# Integrating AO in a performance budget: towards a global system engineering vision

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**Abstract.** EAGLE is a near-infrared wide field multi object spectrograph. It includes its own Multi-Object Adaptive Optics system (MOAO) and its subsystems are cooled to deliver the performance in the K-band. Due to the integrated nature of the instrument, the performance matrix has to deal with a large number of Adaptive Optics (AO) parameters as well as the added complexity of active optical elements. To ensure successful integration of the next generation instruments for ELT like EAGLE, it is of the utmost importance to have method to control and manage the instrument's critical performance characteristics. We discuss the performance matrix we developed to automatically partition and allocate the important characteristics to the various subsystems as well as the process to verify that the concept will deliver the required performance. We also define a method to convert the ensquared energy and signal-to-noise ratio into the "as designed" overall residue wavefront error.

## 1. Introduction

The science that will drive the E-ELT (European-Extremely Large Telescope) concerns the smallest objects visible from Earth in the universe. The cosmologists wish to study the very first galaxies with a sufficient spatial resolution to determine their physical characteristics [1,2]. The usual spectral lines studied are shifted in the K-band and require cooled spectroscopic instruments. In the stellar domain, the science goals consist of observing the stars individually in or close to our galaxy in order to get statistics (different ages, material abundances, etc) to determine the host galaxy history [3]. Giant telescopes may also be capable of seeing giant exoplanets orbiting at separations smaller than 1 AU (Astronomical Unit) or studying planetary systems during their formation to better understand the mechanisms. All of these science drivers, among many others, require a high spatial resolution with medium to high spectroscopic capabilities.

If high spectroscopy requires any new tools, the diameter of the next generation telescopes brings an unprecedented opportunity for high spatial resolution. But the atmosphere blurs the image and the use of AO (Adaptive Optics) becomes necessary. This powerful tool makes an instrument design more difficult, increases the complexity and the number of interfaces with the telescope. Moreover, the next generation telescopes will have diameters larger than thirty meters but only three are planned. As a result, the number of instruments will also be limited. To keep efficiency,

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the logical evolution pushes for versatile instruments, capable of observing multi-objects simultaneously. This will result in instruments with a lot of design constraints. The requirements and design goals will have to be clearly specified.

All of this suggests that the next generation of instruments will increase in mass, volume, complexity and cost compared to that of the 8-meter class instruments. System engineering provides the foundation to balance the constraints and optimise the science goals. This implies a well-defined process to allocate the performance and error budgets (cryogenics, mass, volume, cost, etc.) as required. This paper presents a method to manage these requirements for the EAGLE instrument proposed to ESO. In section 2, we discuss the various units involved in an error budget. In section 3, we explain how we include the AO requirements and properties in our overall performance budget. In Section 4 we evaluate the K-band constraint and Section 5 describes the composition of our performance budget. We conclude with Section 6, where we summarise the EAGLE instrument performance budget.

## 2. Which parameters?

Each trademark involved in a project uses its own metrics. The performance criterion for science is the signal to Noise Ratio. However, for EAGLE, additional science drivers have been considered as part of the trade-off studies. For the signal part, the throughput is not the only parameter that will influence the overall performance of the system. The EE (Ensquared – or Encircled – Energy) is also a crucial parameter because of the spatial resolution. From an optical design viewpoint WFE (Wave Front Error) is a very important parameter whereas in mechanics, engineers use millimetres for their dimensioned sketches as well as for the tolerances for the positioning and the alignment of optical components. On the other hand in adaptive optics the preferred performance parameter used is the SR (Strehl Ratio) or the phase variance. Complex algorithms and simulations are used by the AO specialist to calculate the performance of an AO system. Unfortunately, the EE or the SR value can change rapidly with changing input parameters (seeing, number of LGS – Laser Guide Stars – number of NGS – Natural Guide Stars – their configuration in the sky, etc.). This makes AO very difficult to implement because the values used depend on a large number of input parameters. Changing them is not possible without extensive AO simulations. In this paper we show how the Systems Engineering team has dealt with the adaptive optics challenge and we also describe the SNR model that was developed to allow the team to analyse the impact a design change will have on the overall performance of the instrument despite the complexity coming from the adaptive optics. The model automatically takes care of all the conversions between the various performance parameters listed above. This aspect is very important because it allows the team to observe the change in the performance of the system immediately with any change in the input parameters. It also becomes possible to re-allocate performance and error budgets dynamically to the various system building blocks. As we have seen earlier, this would not be possible using the traditional AO simulation models. In the next section we will describe how the team has dealt with this aspect of the model.

## 3. Including AO in an error budget

**The Multi-object adaptative optics.** There is no requirement for EAGLE to correct the overall science FoV (Filed of View). This instrument, a multi-object spectrograph, aims to observe several

small individual fields distributed anywhere in the FoV. Thus, MOAO (Multi-object Adaptive Optics) proves to be the best topology to use to correct the wave front [5].
In terms of the error budget, the introduction of the MOAO requires us to split the error budget along the spatial frequency domain.

- Firstly, the combination of LGSs and NGSs. It is required because the probability of having a bright (< 17) enough NGS within the 10 arc minutes FoV [5] is about 1%.

- Secondly, the EE strongly depends on the high order phase variance while the other contributors (low order to tip-tilt) decrease the EE by only a few percent. We will use this property in the error budget to include AO without sacrificing its versatility (section 5).

- We assume that the tip-tilt rms and the low order modes (low order aberration) are small enough to maintain the light dispersion within the 75x75 $mas^2$ spatial element.

**Partition of the instrument**. Having 6 meters height, 5 meters in diameter and proposing 20 science channels made of about 40 optical components, EAGLE cannot be mounted sequentially like a single instrument. Indeed, allocating a sufficient budget for the tuning of each component (say 0.5 degree along the three dimensions) would have led to a negligible global performance for each science channel.

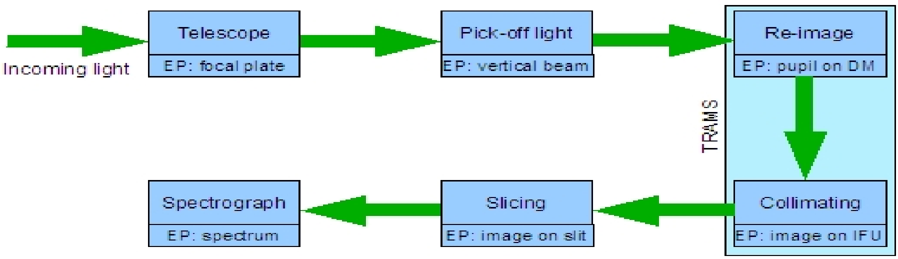


*Figure 1: Telescope and EAGLE modules with their end-product..*

The solution we found consists in splitting the instrument in modules as independent as possible (Figure 1), taking care that each of them has a physical input and output. This was to allow the production of each module to be independent, where the internal alignment error can be compensated for during assembly. Consequently, each module generates an end-product (pupil, collimated beam or field) that can be easily measured and used to ease the tuning. The mounting is also easier since the modules can be assembled directly. An allocation in the error budget for their alignment, including just tip-tilt and bi-dimensional shift is sufficient. As we pointed out in section 2, splitting the spatial domain allows this kind of allocation and alleviates the constraint on the system.

**Non Common Path Aberration Compensation.** The telescope will induce disturbances based on the zenith angle of the telescope and many other sources can degrade the alignment of the instrument such as the temperature variation. Calibrations are thus required. We decided to measure these misalignment errors by using a WFS installed in the instrument. The unit remains the same in term of performance budget and the path aberrations along the optical path from the telescope (included) to the slicer (excluded) can be measured so that they can be compensated for by using the DM. The principle consists in allocating a percentage of the DM stroke for correcting the path aberrations in order to improve artificially the optical path quality. The aberrations introduced by the sensing devices are also part of the NCPA if these are not calibrated. It is not possible to compensate for NCPA and as such their amount of error that can be tolerated has to be divided amongst the various components. This error is much lower compared to that of the aberrations along the rest of the optical path so this will increase the EE without having to over constrain the quality of the optical components which typically are more expensive. This introduces the second feed-back loop of the performance budget (grey box in Figure 2).

## 4. The K-band constraint

The EAGLE science requirements call for a spectral range from 0.8 µm to 2.5 µm. This is due to the cosmological galaxies ($z > 6$) for which the lines Hα and OII are shifted in the K-band. As the scientific sources are very faint, the instrument should not radiate in the K-band while observing. Therefore a cooling system is required which is costly, and requires more volume and increases the total weight of the instrument. We have developed an opto-thermal simulator to generate noise tables based on the external temperature and the internal temperatures of the different modules under consideration. According the input values, interpolation allows to get the better evaluation.

## 5. Building the EAGLE wavefront error budget

With the elements described above we now have the material that can be used to allocate the allowable error terms to the EAGLE modules. For versatility, the budget should also include:

- A user interface to select the science case so that the design of the instrument can be evaluated against the science requirements for each of the science cases.
- Configurable for each of the wavelength bands, the operational temperature, the observation strategy as well as many other parameters such as the detector characteristics. The goal is to be able to determine how a change in the instrument configuration will impact its overall performance. These predictions were used in the various trade-off studies during the instrument design.
- Inclusion and modelling of the AO effects (feed-back loop, EE calculator).
- Derivation of the allowable wavefront error that each of the modules shall comply with, to allow the evaluation of various designs.

The method we followed to allocate the residual errors allowed by each of the instrument modules is based on a close loop. Starting with the requirement and the environmental constraints imposed by the telescope and the outside world, we derived the requirements to allow us to perform the necessary optical alignment and AO calibrations.

In the following paragraphs we explain the method we used to build a performance model complying with the aforementioned requirements and describe the test and calibration process. The overall performance and error budget model is presented in Figure 2.

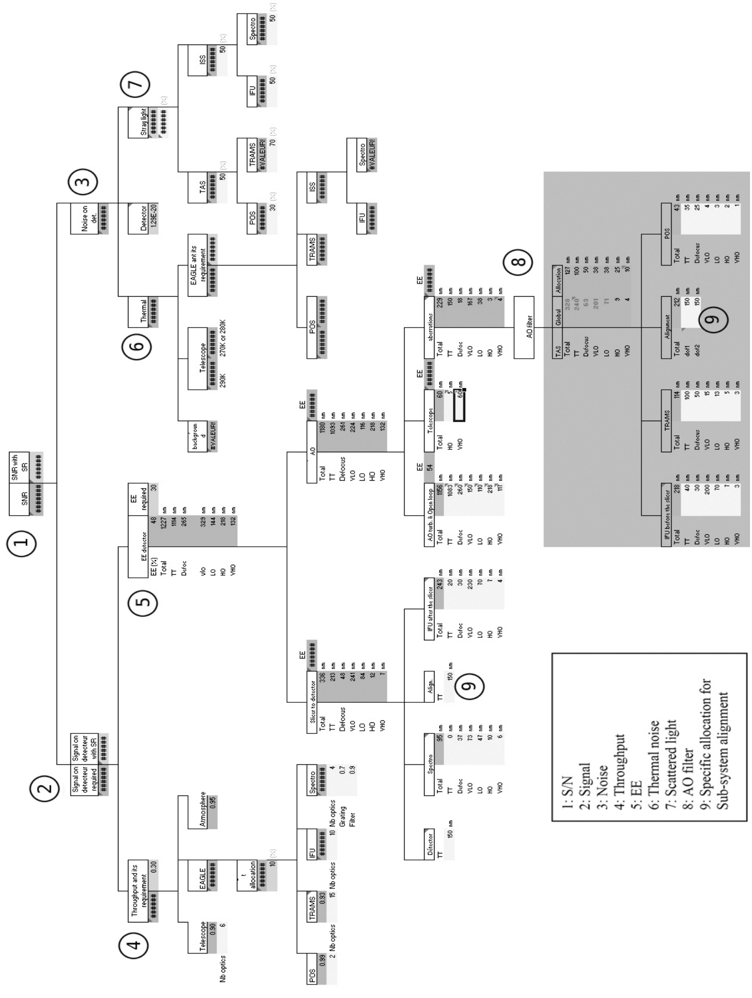


Figure 2: The EAGLE error budget.

**Error budget versus Science requirements**. It is essential to build an error budget that provides link(s) with the science requirements. Th(es)e link(s) must include the signal and the noise at the detector level and must provide a general flag to determine whether EAGLE globally fulfills the requirements or not. We chose the S/N because it provides information on the data quality to produce science. It shall equal 5 for the cosmological topic [3] with a resolution of 4000 and 10 for the resolved stars [6] with a resolution of 10000. To be useful, the error budget must provide the achievable S/N onto the detector. It will also help for simple and easy comparison between the various designs. That supposes to perform the available EE at the detector plane, the instrument throughput and the different noise contributors such as the thermal background.

In order to make the error budget versatile, we also produced a science user interface as already said. It allows changing the main science parameters: the observed line (H$\alpha$ or OII), the redshift, the external temperature (for the thermal noise), the band in which the observation is performed and the desired S/N. The two formers give the characteristics of the line to be observed. The two following are inputs to pick-up the appropriate value for the thermal background database. In this way, the system engineer can see the influence of any change in the science requirements and can flow down a new error allocation to all engineers (in the case of an approved major change).

**Error budget versus EAGLE module**. As we said in section 3, the EAGLE design is split into four sub-systems (or modules) so that each of them is as independent as possible. To perform the best turbulence correction, the pupil must be perfectly centred and oriented with respect to the DM area. A mutual point source shall be used as a common reference in the instrument between the AO components and the optical components. For example, we might need calibration sources around the M4 pupil to image its position and orientation on each DM because it is crucial to superimpose the M4 pupil onto and DM actuator grid to apply the correct wave front correction. This calibration step shall be made with a special care. The accuracy is about 10% of the actuator pitch of the DM, so about 50 µm and a fraction of degree. The main difficulty arises because such accuracies must be applied to sub-systems having a large volume (roughly one meter cube) and mass (about 500 kg). The error budget takes into account this step via a special allocation for each sub-system.

The performance budget will be affected by the residual effects from the E-ELT and will appear in the error budget. All errors but those from ELT are "**static**" between two calibrations under normal operating conditions. Allocations will be made (or flown down in the case of the telescope residuals) for each of the systems/sub-systems in such a way that they can be combined in a linear fashion WFE). It is very important to ensure that we do not double count errors or miss out important error contributors. That is why, for instance, we split the IFU modules into two parts – before and after the slicer – in order to take into account the fact that we can compensate for the NCPA. For the **statistical** errors, such as the residual errors of each sub-system, we can apply a square root summation because we consider these to be independent parameters.

**Adaptive optics contribution.** The interaction with AO is more subtle. The DM performs the AO correction to enhance the EE but it can also take into account the NCPA for the image quality situated *in front of* the slicer situated in the IFU. As mentioned above we must consider two areas in front of and behind the slicer where the former can afford a larger error budget as compared to the latter (IFU + spectrograph). The error budget will take into account this fact by using an "AO filter" in the TAS tree. The error budget for the optical and mechanical engineers is situated in the grey box. This amount of error is then filtered by the AO filter to give the residual error that is not corrected by the AO (ie by the DM). If the TAS errors are lower than this allocation, the residual is only made up of the drifts (thermal, mechanical, etc) and the calibration errors. If the TAS error is larger than the allocation, it is assumed that the DM corrects what is possible with the allocation of 5% of its stroke and allows the difference to go through the filter. In this case, this difference is added to the drifts and calibration errors leading to a greater amount of error. In this version, we assume that drifts and calibration error represent 10% of the 5% allocated for the TAS correction.

Another key issue is the transformation of the WFE in EE. As we said in section 2, WFE is the logical unit for optical designer but EE is one of the science high level requirements. EE depends on many parameters such as the band considered (J, H, K), the Cn2 profile and the number of turbulent layers within the atmosphere as well as their strength, the number of LGS and NGS and their magnitude, the DM characteristics (number of actuators), etc. Changing the value of one parameter usually needs a simulation to perform its impact on the EE. To avoid such a strong interaction between AO and engineering staff when adjusting the error budget, we build it in a way that provides the EE calculation without performing new simulations.

We saw in section 2 and 3 that splitting the spatial frequency domain allows using the same unit and allocating more accurately the error budget. It has a third advantage: optimizing the error budget since we can allocate more precisely the WFE to each of the building blocks. For an instrument such as EAGLE, that includes many sources of error – even if they are minimised by calibration – such a philosophy saves about 10% (absolute) in EE, so a third of that we obtain with the current design!

Because of the DM capabilities, we defined six categories, according to how they impact on the WFE. Tip-tilt and defocus for which the spatial frequency is manageable with NGS, very low order (VLO) and low order (LO) that remains below the DM spatial frequency, high order (HO) and very high order (VHO) which are up to the DM spatial frequency. We demonstrated that VLO shall range in the EAGLE case from Z=5 to Z=11 (Zernicke) whereas the LO is set from Z=12 to Z=231 (the maximum Zernike mode in Zemax). The spatial frequency associated to $f_{box}$ is 0.22 $m^{-1}$ for a spatial sample on the sky of 75 mas so a radial Zernike order equals to 24 and represents the beginning of the HO domain. This means that a gap from Z=232 (n = 20) to Z=325 (n = 24) is not considered. The result is an (likely small) overestimate of the EE.

We first sum the HO and VHO contributors (root sum square) and deduce the EE from the set of the simulations that give the EE contribution due to HO and VHO for various cases (number of LGS and NGS, seeing, etc). The idea of interpolating among a set of simulation makes the error budget calculator suitable whatever the parameters the user enters. This introduces a slight error in the EE estimate but does not impact the S/N by more than a few percent.

The impact of the other spatial ranges is more simple to evaluate as their impact is lower. We again need a set of the curves of the EE over the Airy EE (no error) versus the error variance for the four remaining spatial frequency domains. At a certain variance, the EE loss for each domain corresponds to the ratio value (the ordinate of the curve). This method is of course not exact as it starts from the Airy EE instead of the EE we get after the contribution of the VHO and HO orders. But we can make such an approximation because the VLO, LO, defocus and tip-tilt contributions are small compared to the initial value. Moreover, for the phase A study, we only needed an estimate to drive the trade-offs. Again, a set of curves allows performing an EE recalculation according any change in the setup.

Finally, the main topics of the error budget (throughput, EE, thermal noise and stray light, see numbers 4 to 7 in Figure 2) are split in several branches, dedicated to each sub-system or to the telescope in order to perform a bottom up allocation. For the throughput, we simply split the error budget in four branches plus the grating. For the EE, we considered the IFU and the spectrograph on one hand and the POS and the TAS on the other hand because of the feed back loop. We introduce the telescope and the sky brightness in the thermal noise branch. The stray light budget is split into two branches, one for the POS and the TAS, the other for the IFU and the spectrograph.

## 6. Conclusion

With its size, 20 independent channels, high spectral and spatial capabilities, EAGLE opens new dimensions for the next E-ELT instruments in terms of size, versatility but also in the technologies used (all devices will be addressable via http to get their status). These features make the instrument more complex with a large number of error sources. From system engineering point of view, the allocation of error budget is a complex problem. We partially solved it by:
- Designing the instrument to have as independent as possible sub-systems to minimize the alignment error budget (within and between) them.
- Splitting the budget in the spatial frequency domain (interesting if AO functions are implemented) for a more accurate allocation of budget.
 Including calibration sources inside the instrument to measure and correct the possible errors.
- Measure the internal error to compensate for them with the active optics (if AO is implemented).

Despite these constraints, we succeeded in developing a versatile performance model supporting a science user interface with auto-configuration capabilities that enables us to recalculate the overall performance of the instrument when the top-level parameters and/or design changes. In phase B development phase, such a tool will be very useful, saving time during the design phase by allowing the possibility of modifying key-parameters while ensuring that the overall performance of the instrument will not be compromised in real time.

## 7. References

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