A Roadmap for the European ELT Instrument Suite

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ABSTRACT

We present plans for instrumentation on the European Extremely Large Telescope. ESO is working with its community of astronomers and instrument builders to develop the E-ELT Instrumentation Roadmap. The roadmap is a timeline of the steps towards the full instrument programme, from specification of the scientific requirements, via a technology development phase, to selection of the instrument concepts. Key goals are to be flexibile to new ideas and to ensure the timely, on-budget delivery of instruments that meet the community's scientific needs. The result is an exciting programme of seven instruments planned over the first decade of the telescope construction phase.

Keywords: instruments: optical, instruments: infrared, instruments: extremely large telescopes

1. INTRODUCTION

An important part of the planning for the European Extremely Large Telescope (E-ELT) has been studying a suite of instrument concepts matched to the scientific aims of the ESO community. During the period from 2007-2010, nine instruments and two post-focal adaptive optics modules were investigated by consortia of instruments builders from the ESO member states and Chile and also from ESO itself. These Phase A studies are reported in Ramsay et al SPIE 2010[1]. A summary table is shown below.

Table 1. A summary of the Phase A instrument 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

A key goal of the Phase A study programme was to verify that instruments for the E-ELT can be built at an affordable cost and that they properly address the highest priority scientific goals of the telescope. The consortia developed conceptual designs with a management plan including schedule and cost for the instrument construction phase. The successful outcome of these studies shows that the science case for the telescope can be delivered by facility instruments that, though challenging, are feasible, affordable and can be built in a timely fashion.

The next step has been to define the sequence and timescales for the selection, procurement and construction of the instruments that will be delivered to the telescope. The Phase A studies are the starting point for this, but in most cases the instruments to be built will have different scientific specifications.

Table 2. 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.

2. INSTRUMENT SELECTION

The criteria for selection of the instruments for construction were agreed by the ESO council and are shown in Table 2. The main driver for the instrument selection is scientific, therefore ESO asked the E-ELT Science Working Group (SWG) to make recommendations for a pair of instruments to be developed as the first light instruments for the telescope and to recommend the sequence of delivery for future instruments. The SWG was free to select from any of the instrument concepts with the single exception of the planetary camera and spectrograph: the EPICS[2] study identified a development period of several years for the technology required to realise this ambitious instrument and, therefore, such a capability was not recommended by ESO for selection as a first light instrument.

Candidate first-light instruments were evaluated for their immediate scientific impact, their complementarity with existing high-impact facilities, their scientific flexibility, their secure scientific return and against their coverage of the expected atmospheric conditions. The first-light pair of a diffraction-limited, near-infrared camera ([ELT-CAM], as presented in the MICADO[3] study) and a wideband, integral-field spectrograph ([ELT-IFU], as presented in the HARMONI[4] study) emerged as the clear preference. This powerful combination of an imager and spectrograph satisfied the defined scientific selection criteria very well. These two instruments are able to cover approximately 75% of the science outlined in the science case, as well as offering a solid potential for new discoveries. The impact of the subsequent revision of the telescope baseline to 40-metre-class has not altered this selection. ELT-IFU and ELT-CAM are both versatile workhorse instruments with the goal of achieving high sensitivity and high spatial resolution at the diffraction limit of the largest planned optical–infrared ground based telescope.

A planetary camera and spectrograph (ELT-PCS) was considered to have extremely high scientific priority and should be included in the instrumentation plan as soon as the technology developments required for this instrument are realised. The remaining instruments were considered to have equal scientific priority and the schedule for these should be driven by technical and managerial considerations.

Consequently, the initial instrument plan grouped all instruments beyond first light into a pool from which future selections would be made, providing flexibility against a rapidly changing scientific background. Meetings and discussions with the instrument-building community in ESO Member States highlighted the need for a more forward-looking plan, providing information on instrument planning and selection well beyond first light. This is to enable the community (including funding agencies) to prepare their resource planning and ensure that both staff and funds are in place at the right time. If the construction of a particular instrument is to be deferred for a number of years this is also important information, allowing institutes to undertake other projects in the meantime. For this reason, ESO decided to develop a roadmap for instrument construction to extend and better define the instrumentation plan for a total of seven instruments. Specification developments, decision milestones and project start dates are selected to try to achieve a balance between giving sufficient information to allow funding, effort and technology development planning while keeping sufficient flexibility to allow for changing scientific priorities

3. THE E-ELT INSTRUMENT ROADMAP

The considerations taken into account when developing the roadmap are given in this Section. The scientific requirements for each of the instruments are presented first, followed by the technical and managerial constraints that must be addressed.

3.1 Scientific Requirements for the Instruments

The discussions with ESO committees lead to the following first requirements for the instruments. These are being actively developed and defined in more detail as the procurement process for the instruments proceeds.

The concept for the diffraction-limited NIR imager, ELT-CAM, is based on two concepts from the Phase A studies — the multi-conjugate adaptive optics (MCAO) module MAORY[5] and MICADO. The top-level science requirements are for a near-infrared imager capable of sampling the diffraction limit of the 40-metre-class telescope and equipped with a range of standard and narrowband filters. The field of view of the camera should be comparable with the 53 arcseconds x 53 arcseconds field of MICADO and sufficient to meet the astrometric requirements derived from the science case of that instrument. An adaptive optics system capable of delivering diffraction-limited imaging over a moderately wide field is required to fulfil the science case of this instrument.

The requirements for ELT-IFU are based on those for HARMONI, a wideband (optical to NIR) single field IFU spectrograph. ELT-IFU should operate in seeing-limited conditions, as well as at the telescope diffraction limit, particularly as the instrument will operate side-by-side with the diffraction-limited ELT-CAM. In addition to spectral resolving powers of R~4000, a higher spectral resolving power (R > 10 000) mode is considered for ELT-IFU, to address science cases in the field of stellar populations and galactic archaeology. An AO module, capable of delivering high Strehl in the NIR over a small field, is required from the outset of science operations. During Phase A, HARMONI used the corrected beam delivered by the laser tomography adaptive optics (LTAO) module, ATLAS[6]. Whether the AO performance required by HARMONI is provided by a separate module or is combined with the instrument is one of the areas being considered currently.

As a starting point, the requirements for ELT-MIR are adopted from the METIS[7] study without significant change. The instrument shall offer imaging and spectroscopy at the diffraction limit of the telescope – these are fundamental requirements for complementarity with the JWST. Key science cases for this instrument require velocity-resolved information for known Mid-Infrared (MIR) sources and so spectral resolving power in the range R > 100 000 (for example for observations of circumstellar discs) and at lower resolving power (R ~ 3000), for the kinematics of high redshift galaxies, is desirable. LMN-band operation is the baseline for low-resolution spectroscopy and imaging, with high-resolution IFU spectroscopy (R ~ 100 000) at L and M only. The METIS study showed that very high Strehl observations can be achieved in good conditions with just the telescope AO and the on-board SCAO Wavefront Sensors (WFS). However, operation with a full laser guide star AO system for complete sky coverage was also studied, to ensure a scientific advantage over competing facilities, and shall be considered as part of the requirements.

Efficient use of any telescope for observing large numbers of objects leads to a requirement for Multi-Object Spectroscopy (MOS). Optical MOS instruments have long had success as the workhorses of the 8-metre-class telescopes with NIR MOS instruments now coming online (e.g., KMOS[8] at the VLT, MOSFIRE[9] at Keck, FLAMINGOS-2[10] at Gemini). The Phase A Studies explored the scientific possibilities of high multiplex spectroscopy over the 10-arcminute telescope field via three different studies: EAGLE[11]— a multi-IFU spectrograph with AO-enhanced spatial resolution and spectral resolving power 5000 and 10 000; OPTIMOS–DIORAMAS[12] — highly optimised for high-z astronomy with high (480) multiplex, high throughput and low resolution (R ~ 300, 5000), uniquely with an imaging mode, and OPTIMOS–EVE[13]— more specialised for stellar astrophysics using higher resolving power (R ~ 10 000–20 000) optical to NIR spectroscopy with high multiplex and a versatile configuration using single fibres and fibre-bundle IFUs. From these different concepts and their scientific goals, the top-level scientific requirements of a future ELT-MOS will be defined.

Two high spectral resolution instruments were studied — CODEX[14] in the optical wavelength range and SIMPLE[15] in the NIR wavelength range. High stability and a fixed spectral format will likely remain as important top level goals for ELT-HIRES. For CODEX, resolving power R > 100 000, high throughput and stability allowing radial velocity measurements in the cm/s regime were key requirements. For SIMPLE, similar spectral resolving power (R > 100 000) was required to meet the science cases. An additional requirement was for an AO capability delivering high angular resolution to meet science cases such as those on the structure of protoplanetary discs or on the IMF in galaxies. The requirements for the ELT-HIRES capability will evolve based on these concepts and taking into account results from new instruments are commissioned on existing telescopes. Of particular interest are ESPRESSO[16] and GIANO[17] on the Telescopio Nazionale Galileo.

For the planet-finding instrument, ELT-PCS, the baseline is to implement the science requirements as derived from the EPICS study. Both the IFU and differential imaging polarimeter will be maintained as, of course, will the XAO system. However, this is a fast-moving scientific field and so some significant modifications to the science requirements may be anticipated. These may also be driven by the success of the enabling technology programme for this instrument. Important inputs to the instrument specification are expected to follow the commissioning of SPHERE[18] on the VLT.

3.2 Other Requirements for the Roadmap

In developing the roadmap, the first-light instrument pair of ELT-CAM and ELT-IFU, both with AO capabilities, is adopted from the earlier instrument plan. The other considerations are then as follows.

a. *The three Instruments following the first-light pair should be ELT-MIR, ELT-MOS and ELT-HIRES. These instruments have equal scientific priority.*

This combination covers a broad parameter space with the flexibility to adapt to changing priorities. The Science Working Group ranked these as having equal scientific priority: each contributes substantially to achieving the key scientific programmes of the E-ELT. Therefore their sequencing will be based on requirements readiness and technical maturity.

ELT-MIR has well-defined requirements, a straightforward design and needs relatively little technology development. The key to good performance with this instrument rests with the Aquarius detector which has already been successfully tested in the lab at ESO and is being commissioned on-sky in 2012 in VISIR[19]. This instrument should therefore be ready to go in 2014 as ELT-3 subject to a technological readiness review in 2013. Currently, three concepts exist for a MOS (OPTIMOS–EVE/DIORAMAS, EAGLE) and two for a high-resolution spectrograph (SIMPLE, CODEX). There is technology development to be done in some of these cases, as well as awaiting results from possible precursor instruments. There is therefore preparatory work to do to define the preferred options and their scientific requirements. A selection of the MOS and HIRES instrument capabilities, predominantly on scientific criteria, is planned in 2013. Further delta-Phase A design work and/or technology development will be required before instrument starts. In 2015 a decision will be made, based on technological readiness, as to which of ELT-MOS or ELT-HIRES will be ELT-4 and which ELT-5.

b. *The E-ELT planetary camera and spectrograph (ELT-PCS) is also selected for construction subject to technical readiness.*

This instrument is required for the E-ELT to tackle its principal science case — the imaging and characterisation of Earth-like planets in the habitable zone. The technology required for its construction is ambitious and not yet ready and so the project will begin with technology development for the key components and subsystems. Once the technologies are felt to be at a satisfactory Technology Readiness Level (TRL), the instrument construction project will officially start. This could be as early as 2017 or as late as 2022.

c. After the first-light pair, instrument projects should start every two years

The entire suite represents a large investment and so needs to be phased to achieve a smooth spending profile. A roadmap that foresees two instruments at first light, a third the following year, and an instrument start approximately every two years thereafter stays within the available envelope. This phased start will also ensure a phased delivery of the instruments to the telescope that will help to ensure an achievable commissioning schedule, especially during the first years of operation. Nevertheless the plan is ambitious, envisioning delivery of the first four instruments within the first three years of telescope operation

Table 3. The E-ELT Instrument Roadmap

Year	ELT-IFU	ELT-CAM	ELT-MIR	ELT-4 (MOS or HIRES)	ELT-5 (MOS or HIRES	ELT-6	ELT-PCS
2012	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Call for proposals for ETD
2013			TRL Review	Call for proposals for MOS/HIRES			
2014							
2015				Selection ELT-MOS/HIRES		Call for proposals	
2016							
2017							TRL check
2018							TRL check
2019						Selection	TRL check
2020							TRL check
2021							TRL check
2022 Tel technical first light							

	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
	Decision point
	Development of Technical Specifications, Statement of Work, Agreement, **Instrument Start.**

d. Flexibility should be maintained to allow new concepts and changing scientific priorities.

This has driven considerations from the beginning and has been stressed by both the SWG and ESO Science and Technology Committee (STC). This is incorporated into the roadmap by allocating ELT-6 as an as-yet unspecified instrument whose definition will begin with a call for proposals in 2015, subsequent parallel Phase A studies and technology development if required, and final selection in 2019.

e. There should be opportunities for new Member States to participate in the programme.

Four of the seven instruments in the roadmap will be procured by open competition. This will be done in general by issuing a call for proposals, selecting which will need to be developed via Phase A studies if necessary, and then finally selecting the specific instrument for construction. New Member States will be able to form/join consortia and compete for these instruments. In addition ELT-6 is unspecified and will also be selected by a competitive procedure.

While it is difficult to satisfy all the requirements in a single instrument plan, we believe that the roadmap in Figure 1 provides a satisfactory solution. In particular it attempts to balance a forward look for planning purposes with maintaining scientific flexibility. The following instruments are selected for construction: ELT-CAM, ELT-IFU, ELT-MIR, ELT-HIRES, ELT-MOS and ELT-PCS. Funded work towards the construction of each of these starts in 2012, either by the development of the initial specifications or by the initiation of the research and development programmes required to support them. The final sequence of start dates for instruments beyond the first-light pair (ELT-CAM, ELT-IFU) depends upon a balance of scientific priority and technical readiness.

3.3 Instrument Deployment on Telescope

Figure 1 shows a tentative arrangement for the instruments on the Nasmyth platforms and the coudé area. The sizes of the individual items in the figure are scaled according to actual values. In the case of the instruments these values are the allocated design volumes to heavy instruments and post-focal AO modules that were used during the Phase A studies (except in the case of the coudé instrument, where the constraints were different).

The ELT-IFU is shown in the figure being fed by an LTAO module. Such a facility could be integrated into the instrument. In that case, the allocated space could vary with respect to what is presented. The ELT-CAM is expected to be fed by the MCAO module in a gravity-invariant fashion and, therefore, will be located underneath the module.

The two instruments placed on the straight-through ports are the ELT-MOS and the ELT-MIR. The former is a large field of view instrument that will use the 10-arcminute field, only available at the straight-through ports. The ELT-MIR will benefit by having only five reflections instead of six, as would be the case if located in a lateral port. The ELT-PCS would also preferably be located at a straight-through port, avoiding M6 in the optical path which, given its inclined position, will introduce an additional signature in polarimetric observations.

The ELT-6 is assumed to be located at one of the lateral ports. Finally, the ELT-HIRES, depending on the type of instrument, can be fed by a second port of the MCAO module. In that case this port, already considered in the Phase A study, would have to be implemented. Another option is locating the ELT-HIRES in the coudé focal station. Both possibilities are shown in red in Figure 1.

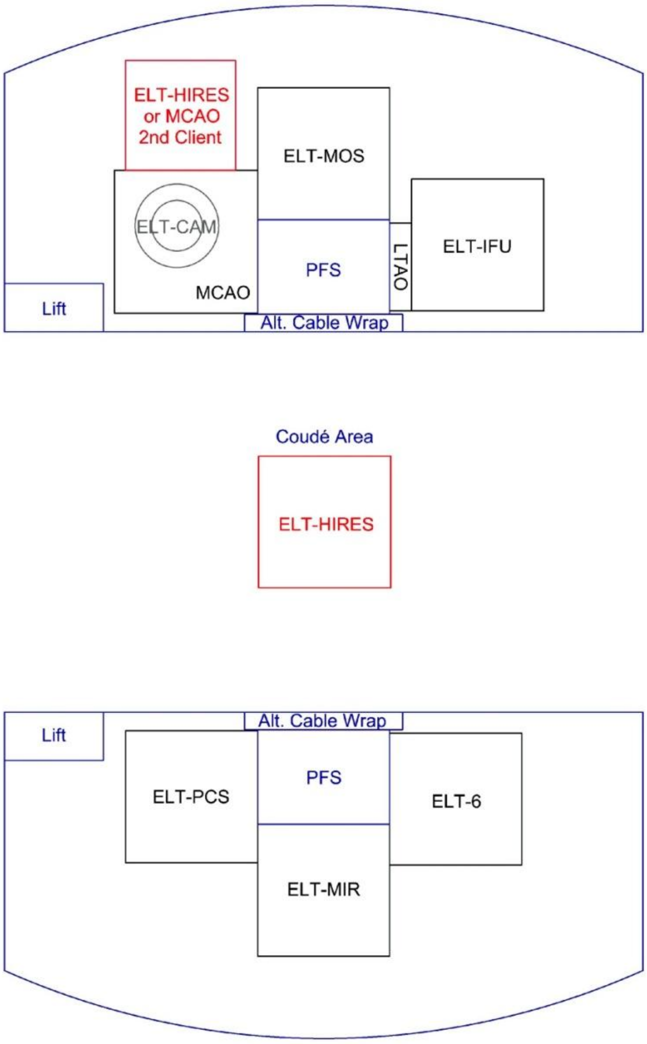

Figure 1. A possible arrangement for the instruments on the Nasmyth platforms and coudé area.

4. NEXT STEPS AND CONCLUSIONS

After extensive work by ESO and the ESO community of scientists and engineers, through the instrument studies and by participation in the ESO advisory committees, the first version of the E-ELT Instrument Roadmap has been presented to and agreed by the ESO Council. Subsequent to the recent conditional approval of the Project, work on the requirements for the first-light instruments is underway in collaboration with the E-ELT Project Science Team (PST). The PST is a committee of external scientists that work with the Project on all aspects relative to the science performance of the E-ELT, including to refine the science goals, advise on trade-offs in the telescope design that impact the science and to develop the instrument top level requirements. It replaces the E-ELT SWG that was put into place to follow the design phases. Once the top level requirements are in place and negotiations with the consortia that will carry out the final design and construction are complete, the contracts for the first-light instruments and AO systems are expected to be in place in the latter half of 2013. The Roadmap remains a living document that will be revised and updated on a regular basis in response to the technological, managerial and scientific developments as presented here.

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