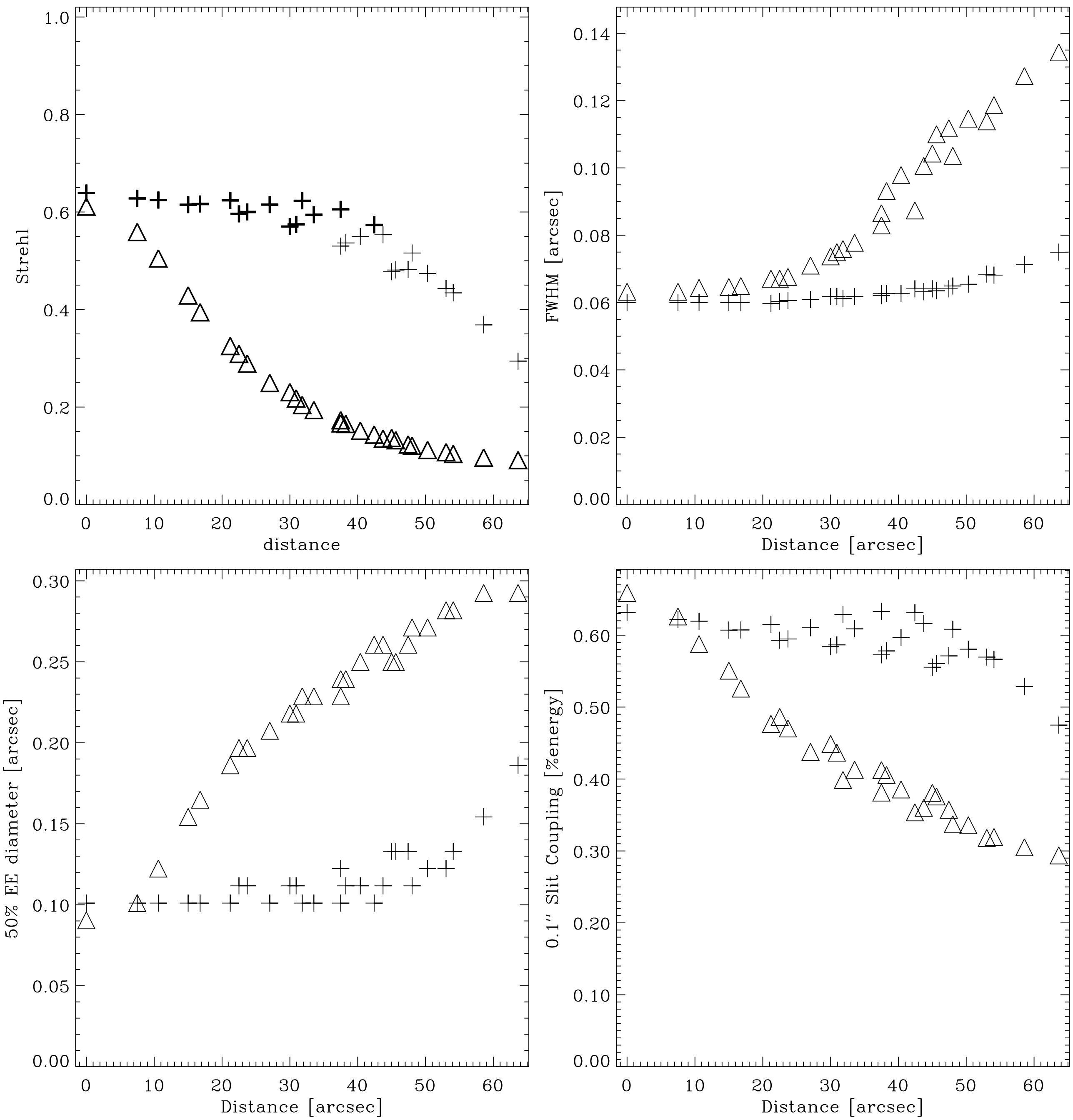

Figure 5. Sample performance of a MCAO system. Several metrics are displayed versus the distance to the center of the field. K band results. System using 5 laser guide stars located at each corners and at the center of a 1x1 arcmin field of view. One 12x12 subapertures shack-hartmann wavefront sensor for each LGS. 3 deformable mirrors at 0, 4 and 8 km and with 13, 10 and 7 actuators across the beam diameter. Cerro Pachon (Chile, site of Gemini south) turbulence profile. 200 photo detected event per subapertures and per frame on the high order sensors. 4 NGSs of $m_R = 18$ for the null mode sensing. Classical LGS AO system using one LGS and one NGS, both on axis, and of same magnitude than for the MCAO case.

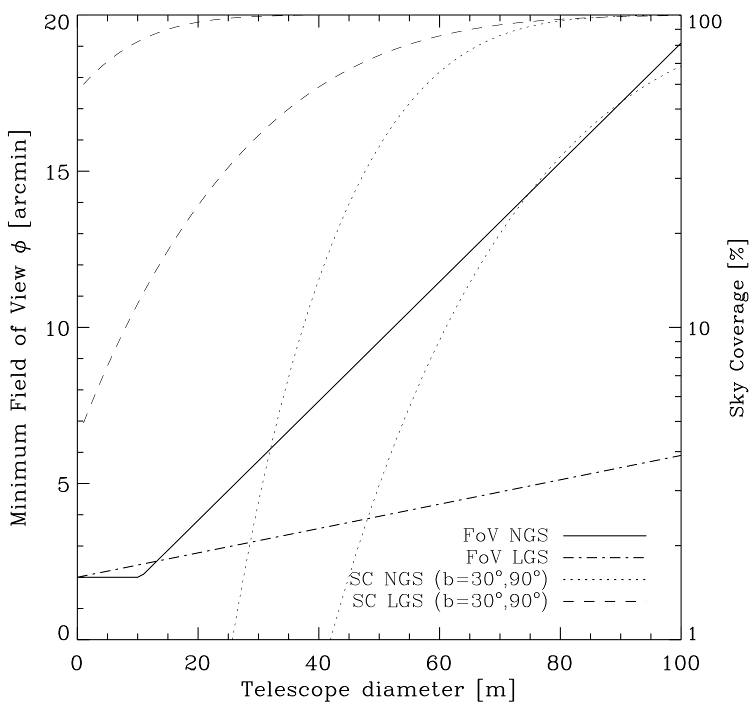

Figure 6. Field of view diameter requirement imposed by MCAO for ELT with LGS (dashed line) and NGS (solid line). A 2 arcmin science field is assumed. In the LGS case, the field of view is determined by the finite range of the LGSs: To cover adequately the science beam, the LGS have to be further off axis. In the NGS case, I have used to condition proposed by Ragazzoni, i.e. FoV = D/hmax, where hmax is the altitude of the highest turbulence layer. In essence, this means that the maximum shear between the GS beams is such that they just overlap at altitude hmax. This choice for the FoV obviously is the best for sky coverage, as you increase the probability of finding GS when the FoV gets larger. The sky coverage was derived using the corresponding FoV, and assuming a Poisson law for the star distribution. The criteria for NGS is 4 NGS of 13th magnitude or brighter in the FoV. For the LGS system, 4 NGSs of magnitude 19th or brighter are needed to compensate the tip-tilt and quadratic modes. The two dashed and dotted curves show the sky coverage respectively for LGS and NGS systems, for b=30 and b=90 degrees (Galactic pole).

- Generalized fitting is the major contributor from the MCAO induced errors. For the Gemini system, this error is of the same amplitude as the AO fitting error.
- Because of a higher redondancy in the measurements, noise does not affect MCAO as much as classical AO. This allow to use less powerful lasers than the one used in one-star LGS systems.

Figure 4 presents for illustration the results of early simulations of wide field MCAO performance, compared to the seeing limited case and a classical AO system. Figure 5 shows actual performance metrics (Strehl ratio, FWHM, 50% encircled energy and percentage of the light through a slit of 0.1 arcsec). The gain with respect to classical AO is not only in the SNR improvements it will bring, but on the uniformity of the PSF. Indeed, one of the main limitation in the exploitation of the AO results to date is the spatial variability of the PSF. PSF uniformity will allow to find applicable PSF in the one arcmin field of view, rendering the extraction of the photometry/spectro-photometry much more robust. A study of the exact implications of this is underway at Gemini in the context of the definition of the science case for the MCAO system for Cerro Pachon.

6. ON MCAO FOR ELTS

In 1999, it was suggested[9] that ELTs could get rid of LGS and use NGS for MCAO wavefront sensing. This study assumed that a GS has to be found within a angular distance with radius $D/h_{\max}$ –$h_{\max}$ being the altitude of the highest turbulence layer one wants to probe–, condition which means that the shear between two beams looking at two opposite guide stars can not be larger than each beam diameter at the highest layer if one does not want to “miss” a part of this layer. However, the previous analysis on the limitations of MCAO proves that such GS configuration will lead to very large compensation errors, induced both by generalized fitting and anisoplanatism. Table 1, for instance, indicates that 50 DMs are required to compensate a 10 arcmin field of view. 50 DMs imply the need for at least as many guide stars, and the probability to find 3 adequate guide stars only is in such a field of the order of a few percent at galactic pole, without even mentionning the probability to get 50 of them ! This is a catch 22: Given the sparse density of bright enought natural guide stars, wide field of view are needed; but wide fields mean a large number of DMs to keep the MCAO errors down, therefore requiring even more guide stars. It is clear that this NGS approach fails, at least in the scheme proposed by Ragazzoni. Other schemes (Ragazzoni, this conference), using layer oriented wavefront sensing with much fainter guide stars, are more promising but still require full assessment.

Figure 6 presents the field of view requirements for the method proposed by Ragazzoni[9] and for a system using LGSs. The sky coverage is also computed, using star counts based on Bahcall and Soneira and adapted for the Gemini observatory guiding system. Beside the fact that, as we noted above, the NGS technique does not work (!), it is clear that, purely based on field of view requirements and sky coverage, NGS MCAO can not compete with LGS MCAO.

7. CONCLUSION

In this paper, we have identified several fundamental limitations to tomographic MCAO: The generalized fitting, due to the limited number of DMs, which induces an error proportionnal to $(\mathrm{FoV}/d_{\mathrm{actuator}})^{5/3}$; the generalized anisoplanatism, due to the limited number of GSs, result of uniquely sampled volume of turbulence, which main effect is to produce image quality non-uniformity across the field of view, and the generalized aliasing

In addition, we have underlined several implementation issues with and without LGSs. We have pointed out that LGSs seem to be the only way to provide adequate sky coverage. The case of application to ELTs was briefly discussed, for which we pointed out the inadequacy of NGS approaches.

Additional work is clearly needed to fully understand and quantify the limitations of MCAO. However, this technique appear extremely attractive, promising uniform image quality over field of view much larger than with classical AO. Other approaches to tomography, like layer oriented wavefront sensing (see Ragazzoni et al, this conference), using natural or laser guide stars, are possible alternatives but their viability will have to be assessed.

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