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MULTI OBJECT ADAPTIVE OPTICS DESIGN FOR EAGLE : AN INTEGRAL FIELD SPECTROGRAPH FOR THE E-ELT

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Abstract. We present a preliminary study of a Multi Object Adaptive Optics [MOAO] system for EAGLE : an integral field spectrograph for the European-Extremely Large Telescope [E-ELT]. We investigate each term of error and its impact on the resulting performance and overall design. Performance is computed for different Guide Star configurations including Natural and Laser Guide Stars [NGS-LGS]. Finally, the sky coverage is evaluated and the choice between NGS and LGS is discussed.

1 Introduction

A new era of astronomical telescopes is about to start with the forthcoming generation of Extremely Large optical-infrared telescopes reaching diameters up to 42 meters. With this new generation of ELTs the whole instrumentation has to be reconsidered and redefined. In this context, a consortium formed by Institutes across France and the United Kingdom, is conducting a Phase A study to design a wide field, multi Integral Field Unit [IFU] Spectrograph assisted by Adaptive Optics [AO]. This instrument, called EAGLE, will span a large range of astrophysical fields, from the study of stellar population in nearby galaxies, to the observation of the first galaxies formed in the universe.

In this paper, we focus on one of these science cases : the physics of high redshift galaxies. Indeed, EAGLE will provide a unique tool to map the physical and chemical properties in high redshift galaxies ($z=1-5$). Such studies are of prime importance to directly distinguish between interacting and non-interacting galaxies, probe the evolutionary state of high redshift galaxies and try to understand what are the physical mechanisms driving the mass assembly of galaxies (e.g. Yang et al. 2007).

However, recover the dynamical nature of so distant galaxies will require to obtain spatially resolved spectra of very faint and small objects. Preliminary end-to-end simulations (Puech et al. 07) seem to indicate that 40% of Ensquared Energy [EE] in an spatial element of $\simeq$100mas (Hband) needs to be provided by the Adaptive Optics system to the spectrograph. Moreover, a large Field of View [FoV] (ideally $\simeq$10 arcmin in diameter) is essential to allow the simultaneous 3D spectroscopy of several galaxies. Fortunately, the correction is not required on the whole FoV, and only several scientific directions (goal $\sim$20) have to be compensated. To perform such a correction, an original concept called Multi Object Adaptive Optics have been proposed (e.g. Hammer et al. 2001, Gendron et al. 2005). In a MOAO system, several off-axis GSs (in the technical FoV) are considered to perform a tomographic measurement of the turbulent volume. The optimal correction is then deduced from the turbulence volume knowledge and applied using a single DM per direction of interest. Instead of compensating the whole field, MOAO will perform the correction locally on each scientific object.

Based on the scientific requirements, we present an error budget and a first design study of the EAGLE MOAO system.

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2 System design

In order to design our MOAO system, we assume that the final EE can be expressed as the result of a combination of several terms of error. These terms are the fitting error, the Wave Front Sensor [WFS] aliasing error, the servo-lag error, the WFS noise (photon and detector), the error related to the tomographic reconstruction of the turbulent volume and all the errors related to the Laser Guide Stars system (Tip-Tilt indetermination, Focus Anisoplanatism, Spot elongation, ...). This can be summarized as :

$$EE = f(\text{fitting error, aliasing error, servo-lag error, WFS noises, tomographic error, LGS error}) \qquad (2.1)$$

By the way of Fourier modeling (e.g. Jolissaint et al. 2006, Tokovinin et al. 2001, Gavel et al. 2004), we investigate the impact of each contribution on the final performance, adding these terms one by one. The final goal is to determine the adapted AO parameters and give a global view of a MOAO system for EAGLE (feasibility and first order of performance).

2.1 Simulation Parameters

The main atmospheric parameters and the AO hardware characteristics are summarized in Table 1.

Parameter	**Value**	**Remark**
Diameter	42m	No central obstruction
Turbulence	Typical Paranal Profile	10 layers
Seeing	0.95" @ 0.5 μm	
L_0	25m	
<Wind>	12.5 m/s	
Wave Front Sensor type	Shack-Hartmann @ 0.65μm 4x4 pixels/sub pupils	Same number of lenslets as actuators
WFS Temporal Sampling	300Hz	Total delay = 2 frames

Table 1. Simulation parameters.

2.2 Impact of Fitting Error

The very first step to design our AO system is to evaluate how many actuators are required to meet the scientific performance. In other words, we investigate the first 2 terms of eq. 2.1 : fitting and fitting plus aliasing error. For the fitting error, we assume that the AO correction is characterized by the DM cut-off frequency which is defined by :

$$f_c = \frac{1}{2d} \qquad (2.2)$$

where d (hereafter called pitch) is the WFS sub-aperture size. The number of actuators (or WFS sub-apertures) is then defined by :

$$N = \frac{D}{d} \qquad (2.3)$$

where D is the telescope diameter.
The aliasing error results from the spectral aliasing of the high-order modes into lower order modes and depends on the WFS type and geometry.
In Fig. 1, we present the expected EE in function of pitch size and for different seeing conditions. On the left, we plot the results without aliasing error effects, and on the right, we include the effect of aliasing considering a classical SH-WFS. These figures show that, to achieve the performance imposed by scientific specifications, a large number of actuators is needed. A high coupling factor can only be obtain by using a high order compensation. Moreover, as we only focus on fitting/Aliasing error here, some room has to be kept for the other items. Therefore, we have to consider a limiting EE better than the scientific requirement. We choose two cases, one optimistic : when the requirement in EE is better than 60% and one more pessimistic when the requirement

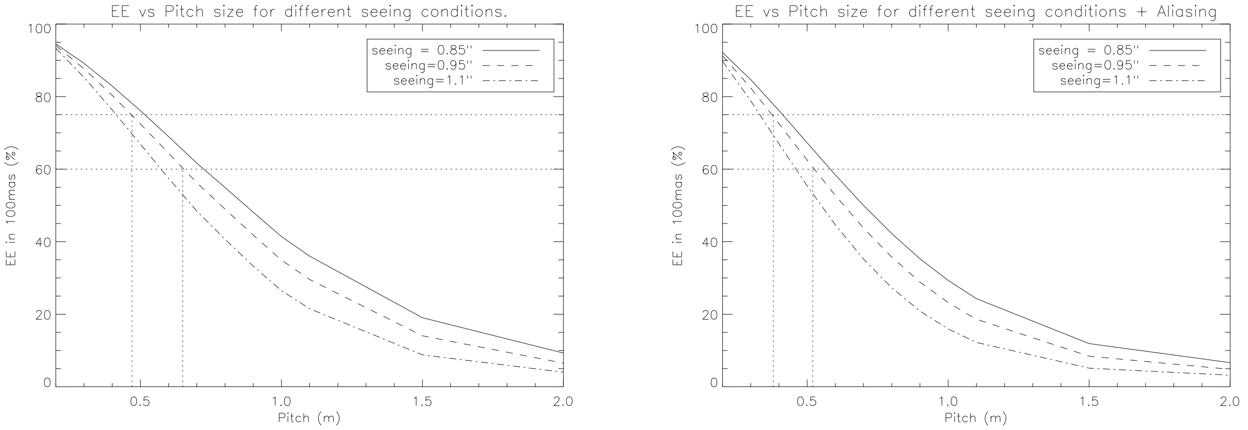

Fig. 1. Impact of Pitch size. *Left :* Without Aliasing error. *Right :* With Aliasing error.

EE is better than 75%. For these specific cases and average seeing of 0.95", we conclude that to achieve the scientific performance, at least 84x84 actuators will be required.

EE value	**60%**	**75%**
Minimum Pitch Without Aliasing	0.65m	0.47m
Minimum Pitch With Aliasing	0.5m	0.39m

Table 2. Required number of actuators to achieve 75% or 60% of EE without and with aliasing error.

2.3 *Impact of GS Magnitude*

We have shown in the previous section that EAGLE will required a large number of actuators. However, multiplying the number of actuators (or WFS sub-apertures) constraints the limiting magnitude of stars available for WFS. To illustrate this point, we now add the next two error terms of eq. 2.1 : WFS noise and servo-lag error. These two new terms are used to evaluate the impact of GS magnitude.

For the WFS photon noise, we assume a global transmission of our system given by a Zero Point = $10^{10} photo\text{-}e^-/m^2/s$. This Zero Point is defined by the number of photo-electrons detected on the WFS CCD for a G0 star with V = 0. It includes the overall transmission of atmosphere and telescope optics ($\tau = 0.25$), the quantum efficiency ($\eta = 0.9$) and the spectral bandwidth of the detector ($\Delta_\lambda = 0.4\mu$m). We consider a detector noise of 1e-/pixel. For the temporal error, we assume a 300Hz sampling frequency system with a delay of 2 frame and an average wind speed value = 12.5m/s^{-1}.

With these two new error terms, we can plot the EE versus Magnitude of the GS for different pitch sizes. These results are shown on Fig. 2-left. If we expect a system not or barely limited by WFS noises in order to keep the more stroke as possible for the other terms, we find that : for a pitch of 0.5m (resp. 0.25m) GS brightest than V=14 (resp. V=12.5) must be used for WFS.

2.4 *Impact of Tomographic Error*

To evaluate the impact of the tomographic error (which correspond to the fifth term of our eq. 2.1), we consider a symmetrical configuration of either 3, 4, 5, 6 and 9 Guide Stars distributed in a circle configuration. We study the evolution of the EE when the radius of the circle constellation is growing from 0 (on axis case) to 3.5 arcmin. The performance is evaluated at the center of this constellation.

We consider that we are dealing with bright GS (V<14 for a pitch = 0.5m), or in other words, that WFS noises can be neglected compared to the other terms of errors. We also consider that Focus Anisoplanatism, Tilt indetermination and all others issues related to LGS are negligible, meaning that the GS considered here

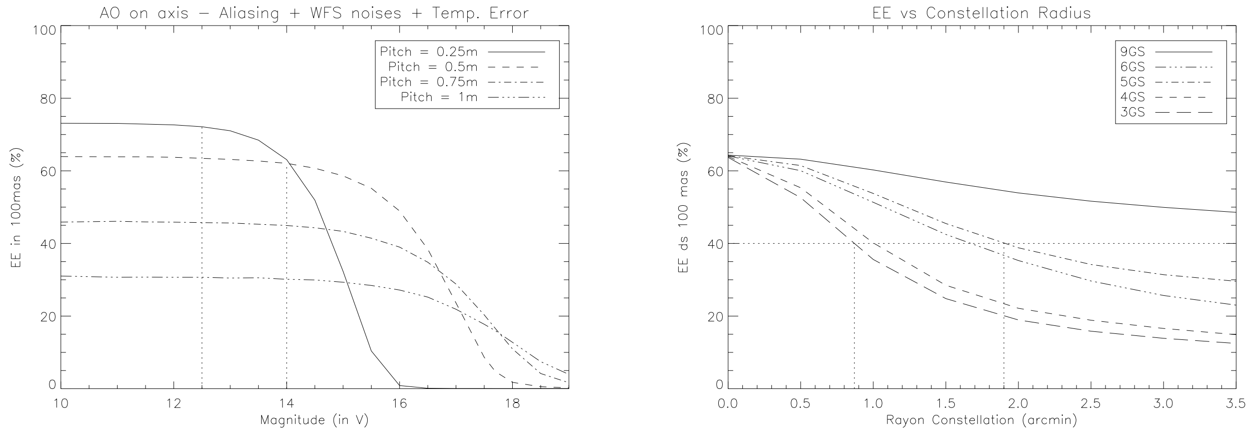

Fig. 2. Impact of Guide Star Magnitude (left) and GS separation (right) on EE.

are perfect Laser Guide Stars or Natural Guide Stars. Results including the tomographic error are presented in Fig. 2-right. As expected, when we move away the GS, the performance decreases. Moreover, when we use more GS for the tomographic reconstruction, the performance become better. Table 3 summarize the maximal constellation radius that could be considered to achieve 40% of EE for different GS constellations.

Number of GS	**3**	**6**	**9**
Maximal Constellation Radius	0.9’	1.9’	3.5’

Table 3. Maximal constellation radius to achieve 40% of EE.

2.5 Impact of Laser Guide Star Error Terms

Up to now, we have considered that all terms related to the LGS solution were negligible. In fact, we can show that, in first approximation, this assumption is not so far from real conditions of operation.

The main issues related to the LGS solution are Focus Anisoplanatism [FA], spot elongation and Tilt indetermination. The Focus Anisoplanatism is due to the finite altitude of the LGS. Rays from the LGS do not sample the same turbulence as the collimated beam coming from the science object leading to a phase estimation error. This effect makes the use of a single LGS useless. However, when several LGS are used the FA effect can be considerably reduced (see Tallon & Foy 1990, Viard et al. 2002). In the following we will make the assumption that FA error is actually solved.

The spot elongation is due to the finite range of the mesopheric sodium layer, leading to elongated spots in the subapertures of the WFS. Nevertheless, new development of CCD with pixels aligned in polar coordinates could be used and optimized for LGS-WFS (Beletic et al. 2004, Adkins et al. 2006, Thomas et al. 2007). These novel techniques lead then to optimistic solutions for solving the spot elongation issue.

Finally, the last critical term related to LGS is the tilt indetermination. As a consequence of the round trip of light the wavefront tilt cannot be obtained from the LGS. Elaborate techniques have been proposed to measure the Tilt from the LGS (Foy et al. 1995, Ragazzoni et al. 1996) but unfortunately, real time correction has not yet been demonstrated. This forces to use a NGS to retrieved the wave front Tilt (Rigaut & Gendron 1992).

To evaluate the impact of Tilt indetermination on our system, we have investigated two configurations : one with no Tip-tilt correction at all and one with a NGS Tip-tilt partial correction (Neichel et al. 2006). Indeed, if the box size is larger than the Tilt motions, a large proportion of the energy will be still coupled in the box, even without total Tip-tilt correction. As Tilt motions strongly depends on outer scale of turbulence, we have computed the EE for different value of L0 in a 100x100mas^2 box and for a pitch = 0.5m. For partial Tilt correction, we assume a system working with NGS correcting either 50% and 75% of the residual tilt variance. The resulting performance are given in Table 4, nominal performance with full tilt correction is given for comparison.

	L0=12m	**L0=21m**	**L0=42m**	**L0=50m**	**L0=84m**
EE without TT correction	64%	64%	63%	60%	40%
EE with 50% TT correction	64%	64%	63%	61%	55%
EE with 75% TT correction	64%	64%	64%	64%	60%
EE with full TT correction	64%				

Table 4. Performance of a system working without or with partial Tilt correction.

Results of Table 4 show that, for L0 lower than 50m, tilt motions have quasi no impact on the EE for 100x100mas^2 box. When partial Tilt correction is provided, even the largest L0 do not impact on the performance. We can then conclude that the Tilt indetermination issue will not be a critical point for EAGLE.

3 Sky Coverage

Working with NGS only raises the question of the sky coverage. To evaluate this sky coverage, we have computed the number of stars available in different field size and at different galactic latitudes (Fusco et al. 2006). Table 5 summarize the mean expected number of GS with a magnitude lower than 17 (R-Band) for different galactic latitude.

Galactic Latitude	**b=30°**	**b=60°**	**b=90°**
Number of Stars in a FoV of 2.5'x2.5'	4	1	0.6
Number of Stars in a FoV of 5'x5'	14	4	3
Number of Stars in a FoV of 10'x10'	57	18	12

Table 5. Mean number of Natural GS with R<17 available at different galactic latitudes.

For instance, in a 10x10arcmin^2 Field at the galactic pole, we could find 5 stars with R<15, 4 with R=16 and 3 with R=17. If the size of the field is reduced to 5x5arcmin^2, these numbers decrease to 1 with R<15, 1 with R=16 and 1 with R=17. Paradoxically, we have seen in Sect. 2.4 that to increase the FoV accessible with tomography, an increasing number of GS is necessary. Thus, even when working in tomographic fashion, full SC can be obtained only near the galactic plane.

To overcome the sky coverage issue, the solution of using a LGS is mandatory. A solution without Tilt correction would provide a full sky coverage, but with a restriction on the observing conditions (L0 < 50m). For a system working with a wider range of observing conditions, a partial Tilt correction must be considered. In this case, as the Tilt correction is provided by a NGS, the sky coverage has to be re-estimated. To do so, we establish the link between the Tilt residual variance and observational parameters (NGS magnitude and distance from optical axis). We find that, to partially correct the tilt residual variance, NGS even far or faint could be used. In term of sky coverage, this leads to a sky coverage of 99% near galactic pole for a residual tilt variance correction of 50%, and around 80% for a correction of 75%. Then, a good correction of the residual Tilt variance can be achieve together with a quasi full sky coverage even at high galactic latitudes.

4 Conclusion

We have presented here results concerning AO concepts for future 3D spectrographs on ELTs. We have shown that Sky Coverage issue is a critical point when working with NGS-based system and the LGS solution seems mandatory for observations at high galactic latitudes. For LGS systems, we demonstrate that Tilt indetermination is not an issue and rather simple LGS systems without Tip-tilt correction could be considered.

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