Invited Paper

An overview of the E-ELT instrumentation programme

S. Ramsay, S. D'Odorico, M.Casali, J.C. González, N. Hubin, M.Kasper, H.U.Käufl, M. Kissler-Patig, E.Marchetti, J.Paufique, L.Pasquini, R.Siebenmorgen, A.Richichi, J.Vernet, F.M.Zerbi

European Southern Observatory, Karl-Schwarzschild-Strasse, 2, Garching bei München, D-85748.

ABSTRACT

In this paper we present a brief status report on the conceptual designs of the instruments and adaptive optics modules that have been studied for the European Extremely Large Telescope (E-ELT). In parallel with the design study for the 42-m telescope, ESO launched 8 studies devoted to the proposed instruments and 2 for post-focal adaptive optics systems. The studies were carried out in consortia of ESO member state institutes or, in two cases, by ESO in collaboration with external institutes. All studies have now been successfully completed. The result is a powerful set of facility instruments which promise to deliver the scientific goals of the telescope.

The aims of the individual studies were broad: to explore the scientific capabilities required to meet the E-ELT science goals, to examine the technical feasibility of the instrument, to understand the requirements placed on the telescope design and to develop a delivery plan. From the perspective of the observatory, these are key inputs to the development of the proposal for the first generation E-ELT instrument suite along with the highest priority science goals and budgetary and technical constraints. We discuss the lessons learned and some of the key results of the process.

Keywords: optical instrumentation, infrared instrumentation, adaptive optics, spectroscopy, imaging, multi-object spectroscopy, integral field units, instrumentation for ELTs.

1. INTRODUCTION

The European Southern Observatory (ESO) is in the final stages of the preliminary design of the 42-m E-ELT telescope. In parallel with this phase of the telescope design, ESO has worked with the community of instrument builders in the ESO member states to explore the possible impact of this new generation of instruments on the telescope design. This has been achieved by initiating a substantial number of studies into possible instruments. In this paper we review the aims of the study programme, present brief summaries of the study results and discuss the outcome of the study programme as a whole.

The E-ELT is a five mirror telescope with built in adaptive mirrors (M4, M5) for fast correction of the ground layer atmospheric turbulence either using natural or laser guide stars. The telescope must always operate in this GLAO mode to maintain the alignment of the optics. The instrument suite should therefore exploit image quality from 'degraded GLAO' (in poor atmospheric conditions) to the diffraction limit of the telescope (at least at infrared wavelengths where the AO can deliver this image quality). Provision is made for locating instruments on two Nasmyth platforms, each with three ports, two gravity invariant foci (GIF) located below the Nasmyth platform and a coudé station with the possibility of two laboratories (Figure 1). On the Nasmyth platform, the instruments are mounted on or adjacent to the telescope pre-focal station which includes the wavefront sensors for control of the telescope and also the deployable M6 mirrors which direct the telescope beam to the different ports. A 5arcmin field is provided to the side ports; the straight-through port has a 10arcmin field partially vignetted by the telescope WFSs. The telescope focal ratio is f17.71 at the Nasmyth foci. To reach the GIF, the telescope focus is adjusted to f/18.85 to increase the back-focal length. In the current baseline, the beam is directed to the GIF by a second, large, M6 mirror which provides this focal station with the maximum field from the telescope - an unvignetted 10arcmin. A more detailed description of the telescope to instrument interfaces is given in [1].

Eight studies of instruments and two of post-focal adaptive optics modules were initiated between September 2007 and November 2008. The overall aims of the study programme were to carry-out a suitable number of instrument studies to verify that instruments are feasible, that they properly address the highest priority scientific goals and can be built at an affordable cost, to work with the ESO community to prepare for construction and to work with telescope and operation

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 773524 · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857037

project offices to identify and define interfaces with the other subsystems and the observatory infrastructure. The initial definition of the instruments to be studied was made by ESO, based on the recommendations of the E-ELT science working group, ESO external committees and the outcome of studies carried out for the 100-m OWL telescope. Consortia were selected to carry out the studies either from an open call for proposals, or by direct negotiation with teams already working on specific concepts. The studies were of varying duration, from 15 months to two years. The last two instrument studies launched (OPTIMOS and SIMPLE) were proposed by the community in response to an open call for suggestions for new instrument concepts. Full details of the studies are given in Table 1, showing the PI, participating institutes and the duration of the study.

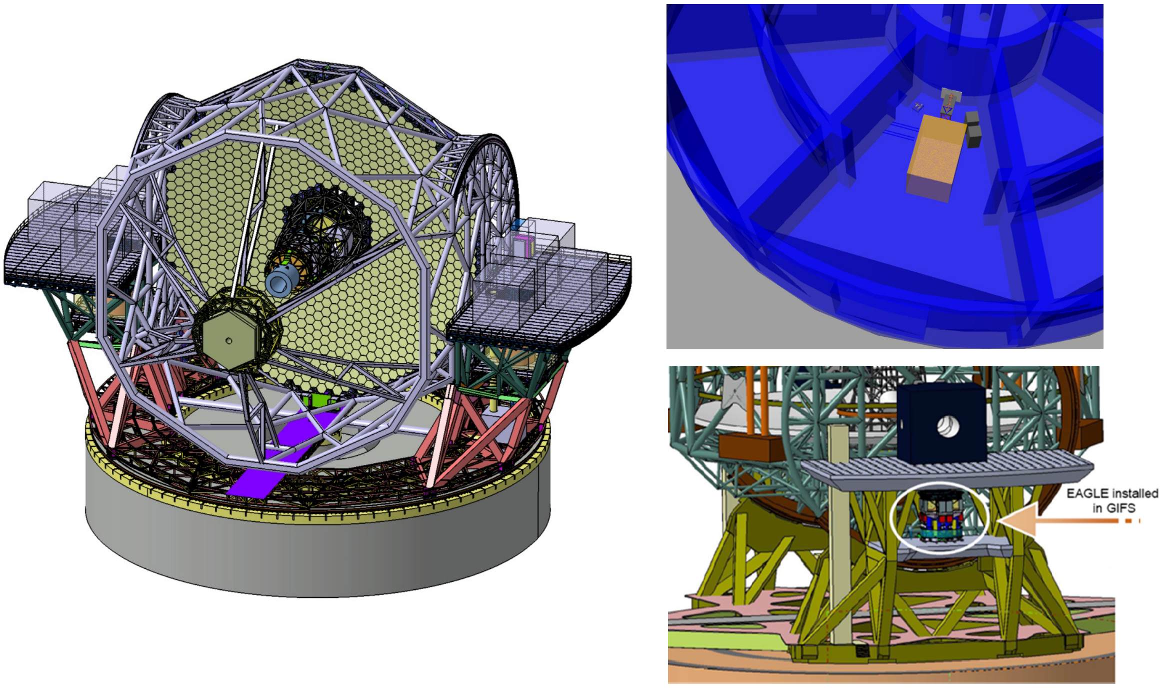


Figure 1: Possible locations for instruments on the E-ELT. The view on the left shows the two Nasmyth platforms of the telecope each with three ports for instruments. The coude laboratory, located under the telescope pier, is shown above right and the gravity invariant focus below right.

Each study was managed in line with the practices for ESO VLT instruments. A statement of work specified the deliverables of the study that, in most cases, was simply the documentation that constituted the Final Report of the study; an initial technical specification was agreed before the project kick-off and was expected to be modified as a result of the design work and each of the external studies was followed up by an instrument scientist as ESO. The statement of work also specified that the acceptance of the Final Report represents the conclusion of the study. There was no commitment by ESO to continue the project into a construction phase or to award the contract for design and construction to the consortium undertaking the study.

The content of the final reports was specified in the agreed statement of work for each study. The reports were typically of 500-1000 pages covering aspects of the instrument concept from the science case and derived requirements to the opto-mechanical concept, electronics and software architecture. In the case of the post focal AO modules, no science case was requested but instead the performance of the module with the 'client' instruments was analysed and presented. The final milestone of each study was a formal review by a Review Board consisting of ESO staff and also including one external expert in the field, from a non-ESO member state. The E-ELT Science Working Group (a committee of community scientists that advises the project) sent two observers to each meeting, who were not formally part of the Review Board but were able to comment fully on the documentation. Uniformity of the review process was considered an important goal since 10 studies were to be reviewed over 6 months. A written review procedure was developed within

ESO which included the charge to the Board and the reviews were chaired by one of a pool of three ESO staff members to ensure consistency. Written feedback was then provided to the instrument PI by the Head of the Instrumentation Project Office. The major success of the instrument studies was that all were passed by the Boards. This is a great credit to the quality, professionalism and strength of the instrument building community in the ESO member states and is very encouraging for the future success of the E-ELT project. In the following section we give a high level overview of each of the studies. In the final section we discuss the extent to which the goals of the study programme have been met.

Table 1: Summary of the E-ELT instrument and post-focal adaptive optics (PFAO) module studies.

Name	PI	Institutes	ESO Responsible	Kick-off	Final Review
PFAO-ATLAS	T. Fusco	ONERA, LESIA, GEPI, LAM, UK ATC	J. Paufique	19/09/08	2/02/10
PFAO-MAORY	E. Diolaiti (INAF OABo)	INAF-OABo, OAA, OAP, Univ. Bologna, ONERA	E. Marchetti	09/11/07	10/12/09
CODEX	L. Pasquini (ESO)	ESO, INAF Trieste&Brera,IAC, IoA Cambridge, Obs. Genève.	NA	16/09/08	23/02/10
EAGLE	J.G.Cuby (LAM)	LAM, GEPI, LESIA, ONERA, UK ATC, Univ. Durham	S. Ramsay	27/09/07	27/10/09
EPICS	M.Kasper (ESO)	ESO, LAOG, INAF-OAPd, LESIA, NOVA ASTRON, Uni. Utrecht, ETHZ, ONERA, Univ-Oxford, FIZEAU, LAM	NA	24/10/07	16/03/10
HARMONI	N. Thatte (Oxford)	Univ. Oxford, CRAL, CSIC-DAMIR, IAC, UK ATC	J. Vernet	1/04/08	28/01/10
METIS	B.Brandl (Leiden)	NOVA Leiden&ASTRON, MPIA, CEA Saclay, KU-Leuven, UK ATC	R. Siebenmorgen	07/05/08	17/12/09
MICADO	R.Genzel (MPE)	MPE, MPIA, USM, INAF-Padova, NOVA ASTRON, Leiden, Groningen, LESIA	A. Richichi	28/02/08	30/11/09
OPTIMOS-DIORAMAS	O.LeFèvre (LAM)	LAM, STFC RAL, INAF IASF-Milano & OATs, Obs. Genève, IAC, Obs. Haute Provence	S. Ramsay	3/11/08	30/03/10
OPTIMOS-EVE	F.Hammer (GEPI)	GEPI, NOVA ASTRON, RUN, Uni. Amsterdam, STFC RAL, INAF OATs&Brera, NBI Copenhagen	S. Ramsay	3/11/08	30/03/10
SIMPLE	L. Origlia (INAF-OABo)	INAF – OABo, Arcetri, Roma, Univ. Bologna, UAO, TLS, PUC	H-U. Käufl	30/10/08	04/03/10

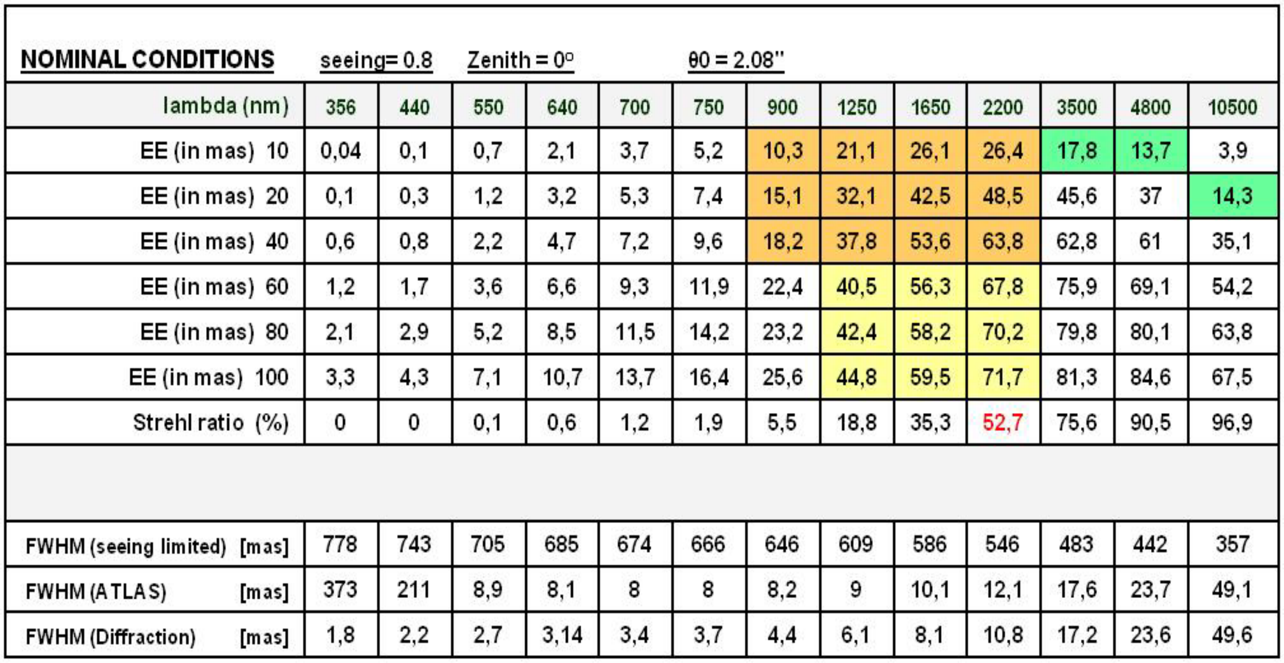
2. SUMMARY OF THE INSTRUMENT STUDIES

A brief summary of the instruments concepts as given in the final report is presented here. Readers are referred to the individual papers on each concept that are cited below for a more detailed description. The AO concepts are presented first, followed by the instruments in the order in which they were completed and reviewed by ESO.

2.1 ATLAS – Laser Tomographic Adaptive Optics System.

ATLAS is one of the two post-focal AO modules investigated for the telescope (Fusco et al. [2]). ATLAS was conceived of as a module which could be replicated for each instrument requiring a high Strehl ratio over moderate fields and with the sky coverage that can be delivered by a laser guide star system (~90% is estimated). ATLAS is a Laser Tomography AO system providing atmospheric turbulence correction on a 30" FoV diameter over the complete wavelength range of the telescope: the science FOV is free from any ATLAS optics. Thus the LTAO system offers and excellent AO solution for the smaller field infrared instruments, HARMONI, METIS and SIMPLE. In the Phase A study, the performance of ATLAS was considered in the context of those instruments (see performance estimates in Table 2). The correction is made using the telescope adaptive mirror M4 and the wavefront sensing is assured by 6 Laser Guide Star (LGS) visible wavefront sensors (WFS) and 2 Natural Guide Stars (NGS) infrared WFS. The 6 LGSs are used to perform the tomography of the atmosphere above the telescope and therefore to overcome the focus anisoplanatism of a single laser beam on a 42m telescope. To maximise the sky coverage close to 100%, the two IR NGS arms, required to measure the low order mode perturbations not sensed by the LGSs, are equipped with a local deformable mirrors providing an optimised additional atmospheric correction in the direction of the NGSs using the LGS tomographic measurements. This correction, combined with an innovative full aperture Low Order Focal Plane Sensor, maximises the sensitivity of the NGS WFS and therefore the NGS WFS signal to noise and NGS limiting magnitude. The low order control performance benefits from an optimal control law (Kalman filter) to overcome the telescope windshake.

Table 2: The modelled Strehl ratio delivered by ATLAS. The shaded areas show parameters relevant to the science instruments studied. LMN bands - METIS; JHK bands with <40mas EE - HARMONI; JHK with EE >40mas - EAGLE or OPTIMOS.



NOMINAL CONDITIONS seeing= 0.8 Zenith = 0° θ0 = 2.08"

lambda (nm)	356	440	550	640	700	750	900	1250	1650	2200	3500	4800	10500
EE (in mas) 10	0,04	0,1	0,7	2,1	3,7	5,2	10,3	21,1	26,1	26,4	17,8	13,7	3,9
EE (in mas) 20	0,1	0,3	1,2	3,2	5,3	7,4	15,1	32,1	42,5	48,5	45,6	37	14,3
EE (in mas) 40	0,6	0,8	2,2	4,7	7,2	9,6	18,2	37,8	53,6	63,8	62,8	61	35,1
EE (in mas) 60	1,2	1,7	3,6	6,6	9,3	11,9	22,4	40,5	56,3	67,8	75,9	69,1	54,2
EE (in mas) 80	2,1	2,9	5,2	8,5	11,5	14,2	23,2	42,4	58,2	70,2	79,8	80,1	63,8
EE (in mas) 100	3,3	4,3	7,1	10,7	13,7	16,4	25,6	44,8	59,5	71,7	81,3	84,6	67,5
Strehl ratio (%)	0	0	0,1	0,6	1,2	1,9	5,5	18,8	35,3	52,7	75,6	90,5	96,9
FWHM (seeing limited) [mas]	778	743	705	685	674	666	646	609	586	546	483	442	357
FWHM (ATLAS) [mas]	373	211	8,9	8,1	8	8	8,2	9	10,1	12,1	17,6	23,7	49,1
FWHM (Diffraction) [mas]	1,8	2,2	2,7	3,14	3,4	3,7	4,4	6,1	8,1	10,8	17,2	23,6	49,6

2.2 MAORY – Multi Conjugate AO system for the E-ELT

The second AO system studied is a multi-conjugate AO system, MAORY (Diolati et al. [3]). MAORY provides tridimensional atmospheric turbulence correction on a 2 arcmin FoV diameter in the wavelength range 0.8µm–2.4µm. An important advantage of the MCAO system is the stable PSF: MAORY estimates K band Strehl ratio of 0.48 with variation <0.05 over a 2' field. The MAORY studied presented a solution with two post-focal deformable mirrors conjugated to atmospheric layers at 12.7km and 4km. These work in combination with the telescope mirrors which correct for ground layer turbulence to provide the performance seen in the table below. The wavefront sensing is assured by 6 Laser Guide Star (LGS) visible wavefront sensors (WFS) and 3 Natural Guide Stars (NGS) infrared WFS. In the current configuration, MAORY can deliver a corrected beam to one of two ports at which instruments can be located. MAORY is required to deliver the wide field diffraction limited images for the MICADO camera described below that would be located at the vertical port of the instrument. The second, horizontal, port was considered for the SIMPLE spectrometer by the instrument consortium. Cooling of the complete AO system was investigated as part of the study. For an imager, the increase in background from the warm AO mirrors (8 additional mirrors) is not significant compared to the sky background and telescope thermal background. For the high spectral and spatial resolution spectrometer, SIMPLE, the thermal background remains negligible relative to the read-noise from the current technology detectors. For use with an intermediate resolution NIR spectrometer cooling would be required.

Table 3: The predicted performance of MAORY for the instrument parameters relevant for the NIR diffraction limited camera, MICADO (described in Section 2.4).

Minimum Strehl Ratio averaged over MICADO field of view (53"×53")					**Sky Coverage**
λ=2.16μm	**λ=1.65μm**	**λ=1.215μm**	**λ=1.021μm**	**λ=0.9μm**	
0.54	0.34	0.14	0.06	0.03	39%
0.52	0.32	0.13	0.05	0.03	50%
0.50	0.30	0.11	0.04	0.02	60%
0.48	0.27	0.09	0.03	<0.01	70%
0.42	0.22	0.06	0.02	<0.01	80%

2.3 EAGLE- An AO assisted multi-integral field NIR spectrograph

The EAGLE study was led by Jean-Gabriel Cuby (LAM) with co-PI Simon Morris (University of Durham). EAGLE [4] is a multi-integral field spectrometer which uses on-board multi-object adaptive optics to deliver encircled energies of ~30% within 75mas pixels. This provides optimal sensitivity to point-like sources such as unresolved features in moderate redshift (z~2) galaxies, for studies of the mass assembly and evolution of galaxies in clusters, or for stars in local group galaxies for stellar population studies. EAGLE is a survey instrument offering IFU observations (1.65x1.65arcsec field of view) for 20 objects distributed over an equivalent field of 38 square arcminutes.

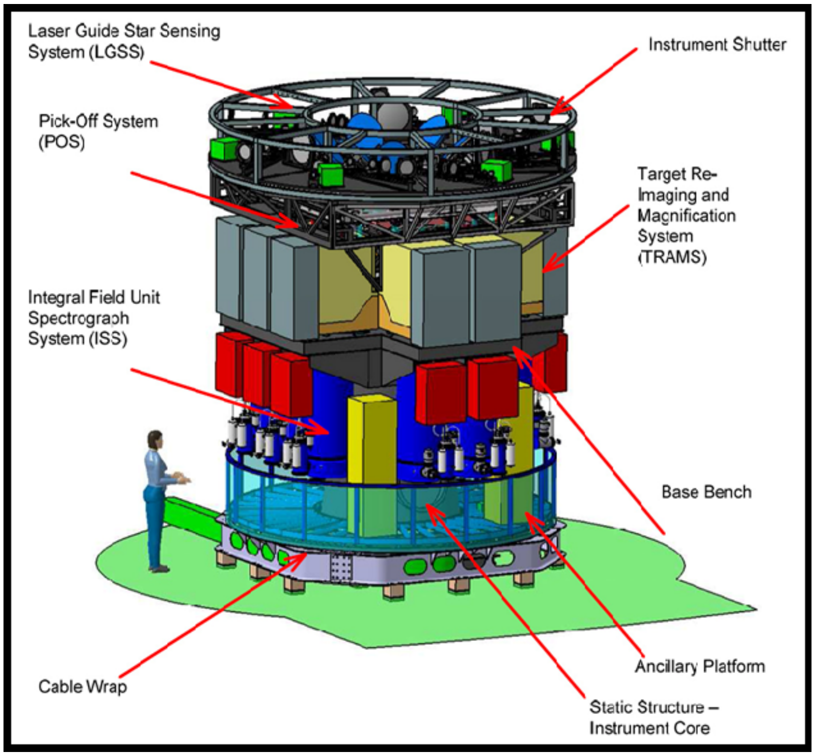


Figure 2: The architecture of the EAGLE instrument can bee seen in the adjacent figure. For the instrument located at the GIF, light is directed into the top of the instrument as shown.

The instrument design is highly modular (Figure 2). The initial selection of the objects is via pick-off mirrors which are placed robotically in the focal plane [4]. The light from each of the 20 sources is then directed towards the spectrograph via the Target Re-imaging and Magnification System (TRAMS) module which contains an optical system for compensating path differences from the different field positions and the deformable mirror controlled by the MOAO system. At the output of the TRAMS, two scientific channels are combined in one image slicing IFU. The baseline technology selected for the IFU is glass polishing of Zerodur. The output from two IFUs is combined into a pseudo-slit which is the input to a spectrometer module. There are therefore 10 spectrometers, each with a 4k x 4k detector array. Two spectral resolution modes are offered: R~4000 to resolve the atmospheric OH lines and for a good match to the velocity resolution in galaxies and R~10000 for stellar studies. The preferred focal station for this large (8m tall x 5m diameter cylinder) instrument is the gravity invariant f/18.85 focus of the telescope. EAGLE requires the maximum, 10arcmin, science field to be folded to this focus by a large M6 mirror in the pre-focal station. Since this vignettes the telescope wavefront sensors, the instrument must reproduce the signals necessary to control the telescope figure as well as those required for the adaptive correction of the individual optical paths through the instrument. This requirement, combined with the scientific requirements on image quality, lead to a design for EAGLE which envisages using 6 laser guide stars and 5-6 natural guide stars. The NGSs are selected from the focal plane using the same robot system as the astronomical sources; the LGS pick-offs are located above the focal plane and form a separate module of the instrument along with their wavefront sensors. EAGLE is partially cooled to reduce the thermal background giving the best sensitivity to the end of the K-band. The whole instrument is mounted on a mechanical rotator.

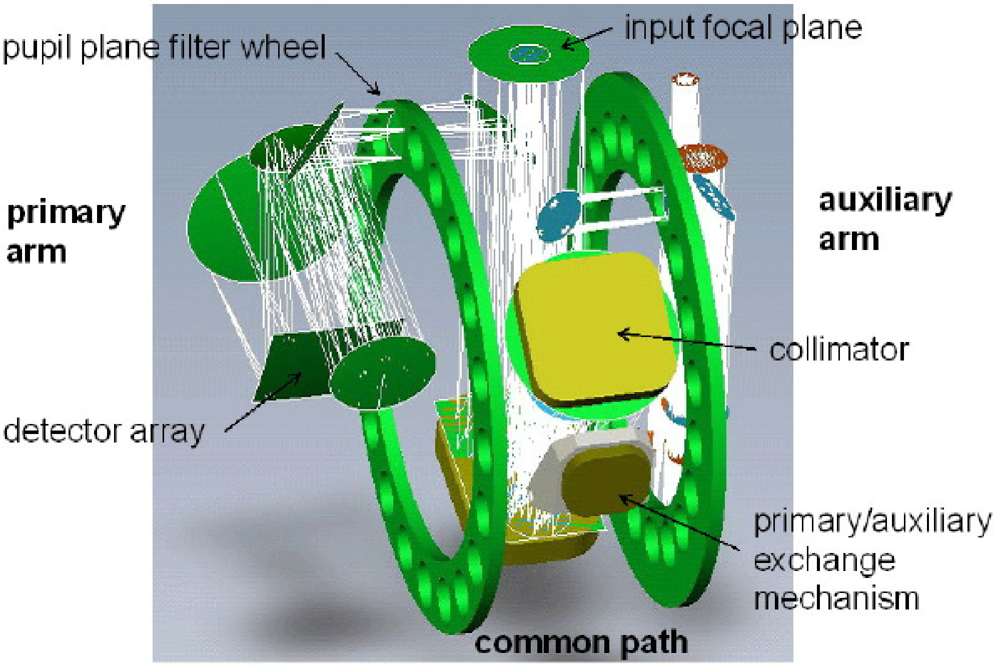


Figure 3: MICADO concept showing the separation of the instrument into the primary and secondary arms. Note also the upward looking port which allows MICADO to be located in a gravity invariant way, for example under MAORY.

2.4 MICADO – a NIR diffraction limited camera

MICADO is an infrared (0.8-2.5μm) camera designed to address a wide range of astronomical observations that fully exploit the diffraction limit of the 42-m telescope [5]. The PI for the study was Reinhard Genzel (MPE). The MICADO opto-mechanical concept is for an instrument with two separate optical paths. The main or primary arm of the instrument contains a fixed-plate scale camera; the optical design is a three mirror anastigmat. A key goal for the instrument is to deliver astrometric accuracy of 50μas and so the primary arm has fixed optics with the only mechanism being a filter wheel providing a selection of 20filters. The field of view of this arm is 53” x 53” with 3mas sampling (Nyquist sampling the diffraction limit at 1.0μm). The focal plane is an array of sixteen 4k x 4k NIR detectors. The whole instrument is designed to operate in a gravity invariant location with the telescope beam folded into the up-ward looking cryostat (Figure 3). An auxiliary arm in the instrument is selected by a fold mirror and provides additional scientific capabilities, including long slit spectroscopy, polarimetry, a small field with finer pixel scale for astrometry in crowded fields (1.5mas pixels), possibly a high time resolution mode. The science case for MICADO demands the moderately wide field with uniform PSF that can be delivered by a multi-conjugate adaptive optics system. Therefore the baseline defined for this instrument during the study is to be fed by the vertical port of MAORY. An on-board SCAO module was also explored in the MICADO study. This would deliver high Strehl images (>70% on-axis at mv=12) and a 27''x27'' corrected field for fields with a bright guide star.

2.5 METIS – a mid-infrared imaging spectrometer

METIS [6] is a workhorse instrument for the thermal infrared (2.9 µm -14µm) region, designed by a team led by Bernard Brandl. Scientifically, it covers a broad range of targets from exo-planets to high redshift galaxies and is well positioned for high spatial and spectral resolution follow-up of objects discovered with the JWST. METIS has 9 different observing modes – diffraction limited imaging in the LM and N bands over an 18" x 18" field, long-slit spectroscopy with moderate resolution (R~5000) for the LM and N bands ; integral field spectroscopy at high resolution (R~100000) in the LM bands; coronography and polarimetry. The instrument conceptual design includes the possibility of a number of parallel modes – imaging over the full wavelength range; spectroscopy over the full wavelength range; high resolution spectroscopy plus imaging. On entering the METIS cryostat, light from the telescope is split with the visible light sent to the wavefront sensor for the instrument SCAO mode (see Figure 4). The infrared beam then passes through a Dicke switch which acts as an internal, fast chopper, through the optical derotator and then may be directed into the modules containing either the hi-res spectrograph, the LM imaging+low res spectroscopy or the N band imaging plus low res spectroscopy (see Figure 4). This whole system is at 80K temperature, with the N band spectrograph cooled to 30K. Although the SCAO system is cooled, there is no cold deformable mirror since it uses the telescope mirrors for the adaptive correction of the beam. The optics are largely diamond-machined aluminium including the integral field unit, which is based on the design for VLT KMOS and JWST MIRI.

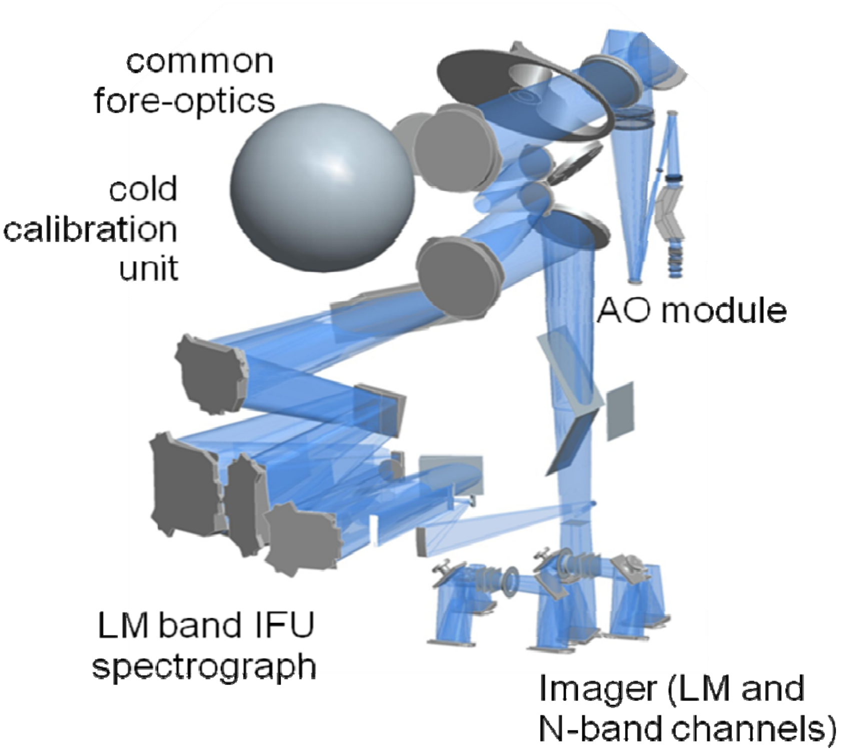


Figure 4: The optical layout of METIS showing the two science modules – the imager with low resolution spectroscopy and the high resolution spectrometer. The on-board AO module is shown. This complete system is inside the METIS cryostat.

2.6 HARMONI –a wide band IFU spectrometer

HARMONI (Thatte et al. [7]) is an integral field spectrometer covering a broad wavelength range (0.47µm – 2.45µm) designed for operation with the Laser Tomographic Adaptive Optics system. It is a multi-mode instrument covering a wide range of observational conditions and scientific programmes. The scientific case for HARMONI calls for three spectral resolution modes (R~4000, R~10000 and R~20000). Four selectable plate scales (4mas, 10mas, 20mas, 40mas) are matched to the size scale of the astronomical objects to be studied with the resulting field size being derived from consideration of the source sizes, the expected PSF (whether seeing limited or delivered by an AO system) and the requirement to obtain the best sky-subtraction in the near-infrared by beam-switching on the IFU. The most challenging pixel scale, in terms of the opto-mechanical design, is set by the desire to do seeing limited spectroscopy; a compromise results in 40mas as the large field size and 5” x 10” are the largest field size for the near-infrared. The number of spaxels comes from the combination of the smallest acceptable field size with the pixel scale required to sample the diffraction limit (1” x 05” at 4mas) leading to 32000 spaxels in the NIR. To achieve the large fields with fine sampling, HARMONI partitions the input focal plane into four sub-fields which feed four integral field units. The output of the IFU is two pseudo-slits which form the input to two spectrographs. Thus for the full-field, there are eight spectrographs in total. The spectrometer collimator is a three mirror anastigmat with one of three mirrors articulated to control the angle of incidence of the beam onto the disperser. VPH gratings are the baseline for these components – 10 gratings are mounted in a wheel for the NIR. The correction of the direction of the angle of refraction towards the cameras is done by a fixed mirror mounted along with each grating. The detector is a 4k x 4k NIR detector array.

For optical spectroscopy (0.48-0.8µm) the expected performance of the AO implies that the 40mas pixel scale is adequate in all cases. Since there is no need for fast jittering for sky-subtraction, one quarter of the field is sufficient (5.0”x2.5”). Therefore, one of the IFU channels is equipped with two optical spectrographs and wheels containing 5 VPH gratings to cover the visible wavelength range; the detector is a 4kx4k CCD. To reduce the thermal background, the complete optical-train for HARMONI is contained in a 4-m diameter cryostat statically mounted on the Nasmyth platform (Figure 5). The field rotation for the small input field is compensated by an optical de-rotator in the instrument fore-optics. HARMONI is designed for use with the LTAO system and with GLAO. An on-instrument SCAO system has also been designed.

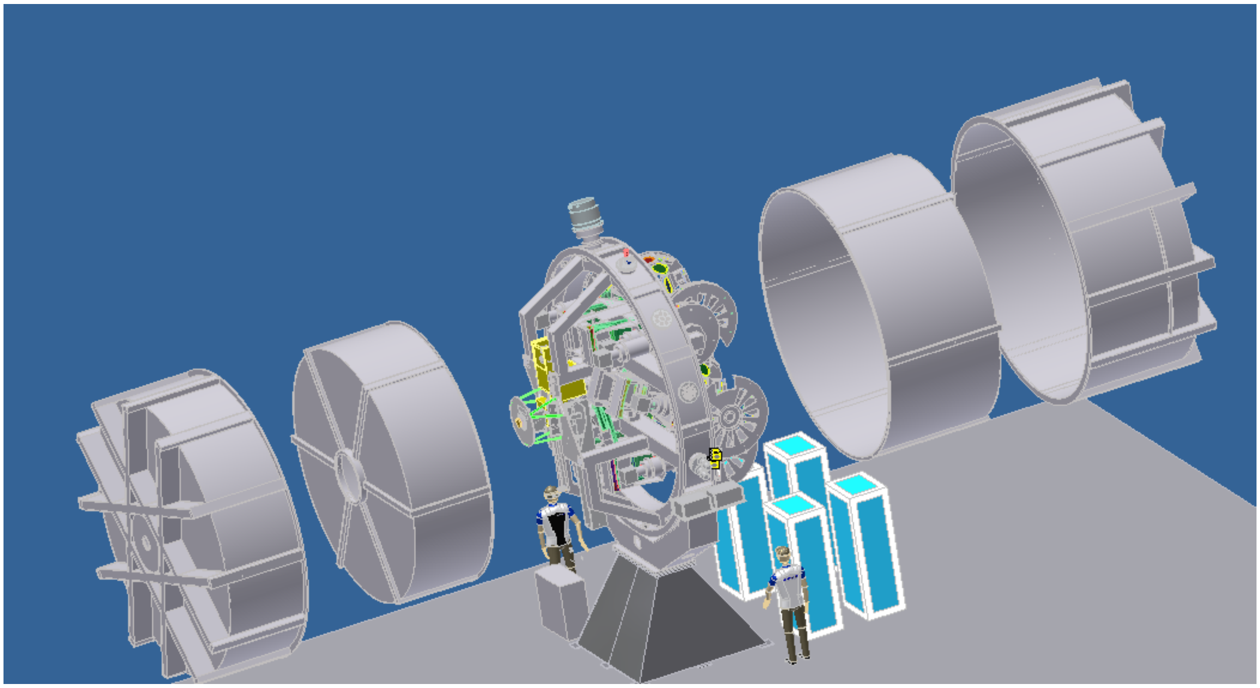


Figure 5: an exploded view of the HARMONI cryostat.

2.7 CODEX – a high stability, high resolution optical spectrograph

The CODEX study was one of two led by ESO (PI: Pasquini). CODEX [8] is a high stability, high resolution (R~130,000) optical spectrograph optimised for the wavelength range 0.37-0.71μm. The instrument is designed to tackle some of the key science cases of the telescope – the search for Earth-like extra-solar planets, direct measurement of the expansion of the Universe, and measurement of the variability of fundamental physical constants. To achieve this, CODEX is designed to reach the goal of Doppler precision of 2cms^{-1} over a 30year timescale. The design builds on the scientific and technical experience with the HARPS spectrograph, particularly in consideration of the steps required to control the radial velocity error budget. The input to the spectrograph is a single large (0.82arcsec) fibre for the object and a second for the calibration source or sky. Fibre-scrambing by mechanical means is required to reduce the radial velocity error due to movements of the photocentre of the target on the fibre input. A laser frequency comb will provide stable, simultaneous wavelength calibration over long timescales. A highly anamorphic pupil (x12) is formed and sliced into 6 slices which are fed into the spectrograph by a three-mirror anastigmat used in double pass. The echelle grating is based on those in UVES and is a mosaic of four 408 x 200mm2 R4 gratings. After the grating, the beam is split to feed blue and red cameras for optimal efficiency and to allow a stable spectrometer format with no moving parts in the instrument (Figure 6). Cross-dispersion is achieved using slanted VPH gratings that are being tested in prototype. The dioptric cameras have final focal-ratio f/1.5 onto the 9cm x 9cm detectors. For high stability, CODEX is to be located in the coudé room of the E-ELT where it will be housed in a temperature stable environment.

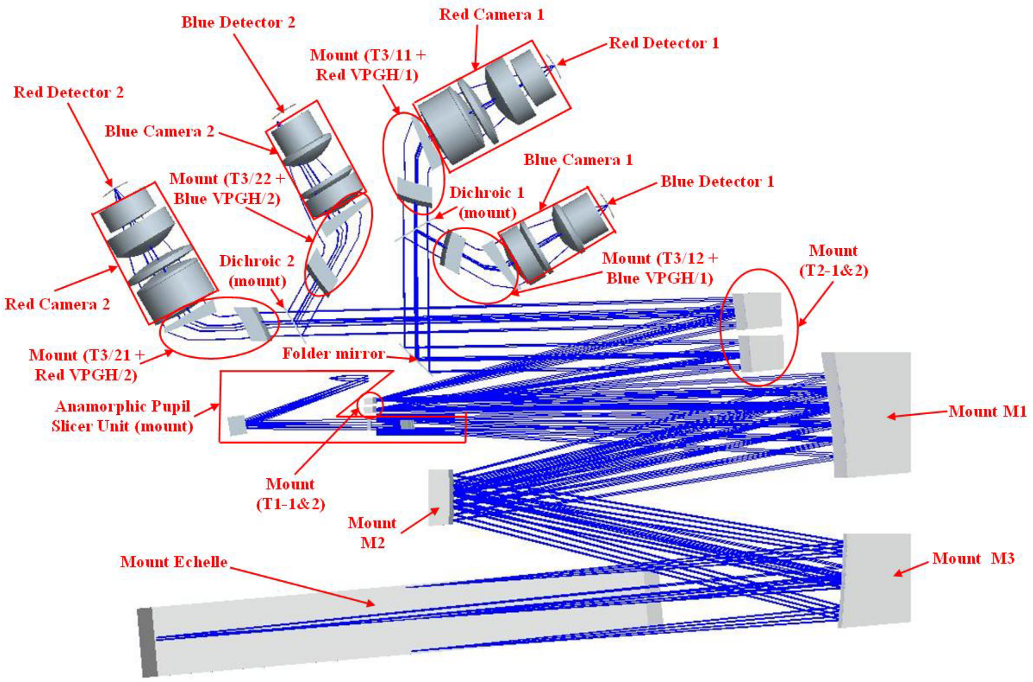


Figure 6: The opto-mechanical concept of the CODEX spectrograph.

2.8 SIMPLE – a high resolution NIR spectrometer

The SIMPLE design study was proposed by PI Livia Origlia and team in response to the open call for new instrument concepts launched by ESO. The SIMPLE instrument [9] is a fixed-format cross-dispersed echelle spectrometer delivering complete coverage from 0.84μm to 2.45μm in a single exposure with spectral resolution R=130,000. The spectrometer aperture is a 27mas x 450mas in the primary mode and can be used in a long (4”) slit mode by selecting between 1 and 6 orders using a spatial filter. For high stability and reliability, the spectrometer has minimal moving parts – just the slit mechanism and the post-slit viewer – in a continuous flow Ln2 cryostat (Figure 7). Outside the cryostat, an on-board SCAO system can be used in conjunction with the telescope adaptive mirrors to correct the PSF, otherwise SIMPLE may be used with either the MCAO or LTAO post-focal adaptive optics modules. The instrument pre-optics contains also a secondary guiding system to maintain alignment between SIMPLE and the telescope axis, the field derotator for the long slit mode and the instrument calibration unit. The spectrometer works on the principle of a double pass from a standard reflection grating and focuses the spectrum onto a 12k x 4k pixel focal plane array. SIMPLE can address a wide range of scientific programmes from spectroscopy of exo-Earth atmospheres to the chemistry of Population III stars.

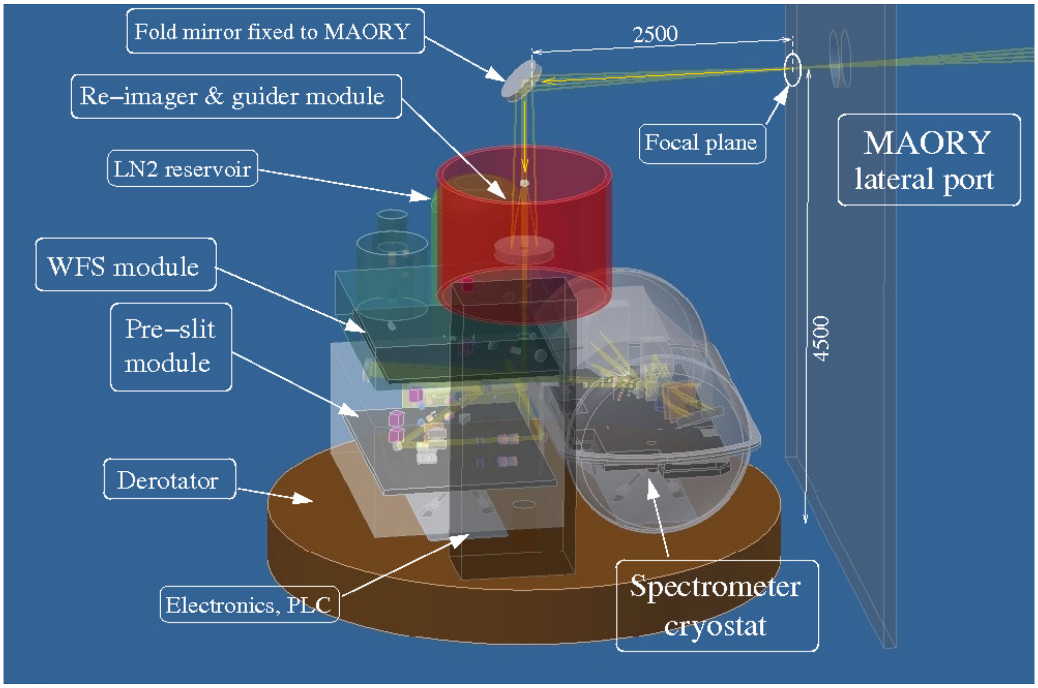


Figure 7: The SIMPLE layout showing the beam picked-off from the re-imaged (by the MCAO) telescope focal plane. SIMPLE is mounted on a mechanical rotator. The spectrometer cryostat contains only two moving mechanisms for stability of the wavelength measurements.

2.9 EPICS – a planetary camera and spectrograph

The EPICS instrument (Figure 8) combines extreme adaptive optics with the capabilities of two science instruments to extend the limits of planet detection and characterisation beyond anything currently possible or planned (Kasper et al. [10]). Predictions of the instrument performance show that planets with masses <10 Mearth at radii of 1AU can be detected and characterised with EPICS. Contrast ratios of 10^{-8} – 10^{-9} are required and are reached using a combination of innovative optical design, extremely high Strehl AO (>90%) and techniques such as differential polarimetric imaging or integral field spectroscopy. The final step in achieving these contrasts is in the data reduction. EPICS is a bench mounted instrument for the Nasmyth platform; the preferred location is the straight through port since this benefits the polarimetric mode by avoiding a 45degree reflection from the telescope M6. After the Nasmyth focus, 10% of the light is directed into an on-instrument single conjugate adaptive optics system which provides signals for the telescope M4/M5. The common optical path contains an atmospheric dispersion corrector and the high-order deformable mirror for the extreme AO module. The science beam may be directed into either the NIR integral field spectrograph (IFS) or the EPOL differential imaging polarimeter. The integral field unit is designed for wavelength coverage from 0.95µm-1.65µm with spectral resolving powers R=125,3000 and 20000. The baseline technology for the IFU is a lenslet design based on the SPHERE design; there are 343x343 lenslets for a 0.8arcsec field. An alternative image slicing design remains under study. The spectrometer optical design has a six lens collimator and five lens camera which focuses the light on a mosaic of four 4k x 4k NIR detector arrays. The only cryogenic element is the detector. The EPOL wavelength range is from 0.695µm-0.8µm field with a 1.37x1.37arcsec field. In this two channel camera, each channel is equipped with a 4k x 8k CCD detector. A third science instrument – a differential speckle imager – is also part on the ongoing work on conceptual design and prototyping. The XAO system uses a roof-pyramid wavefront sensor to measure the signals to control a 210 x 210 actuator deformable mirror of ~300mm diameter. The DM is the subject of a major prototyping effort within the project as it requires a very high actuator density (1mm pitch) combined with large stroke (3µm).

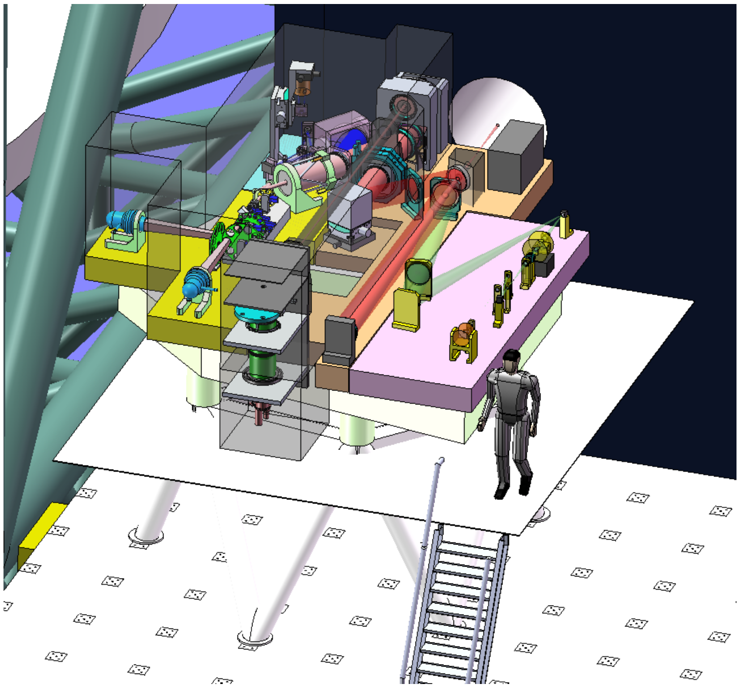


Figure 8: a schematic view of EPICS on the E-ELT Nasmyth platform.

2.10 OPTIMOS-DIORAMAS – an slit mask MOS spectrometer and imager

OPTIMOS-DIORAMAS (PI Le Fèvre [11]) is an imager and slit-mask based multi-object spectrometer for the wavelength range 0.37-1.6µm. A 6.78x6.78arcmin field is split into four quadrants at the telescope focal plane and feeds four spectrometers – two optimised for the wavelength range 0.37-1.0µm and two for the range 0.6-1.4µm. In the overlap wavelength range (0.6-1.0µm), OPTIMOS-DIORAMAS can survey a field of 44arcmin2, outside this range the field is 22arcmin2. For spectroscopy, the multiplex may be as high as 480 in the optical and with the lowest spectral resolution (R~300); in the near-infrared, a multiplex gain of 160 is foreseen (R~3000). The 0.8mm thick steel slit masks are 780mm x 780mm, weigh 3kg and are laser cut on site. The baseline slit width of 0.5arcsecs is designed to exploit the best performance of the LGS GLAO system, though the instrument can be used in poorer conditions with some slit losses or some reduction in resolving power. The optical design is based on a focal-reducer; the final camera focal ratio is f-1.5. The number of optical elements in each camera+collimator is 12 and the diameters are large (around 300mm). The spectrographs and focal plane are mechanically rotated to track the field, active flexure compensation based on look-up tables to correct for any movement of the instrument. A novel aspect of the DIORAMAS design is the use of a robotic arm to exchange the filters for imaging or the gratings which removes the need for large gratings wheels (seen in Figure 9). A mixture of transmission gratings and VPHs are used. The final detector focal planes are made up of mosaics of three 4k x 4k detectors in both the visible and NIR arms. The detectors are the only part of the instrument that is cooled.

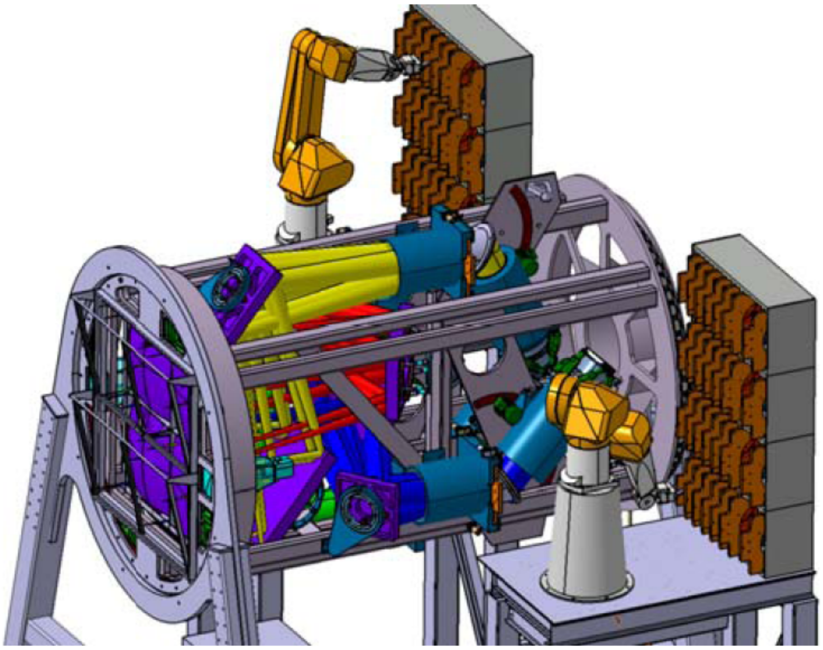


Figure 9: shows a view of the OPTIMOS-DIORAMAS system with the cabinets for the filters and gratings and robotic exchange mechanisms. At the left of the figure, the mask exchange mechanism can be seen. The cylindrical structure is the rotating part of the instrument.

2.11 OPTIMOS-EVE – a fibre based MOS spectrometer

OPTIMOS-EVE (PI Hammer [12]) is a fibre based optical to NIR H-band (0.37-1.7μm) multi-object spectrometer designed for operation in 'seeing limited' conditions, with the telescope NGS or LGS GLAO systems in operation. The instrument exploits the maximum field offered by the E-ELT, which is 10arcmin in diameter, though the field beyond 5armin diameter suffers from vignetting due to the telescope NGS guide probes. Fibres are robotically placed onto one of four focal plane plates while a different field is observed. During an observation the plate in use is mechanically rotated to track the field, by a mechanism in the OPTIMOS-EVE carousel (Figure 10). Since the rotator is not attached to the Nasmyth flange, on-sky metrology is used to determine tracking errors. OPTIMOS-EVE offers a multiplex of up to 240 for single objects, when observing with spectral resolving power R~5000; for higher spectral resolving power modes 15,000 and 30,000 respectively the multiplex is 70 and 40. In addition to the single object mode, 30 fibre bundle IFUs with field of view 1.8arcsec x 3arcsec and one large IFU with field of view 7.8arcsec x 13.5arcsec are available for use with the lower spectral resolution mode. The fibres are split between the two spectrometers in the optical and two in the infrared allowing simultaneous observations across the full wavelength range. In the infrared, each spectrometer uses three 4k x 4k detectors for the full multiplex and spectral resolution, with the possibility of a future upgrade to 9 detectors for increased wavelength coverage. The optical spectrographs contain 4 6k x 6k CCD detectors. The spectrometers have large reflective collimators, refractive cameras and use VPH gratings for the dispersing element. The final camera f-ratio is 1.8 and the diameters of the optics are in the range of 300mm. A total of 10 gratings is required to cover the full wavelength range and all spectral resolving powers. Most of the OPTIMOS-EVE optical mechanical system is operated at a temperature of 193K in a cold chamber located in the platform under the focal plate system.

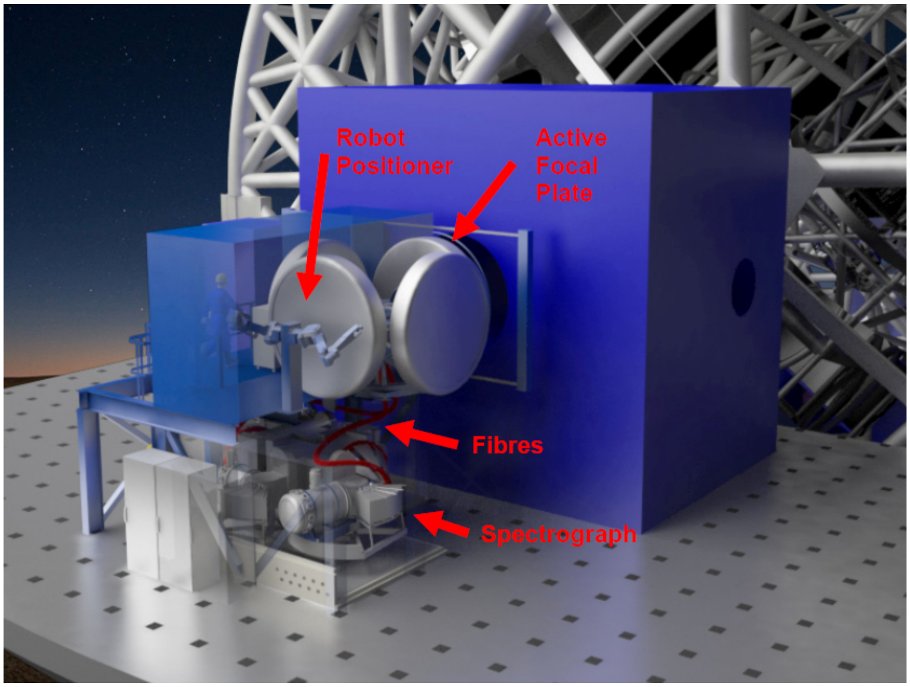


Figure 10: A schematic showing OPTIMOS-EVE on the Nasmyth platform, straight-through port. The spectrographs are mounted under the structure which supports the focal plates and exchange mechanism.

3. OUTCOMES OF THE STUDY PROGRAMME

As stated in the introduction, ESO launched the instrument studies with certain goals in mind and with the completion of the studies it is possible to address whether these were achieved.

The instrument consortia were all advised by large science teams whose efforts have very significantly strengthened the science case for the telescope. In developing the science case for the instruments, the teams drew from the top level science cases presented by the project - for example, the detection and characterization of extra-solar planets naturally appears in the cases for most of the instruments – but also introduced their own ideas. This not only serves to strengthen scientific justification for the project overall, but confirms whether or not the top level science requirements for the observatory have been correctly defined. One example of this is the selection of the telescope coatings, now selected to be optimized in the infrared at the expense of the blue end of the spectrum since no strong case was made for this either through the instrument studies or the Design Reference Science Plan [13]. Instrument requirements were explicitly derived from these science cases. The review of the technical design of the instruments revealed nothing that was considered by the Review Boards to be a show-stopper for any of the instruments or AO modules. Therefore the feasibility of a powerful set of instruments that can deliver the E-ELT science case has been very effectively demonstrated.

During the studies there has been a regular input of interface and infrastructure requirements from the instrument teams. The requirements generated have been from a combination of spontaneous requirements arising from the studies and also responses solicited by ESO concerning specific areas – for example the requirements for calibration sources within the telescope. Specific requests for facilities within the telescope have tended to centre on the area around the intermediate focus, which is very well suited for placing calibration sources but also a possible atmospheric dispersion compensator and a half-wave plate polarmetric calibration. The provision of these is still under discussion as the telescope design progresses; the key point is that quantitative information on the impact of including these facilities is available. At the launch of the studies, an early version of the telescope to science instrument interface was available. Two subsequent revisions of this document have been developed over the duration of the studies, reflecting the effectiveness in existence of the instrument studies in driving forward progress in this area. For the instrument teams and for ESO, the challenge has been to progress the instrument design with reference to a changing interface, necessitating frequent discussion to reach agreement on the applicability of new requirements at the later stages of the studies.

Concerning the affordability of the instruments, guidelines for the available budget were given as part of the instrument technical specification. Thanks to the work by the instrument teams on the construction proposal, we now have a clearer picture of the capabilities that fit within this guideline and the estimated cost of the fully capable instrument which can be used to formulate the plan for the instruments in the telescope construction proposal (see below).

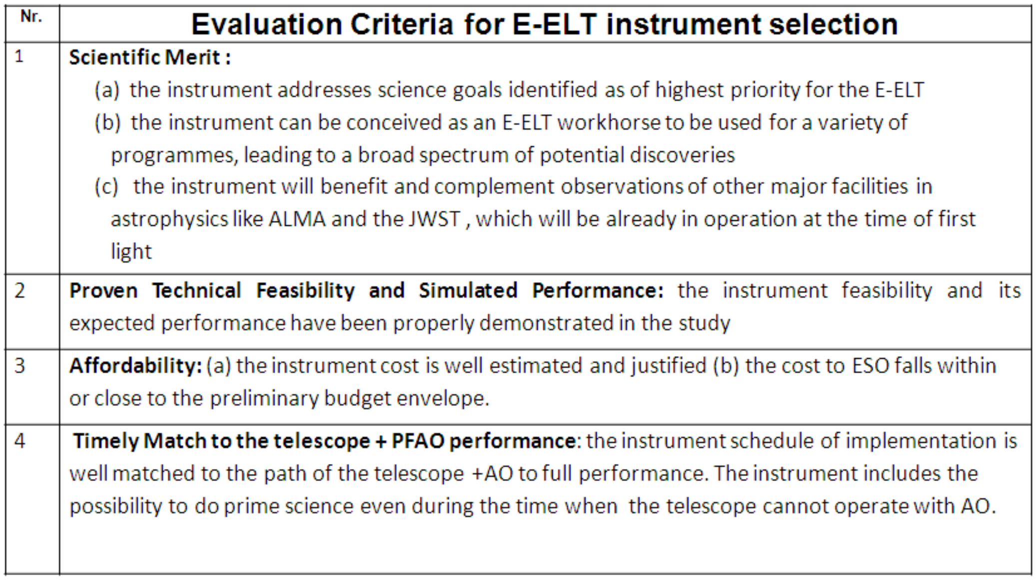
An important outcome in preparing for the construction phase is the identification by the teams of the prototyping activities that each instrument requires. ESO is now in a position to identify requirements for new technologies which are common to the studies and to assimilate these into a technology development plan either to be carried out in the external institutes as part of the instrument development or to be carried out by ESO in collaboration with the relevant external experts. While it is easy to identify qualitatively the types of new devices and components required in the E-ELT era, the studies produced invaluable quantitative information. This may be illustrated by an example from an area in which ESO has traditionally worked closely with the instrument community – deformable mirrors. We now understand that an instrument like EPICS on an E-ELT requires high density deformable mirrors with 210x210 actuators with 1mm pitch and 3µm stroke (placing stringent requirements also on the real time controller) whereas the performance of EAGLE would benefit greatly from the development of small DMs with 84 x 84 actuators, 1mm pitch and a 6µm stroke rather than relying on the currently available 64x64 actuator DMs.

And finally, a very significant success of the studies has been the fantastic response of the ESO community and the demonstrated willingness and ability to contribute to the instrumentation programme for the E-ELT telescope project, and to design and deliver the instruments that will deliver the E-ELT science case.

4. STATUS AND NEXT STEPS

Since the conclusion of the Phase A study reviews in March 2010, ESO has been working with its advisory committees to select the capabilities that will make up the first generation of instruments on the telescope. The plan for the E-ELT instrumentation will be submitted along with the telescope construction proposal for external review in September 2010. Not all of the capabilities that have been studied can be included in the first generation. The plan will identify the two first light instruments and the pool of capabilities from which the remainder of the first generation instruments will be selected. The selection is primarily driven by the scientific goals of the project and community, though factors such as feasibility, affordability and timeliness are also critical (Table 4).

Table 4: selection criteria for the first generation capabilities.



Nr.	Evaluation Criteria for E-ELT instrument selection
1	**Scientific Merit :** (a) the instrument addresses science goals identified as of highest priority for the E-ELT (b) the instrument can be conceived as an E-ELT workhorse to be used for a variety of programmes, leading to a broad spectrum of potential discoveries (c) the instrument will benefit and complement observations of other major facilities in astrophysics like ALMA and the JWST , which will be already in operation at the time of first light
2	**Proven Technical Feasibility and Simulated Performance:** the instrument feasibility and its expected performance have been properly demonstrated in the study
3	**Affordability:** (a) the instrument cost is well estimated and justified (b) the cost to ESO falls within or close to the preliminary budget envelope.
4	**Timely Match to the telescope + PFAO performance**: the instrument schedule of implementation is well matched to the path of the telescope +AO to full performance. The instrument includes the possibility to do prime science even during the time when the telescope cannot operate with AO.

The table of agreed selection criteria is shown above. A scientifically based recommendation for the first light instruments has been provided by the E-ELT Science Working Group. A draft version of the initial plan, in line with the SWG recommendation and factoring in the other criteria, has been presented to the ESO Science and Technical

Committee. The plan will be revised following their recommendations and submitted with the construction proposal in July 2010.

In parallel with the work on the construction proposal, ESO will also develop a technology development plan to be enacted in collaboration with the community. Work also continues on the telescope interface and infrastructure required to support the instruments and on a plan for developing standards for the E-ELT instruments. For the first light instruments, new specifications and a statement of work will be drawn up to reflect the recommendations of the Review Board and the procurement of those instruments will be initiated once the construction phase of the telescope is underway. We expect that the kick-off meeting for the first generation instruments will take place in late 2011.

REFERENCES

[1] J.C. González, S. D'Odorico, S. Ramsay "E-ELT phase-A instrument studies: a system engineering view", Proc. SPIE 7738, 7738-53 (2010)

[2] Fusco, T., Meimon, S. C., Clenet, Y., Cohen, M., Paufique, J., Schnetler, H. "ATLAS: the LTAO system for the E-ELT: design, performance, and sky coverage", Proc. SPIE 7736, 7736-11 (2010)

[3] Diolati, E., Conan, J.-M., Foppiani, I., Marchetti, E., Baruffolo, A., Bellazzini, M., Ciliegi, P., Lombini, M., Petit, C., Robert, C., Schreiber, L., Cosentino, G., Biliotti, V., Bregoli, G., Fusco, T., Hubin, N., Meimon, S.C., Sauvage, J.-F. "Conceptual design of the multi-conjugate adaptive optics module for the European Extremely Large Telescope", Proc. SPIE 7736, 7736-26 (2010)

[4] Cuby, J.-G., Morris, S., Evans, C.J., Fusco, T., Jagourel, P., Le Mignant, D., Parr-Burman, P.M., Rousset, G.C., Schnetler, H., "EAGLE: the multi-IFU, AO assisted, near-IR spectrograph for the EELT: a status report", Proc. SPIE 7735, 7735-83 (2010)

[5] Davies, R., "MICADO: the adaptive optics imaging camera for the E-ELT", Proc. SPIE 7735, 7735-80 (2010)

[6] Brandl, B.R., Lenzen, R., Pantin, E.J., Glasse, A.C.H., Blommaert, J., Venema, L.B., Molster, F., Ralf Siebenmorgen, R., "Instrument concept and science case for the mid-infrared E-ELT imager and spectrograph METIS", Proc. SPIE 7735, 7735-86 (2010)

[7] Thatte, N.A., Tecza, M., Clarke, F., Goodsall, T.M., Lunney, D.W., Bacon, R.M., Arribas, S., Mediavilla, E., "HARMONI: a single-field, wide-band, integral-field spectrograph for the E-ELT", Proc. SPIE 7735, 7735-88 (2010)

[8] Pasquini, L., "CODEX", Proc. SPIE 7735, 7735-85 (2010)

[9] Oliva, E., Origlia, L., Maiolino, R., Piskunov, N. A., Hatzes, A. P., Vanzi, L., Gustafsson, B., Rossetti, E., "SIMPLE: a high-resolution near-infrared spectrometer for the E-ELT", Proc. SPIE 7735, 7735-81 (2010)

[10] Kasper, M.E., Beuzit, J.-L., Verninaud, C., Baudoz, P., Boccaletti, A., Gratton, R.G., Bonavita, M., Keller, C.U., Kerber, F., Schmid, H.M., Thatte, N.A., Tecza, M., Venema, L.B., Jager, R., Yaitskova, N., Aller-Carpentier, E., Martinez, P., Hubin, N., "EPICS: direct imaging of exoplanets with the EELT", Proc. SPIE 7735, 7735-84 (2010)

[11] Le Fèvre, O.C., Maccagni, D., Tresse, L., "DIORAMAS: a wide-field visible and near-infrared imaging multi-slit spectrograph for the EELT", Proc. SPIE 7735, 7735-84 (2010)

[12] Navarro, R., Chemla, F., Bonifacio, P., Flores, H., Guinouard, I., Huet, J.-M., Puech, M., Royer, F., Pragt, J.H., Wulterkens, G., Sawyer, E.C., Caldwell, M.E., Tosh, I.A.J., Whalley, M.S., Woodhouse, G.F.W., Spanò, P., Di Marcantonio, P., Andersen, M.I., Dalton, G.B., Kaper, L., Hammer, J.-F., "Project overview of OPTIMOS-EVE: the fiber-fed multi-object spectrograph for the E-ELT", Proc. SPIE 7735, 7735-91 (2010)

[13] Kissler-Patig, M., Küpcü Yoldaş, A., Liske, J., "A Sneak Preview of the E-ELT Design Reference Science Plan Questionnaire Results", The Messenger, 138, 11 (2010)