EAGLE: an MOAO fed multi-IFU working in the NIR on the E-ELT

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ABSTRACT

EAGLE is an instrument for the European Extremely Large Telescope (E-ELT). EAGLE will be installed at the Gravity Invariant Focal Station of the E-ELT, covering a field of view of 50 square arcminutes. Its main scientific drivers are the physics and evolution of high-redshift galaxies, the detection and characterization of first-light objects and the physics of galaxy evolution from stellar archaeology. These key science programs, generic to all ELT projects and highly complementary to JWST, require 3D spectroscopy on a limited (~20) number of targets, full near IR coverage up to 2.4 micron and an image quality significantly sharper than the atmospheric seeing. The EAGLE design achieves these requirements with innovative, yet simple, solutions and technologies already available or under the final stages of development. EAGLE relies on Multi-Object Adaptive Optics (MOAO) which is being demonstrated in the laboratory and on sky. This paper provides a summary of the phase A study instrument design.

Keywords: Cosmology, high-redshift galaxies, galaxy evolution, stellar archaeology, E-ELT, MOAO, adaptive optics, integral field spectroscopy

1. INTRODUCTION

The European Extremely Large Telescope is currently in phase B at ESO. This phase will end mid 2010 with the release of the proposal for the E-ELT construction. Meanwhile ESO has launched eight instrument conceptual studies (phase A) to be carried out by community-based consortia of institutes, including ESO. A high priority instrument common to all US and European ELT projects, as derived from their science cases, is a near IR spectrograph with multi, deployable Integral Field Units (IFUs), assisted by Adaptive Optics. This type of instrument is particularly required for the study of the evolution of galaxies across cosmic times, from the first light objects at redshifts above 7, to the galaxies at reshifts ~ 1. While GMT and TMT have deferred the implementation of this type of instrument to the second generation, the case for an early implementation at the European ELT appears much more feasible. Indeed, thanks to the many precursor studies performed for the OWL 100-m telescope project and for the ELT Design Study (DS) programme of the 6th Framework Programme (FP6) of the European Commission (EC), it has been possible to design EAGLE as a relatively simple instrument relying exclusively on proven and mature technologies, and on an AO concept for which extensive demonstration programmes are under way and that will be completed over short timescales.

The EAGLE consortium consists of six institutes in France and in the UK. The phase A study is supported by an ESO contract, and several other contracts and grants from the European Commission and the French and UK national agencies. The EAGLE Phase A study started mid-2007 and is ending in the third quarter of 2009. Prototyping and demonstration activities will continue throughout 2010 and beyond. We present in this paper the phase A study advanced design.

This paper is organized as follows: in the next section we briefly outline the EAGLE science case and the instrument top level requirements, in section 3 we present the baseline instrument design and in Section 4 we provide further details on the Multi-Object Adaptive Optics (MOAO) system.

2. SCIENCE CASE

Recent years have witnessed the realisation of facility-class spectrometers on 8-10 m telescopes that employ adaptive optics to improve image quality. Instruments such as VLT-SINFONI and Keck-OSIRIS are yielding impressive spatial performances, providing us with new insights in a wide range of targets – from obscured star-formation regions in the Galaxy, right out to spatially-resolved observations of galaxies at $z{\sim}3$. However, current observations are relatively restricted to, for example, the largest and brightest high-redshift galaxies (e.g. left-hand panel of figure 1), and thereby introducing selection biases in the observed samples. The EAGLE science case spans spatially-resolved spectroscopy of targets from five key science areas that will be revolutionised by the E-ELT:

- The physics and evolution of high-redshift galaxies;
- Detection and characterisation of first-light galaxies;
- The physics of galaxy evolution from stellar archaeology;
- The stellar content, mass functions and dynamics of stellar clusters;
- Co-ordinated growth of black holes and galaxies.

EAGLE is motivated by the desire to obtain near-IR spectroscopy of large numbers of objects (across a ≥ 5' diameter field) to build-up representative and unbiased samples of, for example, hundreds of high-redshift galaxies. In this context, its science case calls for improved angular resolution (~75-100 mas) but not diffraction-limited performance. The main scientific drivers are the improvement of the point source sensitivity (e.g. for the stellar science case and for the first light highest redshift objects) and the ability to spatially resolve structures at the 100 mas level for studying the properties of distant galaxies (corresponding to a ~ 0.5 kpc spatial scale in the galaxies). Increasing the point source sensitivity calls for diffraction limited images, but this comes at the expense of sensitivity in surface brightness and more demanding requirements on the Adaptive Optics System. Moreover, as the level of sky background between the OH lines becomes very low at the diffraction limit sampling, the performance is no longer background limited. A scientifically acceptable trade-off has been set to reaching a spatial resolution element (spaxel) in the range 50 – 100 mas, for which the level of correction needs to be substantial but within the capabilities of existing AO components. This spatial resolution corresponds to the apparent size of very high redshifts first light objects. The requirement has therefore been set as 30 to 40% Ensquared Energy in a spaxel size of 75 mas. This trade-off includes other considerations such as estimated performance of AO systems on a 42-m telescope, focal ratio of the spectrographs, etc. With this spatial sampling the background per pixel between the OH lines is similar to the background regime of current spectrographs on 8-10 m telescopes with ~ 0.2" spatial sampling.

The baseline requirements adopted for the Phase A study are summarized in Table 1. Note that the wavelength coverage extends blue-wards to 0.8μm, which includes the calcium triplet lines at zero redshift that are used as a diagnostic of stellar metallicities and radial velocities; the higher-resolution mode ($R{\sim}10{,}000$) is mainly driven by the requirements for studying the stellar populations of nearby galaxies. Also note the requirement for observations of both contiguous and highly-clustered fields (e.g. the right-hand panel of figure 2) to enable ‘mapping’ of selected regions. Figure 2 illustrates the EAGLE functionality.

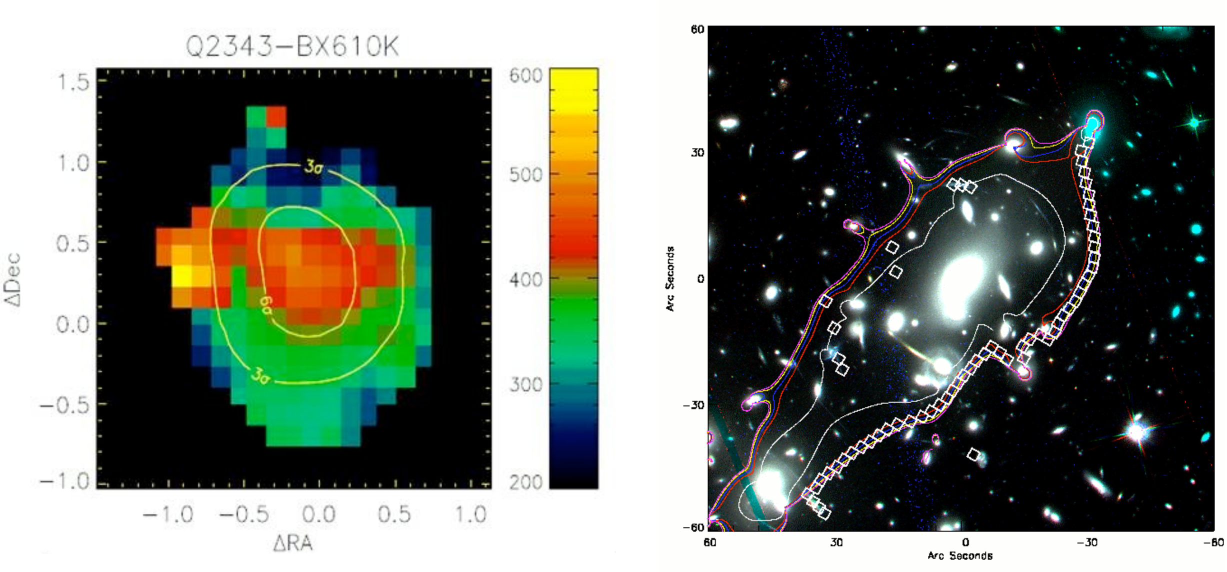

Figure 1. *Left:* VLT-SINFONI observations of rest-frame Hα emission in a z~2 starburst galaxy. *Right: HST* image of the well-studied galaxy cluster Abell 2218, with EAGLE IFUs overlaid to map the critical curves for very high-redshift galaxies.

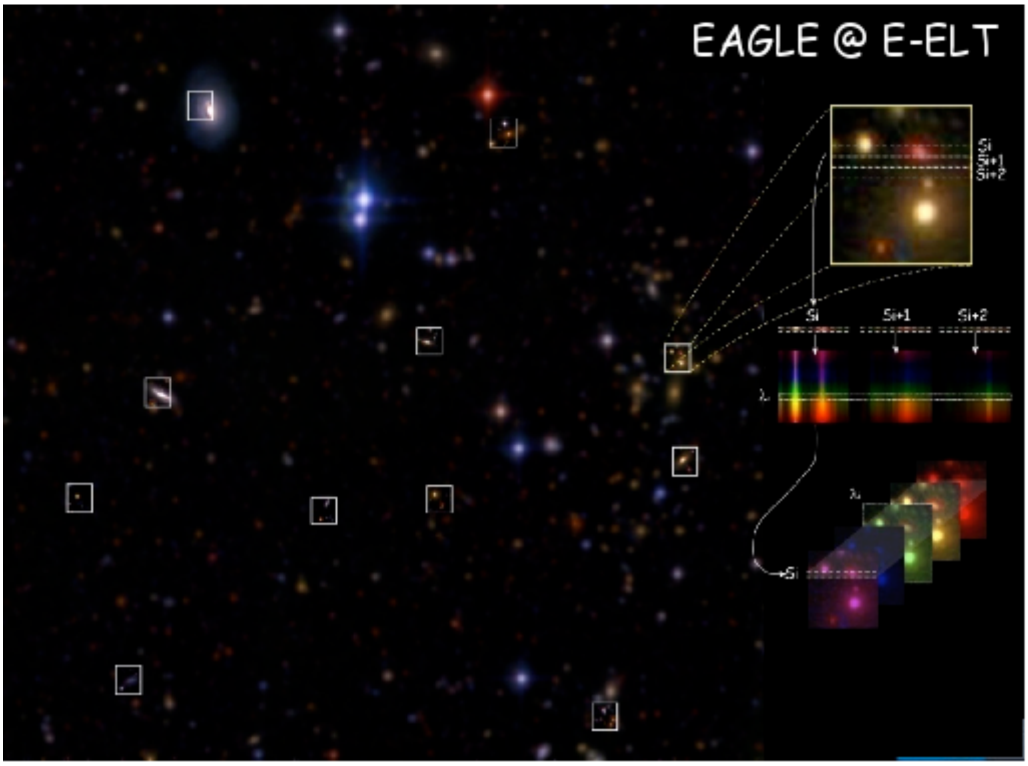

Figure 2. Cartoon of the EAGLE functionality: ability to pick-off targets within a large field of view, correcting for image quality and achieving 3D spectroscopy of each science sub-field.

Table 1. Baseline EAGLE science requirements for the Phase A study.

Parameter	Requirement
Patrol field	≥ 5' diameter
Science (IFU) sub-field	≥ 1.5" x 1.5"
Multiplex	≥ 20
Spatial resolution	≥ 30% Ensquared Energy in 75 mas (*H*-band)
Spectral resolution	4,000 & 10,000
Wavelength coverage	0.8 – 2.45 µm
Clustering/tiling	Distributed & clustered targets + the ability to map contiguous regions

3. OVERALL INSTRUMENT DESIGN

The E-ELT Baseline Reference Design considers a 42-m telescope with a 5-mirror active and adaptive design. EAGLE is planned for installation at the Gravity Invariant Focal Station (GIFS) below the Nasmyth B platform allowing us to reduce significantly the problems associated with gravity induced flexure. While the interface to the telescope is still evolving, the current model contemplates a large retractable M6 mirror bending the full 10’ diameter telescope field of view down to the GIFS, with the focal plane about one metre below the flooring structure of the Nasmyth platform. As a result of this model the instrument will need to take full control of the telescope, including the wavefront sensing of the Laser and Natural Guide Stars for controlling the telescope functions, such as co-phasing, telescope guiding and tracking, field stabilization, active and adaptive optics control.

Figure 3 shows a schematic of the GIFS space envelope at one Nasmyth focus of the E-ELT.

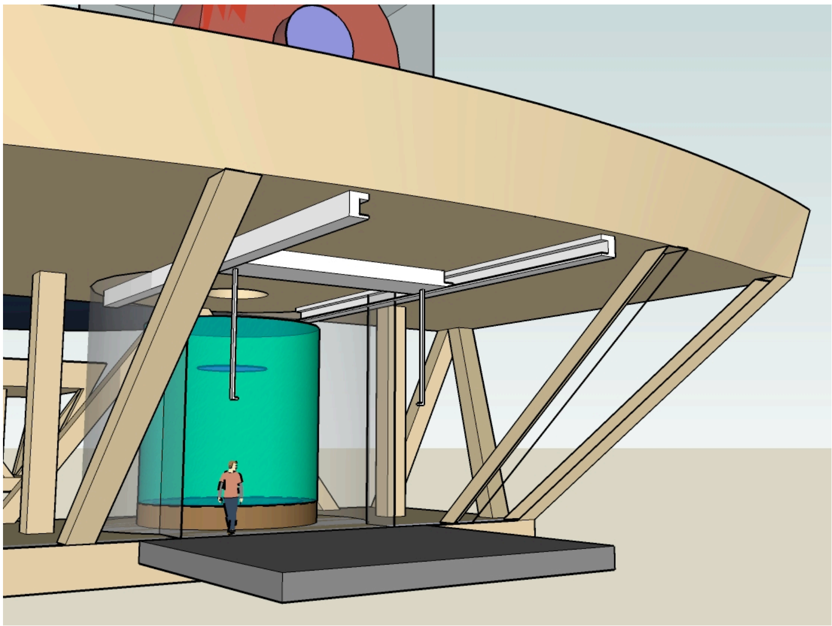

Figure 3. Schematic view of the Gravity Invariant Focal Station (GIFS) of the E-ELT. The M6 mirror bends the whole 10’ telescope field of view to the station located below the Nasmyth platform. The envelope is a cylinder approximately 5m in height and 5m in diameter. (Courtesy ESO)

The EAGLE functional analysis resulted in an instrument architecture consisting of eight systems which will provide the required instrument functionality. These are:

- Laser Guide Star Sensing System (LGSS). This system refers to the front-end of the instrument responsible for picking-off the light from the laser guide stars and delivering it to the appropriate receiving wavefront sensors for real time analysis of the atmospheric perturbations.
- Pick-Off System (POS). The Pick-Off System (POS) refers to the front-end of the instrument and is responsible for picking-off the science sub-fields and the incoming light from the natural guide stars. It also provides a camera for field acquisition and distributes the light required to calibrate and align the instrument.
- Target Re-Imaging and Magnification System (TRAMS). This system refers to the part of the instrument responsible for delivering the incoming light sources picked off by the POS to the appropriate receiving system in the correct format. The TRAMS provides the capability to deliver i) the science light to the IFU and Spectrograph Systems (see below) ii) the NGS light to the appropriate receiving wavefront sensors for the real time analysis of the atmospheric perturbations.
- Adaptive Optics System (AOS). The AO system receives data from the wavefront sensors and uses this to measure the appropriate wavefront parameters. It then corrects the wavefront across each of the science sub-fields.
- Integral Field Unit and Spectrograph System (ISS). The primary function of the ISS is to create a 3D data cube of an astronomical object by slicing the incoming light into thin sections followed by dispersing each slice into its spectrum.
- Instrument Control System (EICS). This system provides for the end to end control of the instrument, from supporting the user for the preparation of the observations to their execution and control of the instrument functions.
- Instrument Core System (ICS). The instrument core includes the static structure, field de-rotator, optical base bench, ancillary platform and cable wrap, the electronic racks, the transport, maintenance tools and facilities.
- Science Data System (SDS). This system provides for the assembly, handling, data reduction and temporary storage of the science data. It is responsible for real-time and off-line reduction and quality control of the science and calibration data.

Note that these systems may not all be physically distinct. Components of the Adaptive Optics System are for instance physically distributed in the Target Re-Imaging and Magnification System and the Laser Guide Star Sensing System.

The first stage of the instrument is the Laser Guide Star Sensing System (LGSS) which extracts the (large) footprints of the LGS from the focal plane and delivers the monochromatic laser beams to the appropriate wavefront sensors. Two alternative optical designs are being studied for this system and a final selection will be made during phase B. One design uses variable curvature mirrors to focus the sodium layer onto the wavefront sensor. This design has the advantage of not having any moving part. A prototype of this system is currently being developed as part of a preparatory program to the E-ELT of the FP7 framework programme of the European Commission. An alternative design relies on a more conventional zoom system. Figure 4 shows the layout of the LGSS at the top of the instrument. The LGSS defines the science field of view of the instrument on which the targets can be selected.

The first optical element on the telescope focal plane is a mirror, dubbed Pick-Off Mirror (POM), part of the Pick-Off System (POS). The 45° Pick-Off mirrors are positioned onto the focal plane by two commercial off-the-shelf X-Y positioners. Beam Steering mirrors located at the periphery of the focal plane are steerable in azimuth and collect the beams from the Pick-Off mirrors and send them onto the receiving re-imaging systems. From the TRAMS the corrected images of each sub-field are forwarded to the entrance of the Integral Field Units (IFUs) (see figure 5). The IFUs consist of image slicers which dissect the AO corrected sub-field images into ~ 40 slices onto the pseudo entrance slit of the spectrograph. There is one spectrograph for each pair of channels. Spectral dispersion is achieved with Volume Holographic Gratings (VPHs). At R = 4,000 one of the Iz, YJ, H or K band is fully imaged onto a 4k x 4k near IR detector. At R = 10,000, a scanning mechanism allows selection of the desired spectral range onto the detector. Each ISS Cryostat houses two IFUs and a spectrograph. There are 10 cryostats in total; they will be cooled with either LN2 or cryo-coolers. Each cryostat is 1800 mm x 700 mm x 1150 mm in volume, the typical size of an instrument cryostat used on mid-size telescopes (see figure 6). The Adaptive Optics system is described in more detail in the next section. Figure 7 illustrates the overall instrument implementation at the Gravity Invariant Focal Station of the E-ELT and figure 8 illustrates the functional behaviour of the instrument in the E-ELT environment.

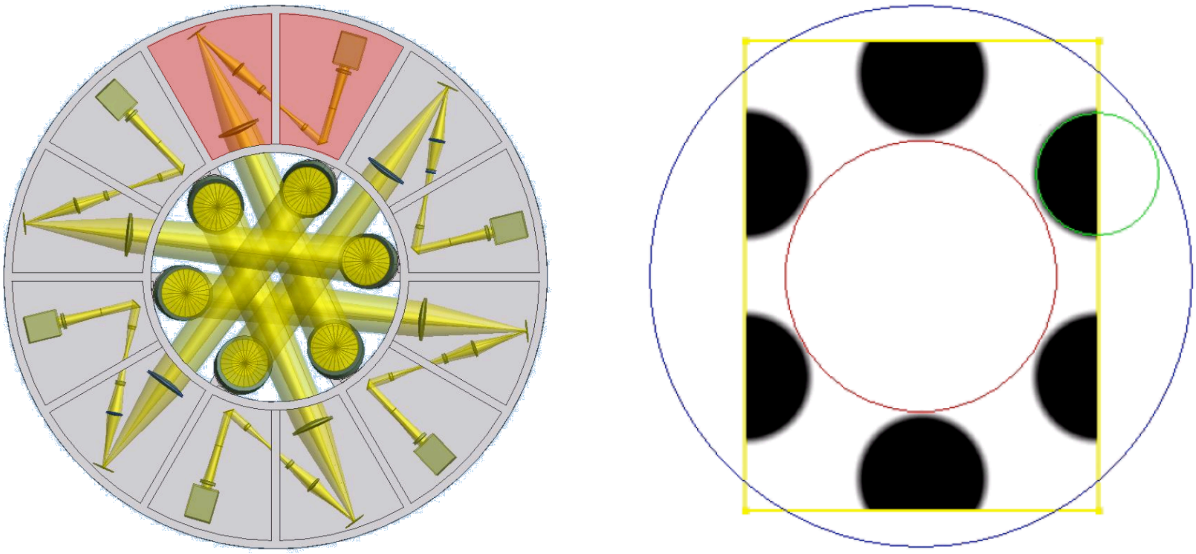

Figure 4. **Left**: Plan view of the six LGS wavefront sensor (WFS) modules (zoom-based focus compensation system shown) within the Laser Guide Star Sensing System. Optics mounts and translation stages not shown. A single LGS WFS module is highlighted in red. The 6 LGS pickoff mirrors are on a 7.3' diameter ring. **Right**: EAGLE field vignetting map due to 20” LGS pickoff position within the EAGLE focal plane (outlined in yellow). The red and blue circles denote the 5 and 10’ diameter E-ELT fields respectively. A single LGS pickoff mirror is shown in green positioned within the 5-10’ annulus.

Figure 5. Illustrations of the Pick-Off System (POS) and Target Re-Imaging and Magnification System (TRAMS). **Left**: pickoff mirrors positioned onto the focal plane plate. The mirrors send the beams to the Beam Steering mirrors located around the focal plane plate. **Right**: TRAMS optical path from the pickoff mirrors to the entrance of the IFU and Spectrograph System. A beam steering mirror folds the optical beam from the pick-off mirror to a trombone which compensates for the optical path difference between positions in the focal plane. An image of the pupil is formed onto a Deformable Mirror (DM) which is used by the Adaptive Optics System to correct the science sub-field wavefront. The TRAMS is operating in a cold environment at ~ -30^{o}C to reduce the thermal background in the K band.

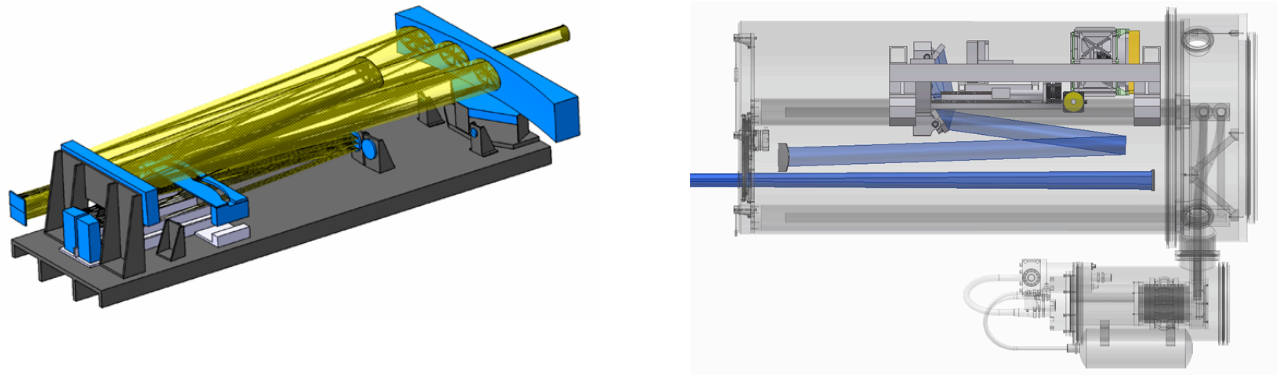

Figure 6. **Left**: The Integral Field Unit optical design. Each sub-field image is sliced into ~ 40 slices which are aligned at the entrance of the spectrographs. **Right**: Opto-mechanical design implementation of one of the ten cryostats embedding two IFUs (not shown) and a single spectrograph.

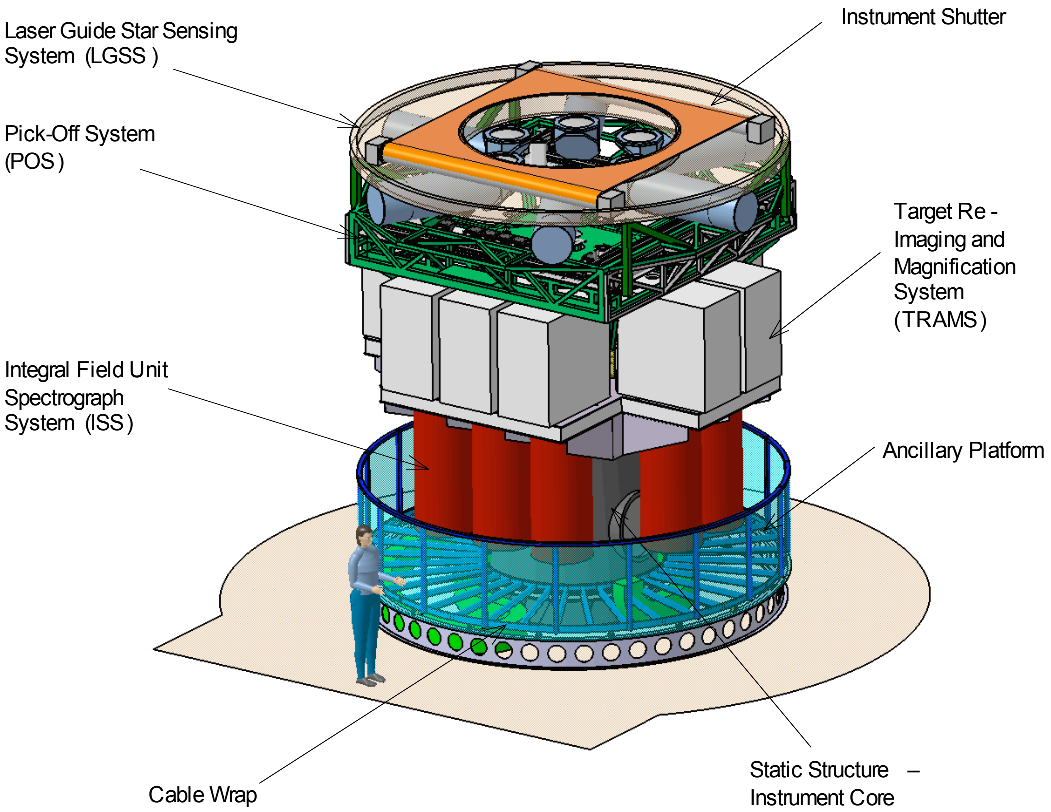

Figure 7. Left: The overall implementation of EAGLE at the Gravity Invariant Focal station of the E-ELT.

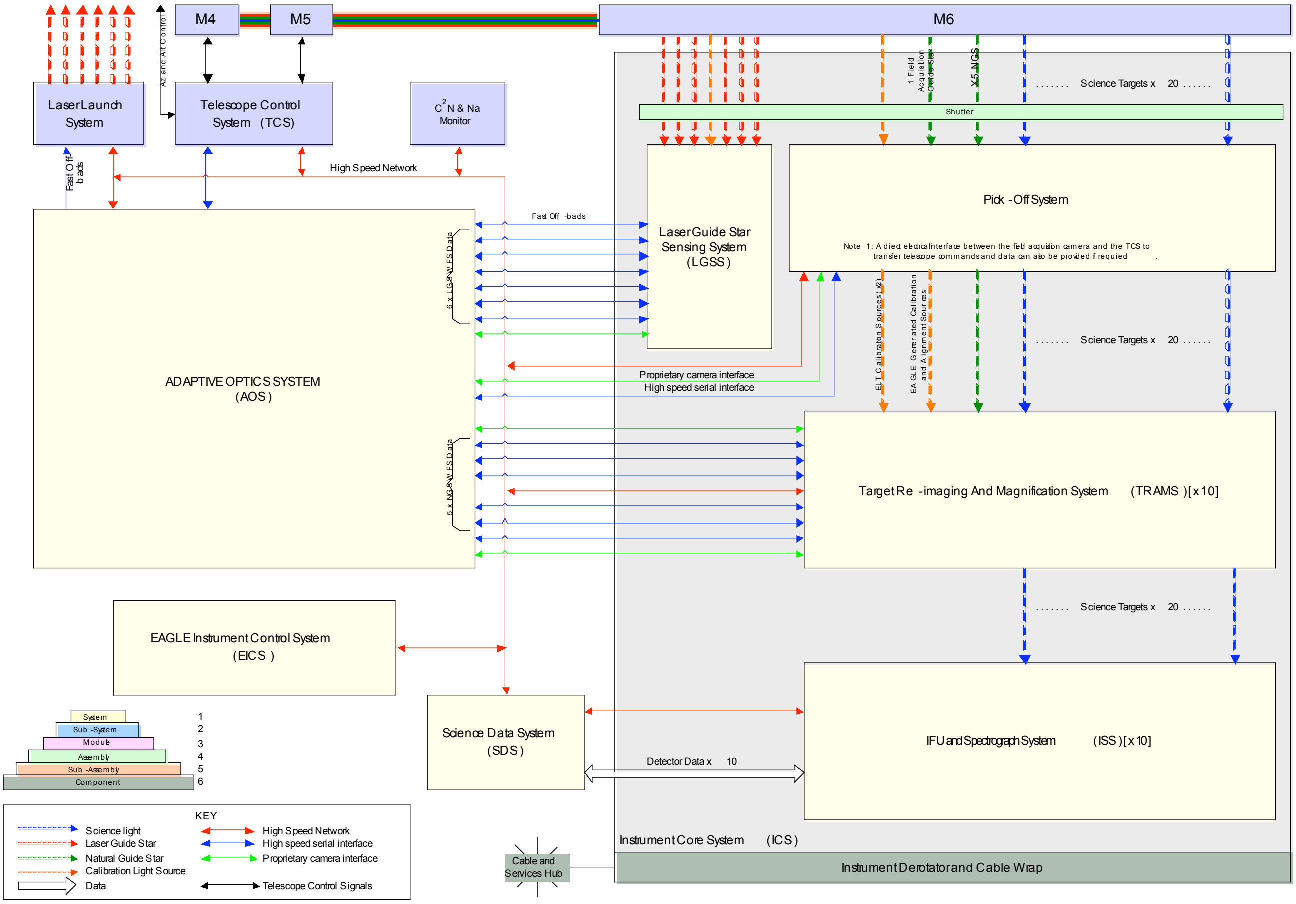

Figure 8. Instrument Block diagram illustrating the various functions associated to the instrument and the main interfaces to the telescope.

4. ADAPTIVE OPTICS (AO)

The E-ELT is an active and adaptive telescope, thanks to the large Deformable Mirror (DM) in its optical train (M4). Various AO modes can be contemplated with the E-ELT, depending on the field of view under consideration and on the instruments. For the wide field of view accessible by EAGLE, the telescope can operate in the Ground Layer Adaptive Optics (GLAO) regime, where only the turbulence from the Ground Layer can be corrected. This results in an improvement of the seeing limited images, typically by a factor ~ 2 in FWHM, which is still insufficient for the EAGLE primary science cases. While GLAO may be used in the early operation of EAGLE, reaching the ultimate desired performance will require additional AO correction from within the instrument. This AO correction does not need to be over the full telescope field of view, but can be localised to correct the wavefronts in the directions of the targets. The corresponding AO mode is referred to as Multi-Object Adaptive Optics (MOAO). Wavefront Sensors (WFS) sense the wavefront over the full field of view in several directions, either on Natural Guide Stars (NGS) or on Laser Guide Stars (LGS). A tomographic reconstruction is performed of the turbulence volume above the telescope, and this turbulence can then be projected in the direction of the targets and be corrected by the telescope DM (Ground Layer turbulence, high stroke) and by the individual DMs present in each channel (high layer turbulence, low stroke). M4 is controlled in closed loop (the wavefront is sensed after correction by M4) while the individual DMs in each science channel are controlled in open loop.

Before embarking on designing EAGLE based on the MOAO concept, we evaluated whether other options might be considered, which would, e.g., allow closed loop operation. The conclusions of this preliminary analysis clearly demonstrated that other types of implementation such as GLAO or a multi-DM or multi-field MCAO would either not provide the required level of correction or be extremely complicated to implement from an opto-mechanical perspective. MOAO was therefore selected as the baseline AO mode of operations for EAGLE. The principle of operations of MOAO is illustrated in figure 9.

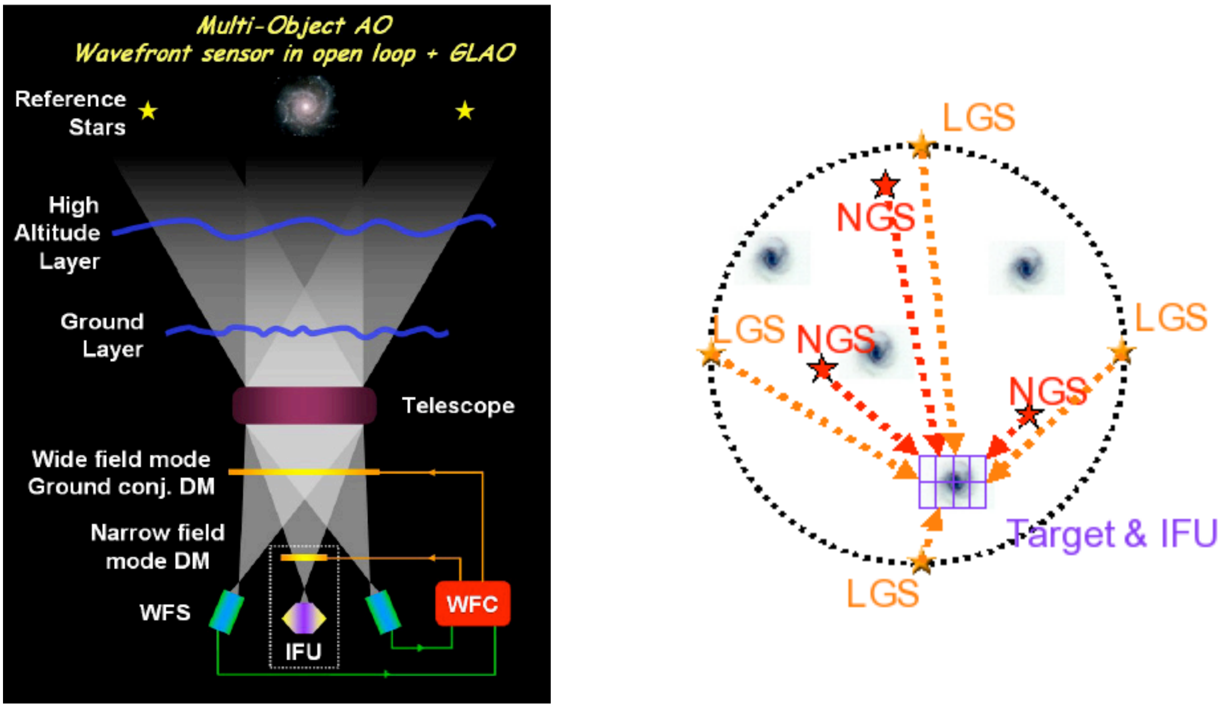

Figure 9. MOAO principle of operations. Wavefront sensors (Laser and natural guide stars) measure the atmospheric perturbations above the telescope. A tomographic reconstruction of the turbulence is performed from which the perturbation in any direction in the field of view is computed, and corrected by a local, narrow field Deformable Mirror. The telescope Adaptive Mirror (M4) performs the high stroke, wide field ground layer correction. Left drawing: courtesy ESO.

We performed an extensive system analysis which demonstrates that the required performance can be achieved with components which are either commercially available or under development. The key component specifications are reported in table 2. From an implementation viewpoint the 84 x 84 (~ 6k) actuator Deformable Mirrors (DMs) are specified to have a physical diameter between 40 and 80 mm. While the 6k DMs are not commercially available today, 4k actuator DMs are under development for a variety of astronomical instruments. The 6k DMs could use the same technology as the 4k DMs and therefore be developed at affordable costs within reasonable timescales. Other technologies could also lead to the development of viable DMs. These might result in slightly larger components (with diameters up to ~ 100 mm). Resorting to the existing 4k DMs would be a backup solution in the unlikely situation where the development of the 6k DM would prove too costly or unfeasible. Similarly, the detector for the LGS WFS is not currently available, but developments of similar detectors are extremely likely to happen in the context of the ELT development. A possible fallback solution could be to use quad-cell wavefront sensors. The EAGLE AO system therefore carries very little risk as far as its key components are concerned. It is anticipated that the hardware for the Real Time Computer will be available at moderate cost, provided that smart algorithms and real time architectures are developed for the ELT AO control systems.

The error budget corresponding to the above AO specifications is reported in table 3. The distribution and brightness of various natural guide star configurations were tested from several sky fields, mostly deep cosmological fields (e.g.

XMM, UDF, etc.) located at high galactic latitudes and which therefore represent worst case scenarios for the natural guide star configurations. The total error budget easily meets the EAGLE high level specification of 30-40% ensquared energy within spatial resolution elements of 75 mas.

At system level, the MOAO is not yet tested on-sky, but there are several on-going programs worldwide which will demonstrate its principle of operations. Within the EAGLE framework, an aggressive technology development plan (see figure 10) is in place which will allow us to demonstrate, test, and characterize MOAO within a couple of years. Demonstration activities are taking place on a laboratory test bench, SESAME, at Observatoire de Paris and an on-sky demonstration programme (dubbed CANARY) is being actively developed for use at the WHT under the leadership of the University of Durham, with the first results expected within 1 to 1.5 yrs with Natural Guide Stars, and within 3 years with Laser Guide Stars, on time to validate the final EAGLE design.

Table 2. Baseline EAGLE Adaptive Optics requirement specifications (from an AO system perspective) assuming a 0.87" atmospheric seeing, an outer scale diameter of 25m and a turbulence Cn^2 profile distributed over 10 layers ranging from 50 m to 18 km above ground.

Sub-system	**Parameter**	**Baseline Specification**
Deformable mirrors	➢ Telescope DM (M4 / M5)	
	• Actuators number	84 x 84
	• Temporal response	> 1 kHz
	➢ Micro DMs	
	• Actuator number	84 x 84
	• Temporal response (5° phase shift)	60 Hz
	• Linearity (single act.)	2%
	• Linearity (spatial coupling)	2%
	• Stroke (Peak to Valley)	6 µm
	• Inter-actuator stroke	1.5 µm
	• Coupling factor (c)	20% < c < 60%
Laser Guide Stars (LGS)	➢ Number	6
	➢ Position on sky	Fixed
	➢ Launch	Side of telescope M1
LGS Wavefront Sensor (WFS)	➢ Type	Shack-hartmann
	➢ Number of sub-apertures	84 x 84
	➢ Number of pixels per sub-aperture	12 x 12
	➢ CCD : readout noise	1 e^- rms
	➢ Minimum Integration time	4 ms
	➢ Read out time	< 1.5 ms
	➢ Flux per sub-aperture and per frame	500 photons
	➢ Centroiding algorithm	Correlation
	➢ Reference update	10 s
Natural Guide Stars (NGS)	➢ Number	Up to 5
	➢ Diameter of the patrol Field of View	5’
	➢ WFS type	Shack-Hartmann
	➢ Number of sub-apertures	64 x 64
	➢ Number of pixels per sub-aperture	6 x 6
	➢ Minimum integration time	4 ms
	➢ Read out time	< 1.5 ms
Real Time Computer (RTC)	➢ Control law	Open Loop Control
	➢ Accuracy on turbulence layer altitudes	250 m
	➢ Accuracy on layer strengths	50%
	➢ RTC delay (from last pixel received fro WFS to last voltages sent the DM)	1.5 ms

Table 3. The Adaptive Optics error budget. See table 2 for the assumptions used in computing this error budget. For reference, 275 nm rms of wavefront error corresponds to 30% ensquared energy in 75 x 75 mas^2 at a wavelength of 1.6 μm.

Error items	**Low orders (in nm rms)**	**High orders (in nm rms)**
Chromatism	25	12
Differential refraction (30°)	6	10
Telescope high frequencies		60
Fitting	-	140
Aliasing	3	45
Temporal error	35 (250 Hz)	59 (250 Hz)
LGS tomography + noise (LGS and NGS) (unfavorable NGS configuration)	55	118
Differential focal anisoplanatism	40	20
Open loop WFS (linearity)	45	41
Sodium layer fluctuations (flux variations)	Not estimated	Not estimated
Turbulence model		
• Altitude knowledge	50	80
• C_n^2 knowledge	30	40
Noise model	30	40
Open loop DM: Linearity & Hysteresis	45	41
DM stroke (saturations effects)	0	0
DM bandwidth	negligible	Negligible
Calibration issues		
• Quality of Interaction Matrix	20	60
• WFS Reference	20	30
Non common path aberrations		
• LGS internal aberrations	60	-
• Science channel aberrations	40	10
Contingencies	100	100
Total	**173**	**244**

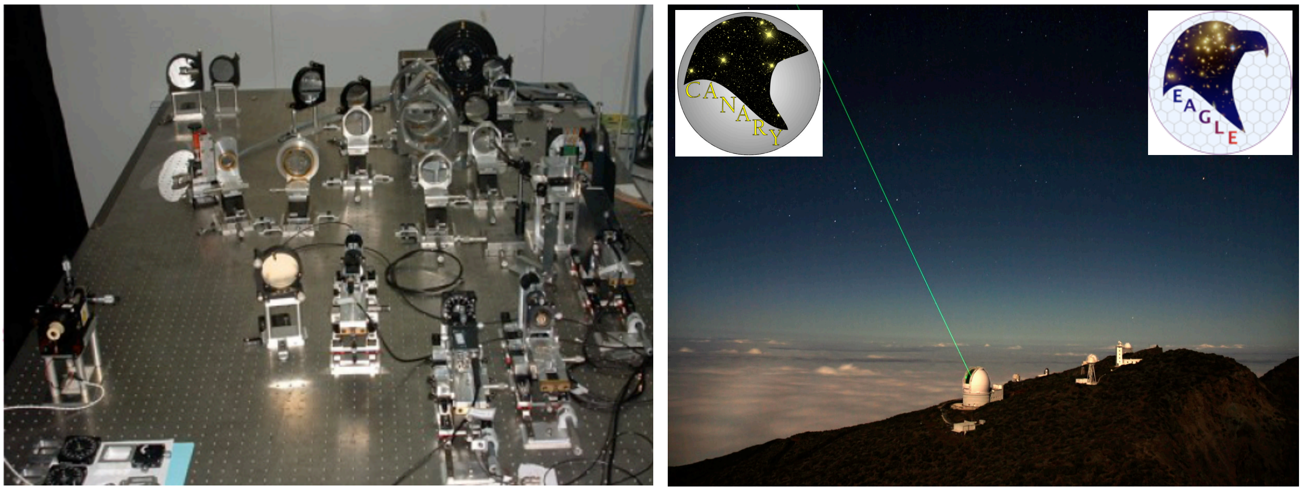

Figure 10. Illustrations of the AO demonstration activities in use or under development in relation to EAGLE. Left: the SESAME bench, Right: cartoon for the CANARY on-sky demonstrator at the WHT in La Palma.

5. CONCLUSIONS

The baseline design of EAGLE is driven by the scientific requirements to answer a number of crucial questions related to developing our understanding of how galaxies formed and evolved. Attempting to meet these requirements has led to a design with realistic performance that does improve the sensitivity of point sources while still critically sampling structures within galaxies. Beyond its core science case, EAGLE, as designed, is a general facility instrument which will serve many of the most prominent and contemporary science cases of the ELTs. The EAGLE baseline design relies on current day state-of-the-art solutions and components which are either commercially available or are due shortly. The two components which require most development are the Deformable Mirrors and the detectors for the LGS Wavefront sensors. For both of these components there exist commercially available solutions, as a backup, which would result in slightly degraded performance. Unlike similar studies performed at other ELTs, and thanks to the longer timescales of our study, we have demonstrated that this much needed type of instrument has the required level of technological maturity to be fully designed and built. This is the result of a well performed study based on a structured and integrated system approach. The EAGLE development plan estimates an 8 to 9 year development from the end of phase A, meaning that this instrument could be available at the E-ELT shortly after its release to science operations. The extreme modular design of the instrument makes its integration, testing, and maintenance easy, despite the apparent, but certainly not real, complexity of the system.

ACKNOWLDEGMENTS

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