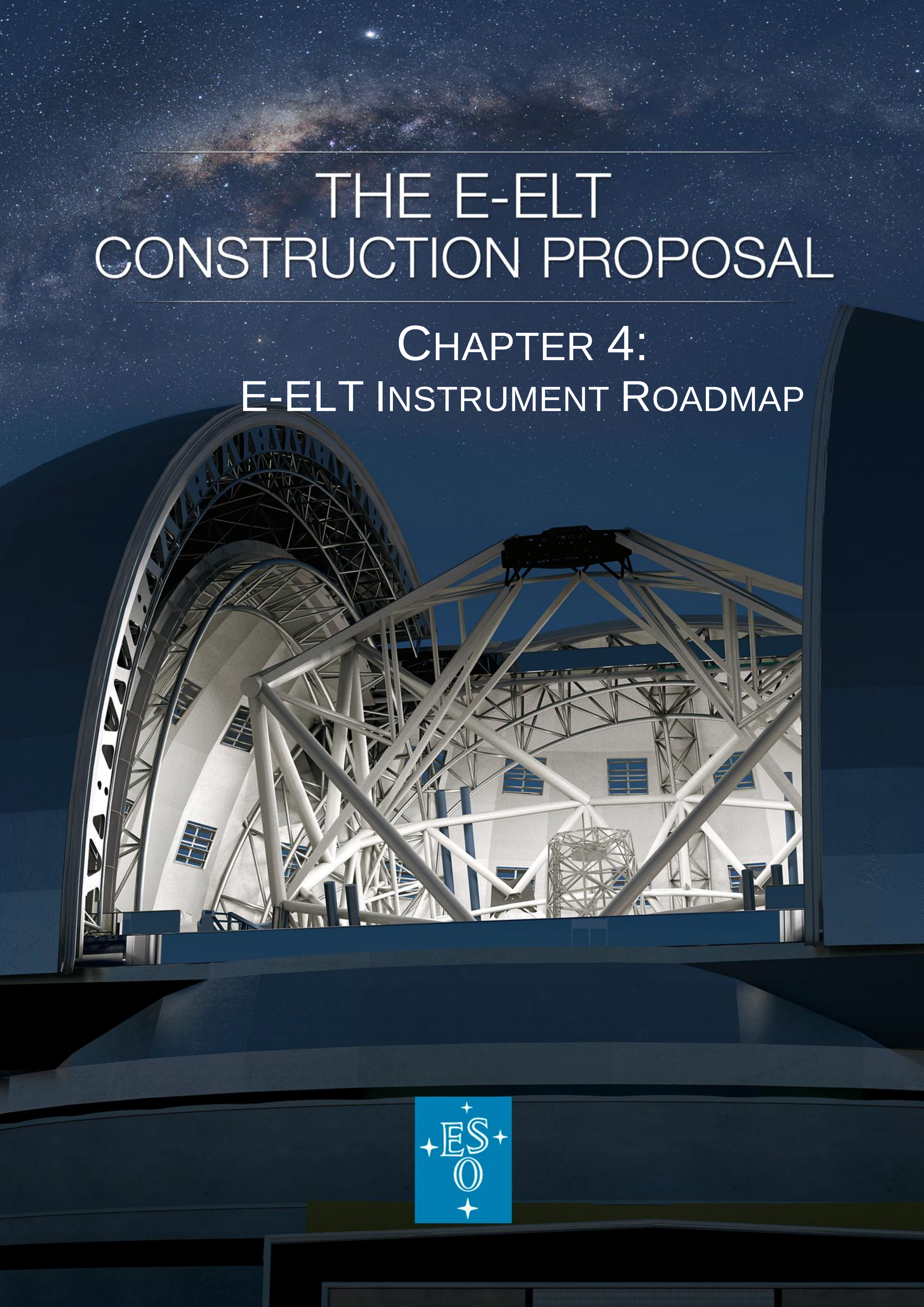
THE E-ELT CONSTRUCTION PROPOSAL

CHAPTER 4:
E-ELT INSTRUMENT ROADMAP



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1 E-ELT INSTRUMENT ROADMAP

1.1 INTRODUCTION

The first instruments developed for a new telescope are a critical component if the facility is to achieve early scientific success. Indeed the success of the VLT can be partly attributed to the early delivery of major instruments to the telescope, covering a wide wavelength range and different observing modes. ESO therefore proposes a major programme of instrumentation development in parallel with E-ELT construction to ensure that the facility will be equipped to tackle the key science cases and make major discoveries soon after commissioning. This chapter gives the background information for E-ELT instruments and presents a roadmap for their construction. A matching plan for technology development is then outlined, followed by a management plan for the procurement of the instruments. Finally an Appendix summarises the phase A studies.

The development of the E-ELT science case was accompanied from the beginning by an evolving instrument suite selected to achieve the scientific goals of the project. The merging of the Science and Instrument Working Group reports in April 2006 led to the definition of a number of phase A conceptual studies of instruments. The instrument concepts were defined so that they covered all key science cases defined for the E-ELT. The phase A studies that took place between 2007 and 2010 were then guided by the Science Working Group, and in particular by the Design Reference Mission and the Design Reference Science Plan initiative. The latter assembled nearly 200 community science cases which were subsequently mapped onto the different instrument concepts under investigation. Table 1 lists the studies with details of the consortium and duration.

In the course of 2009, the Science Working Group defined the scientific criteria by which the instruments would be assessed for suitability as first-light and subsequent instruments. Between December 2009 and March 2010, observers from the Science Working Group attended all final reviews of the phase A instrument studies to report at a meeting in April 2010.

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 study) and a wideband, integral-field spectrograph ([ELT-IFU], as presented in the HARMONI study) emerged as the clear preference of the Science Working Group in 2010. 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.

Name	PI	Phase A Institutes	Kick-off	Final Review
ATLAS	T. Fusco (ONERA)	ONERA, LESIA, GEPI, LAM, UK ATC	19/09/08	2/02/10
MAORY	E.Diolaiti (INAF OABo)	INAF OABo, OAA, OAP, Univ. Bologna, ONERA	9/11/07	10/12/09
CODEX	L.Paquini (ESO)	ESO, INAF Trieste & Brera, IAC, IoA, Cambridge, Obs. Genève	16/09/08	23/02/10
EAGLE	J.G.Cuby (LAM)	LAM, GEPI, LESIA, ONERA, UK ATC, Univ. Durham	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	24/10/07	16/03/10
HARMONI	N.Thatte (Oxford)	Univ. Oxford, CRAL, CSIC-DAMIR, IAC, UKATC, ONERA	1/04/08	28/01/10
METIS	B. Brandl (Leiden)	NOVA Leiden & ASTRON, MPIA, CEA Saclay, KU-Leuven, UK ATC	07/05/08	17/12/09
MICADO	R. Genzel (MPE)	MPE, MPIA, USM, INAF-Padova, NOVA ASTRON, Leiden, Groningen, LESIA	28/02/08	30/11/09
OPTIMOS-DIORAMAS	O. LeFèvre (LAM)	LAM, STFC RAL, INAF IASF-Milano & OATa, Obs. Genève, IAC, Obs. Haute Provence	3/11/08	30/03/10
OPTIMOS-EVE	F. Hammer (GEPI)	GEPI, NOVA ASTRON, RUN, Univ. Amsterdam, STFC RAL, INAF OATs & Brera, NBI Copenhagen	3/11/08	30/03/10
SIMPLE	L.Origlia (INAF-OABo)	INAF-OABo, Arcetri, Roma, Univ. Bologna, UU, TLS, PUC	30/10/08	04/03/10

Table 1.1. A summary of the phase A studies and the responsible consortia.

The other instruments chosen for inclusion in the Instrumentation Plan were selected to expand the parameter space coverage: extending the wavelength range, the spectral resolution coverage and the multiplex advantage. By adding high-resolution spectroscopy, wide-field multi-object spectroscopy, a mid-infrared imager and spectrograph capabilities, as well as a planet imager, nearly all of the science cases would be enabled. The relative timing and priority of these must be revised periodically in order to allow the instrumentation plan to adapt to the fast-changing scientific landscape over the next decade.

The Science Working Group also recommended the inclusion of more specific modes, such as spectro-polarimetry and high time resolution astronomy. Allowing for visitor instruments would further enable the E-ELT to react to important emerging niche science.

1.2 INSTRUMENT ROADMAP

An initial instrument plan defined in 2010 grouped all instruments beyond first light into a pool from which future selections would be made, providing flexibility against a rapidly changing scientific background. However, meetings and discussions with the instrument-building community in ESO Member States have highlighted the need for a more forward-looking plan, which gives 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 has decided to develop a *roadmap* for instrument construction that seeks 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.

1.2.1 SCIENTIFIC REQUIREMENTS FOR THE INSTRUMENTS

In the following section we outline in more detail the requirements that emerged from the phase A studies and advisory group meetings.

The diffraction-limited NIR imager, **ELT-CAM,** is based on two concepts from the Phase A studies — MAORY 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. As mitigation against the risk of late delivery of the MCAO system, it would be scientifically acceptable to deliver the instrument with an SCAO system for the first years of operation. The inclusion of a spectroscopic mode is to be further evaluated during the preparatory phase for the instruments in 2012.

The requirements for **ELT-IFU** are based on those for HARMONI. The extension of the spectral range into the optical, which was a goal for HARMONI, was strongly endorsed by the SWG. The ability for ELT-IFU to operate in seeing-limited conditions as well as at the diffraction limit is also recommended, particularly as the instrument will operate side-by-side with the diffraction-limited ELT-CAM. The high spectral resolving power (R ~ 10 000) mode is also planned for ELT-IFU, to address science cases in the field of stellar populations and galactic archaeology. The AO module for this instrument is required from the outset of science operations. HARMONI was studied as a client instrument of the LTAO system, ATLAS. This is the scientifically preferred AO mode for this instrument as there are no additional surfaces between the telescope and instrument.

The requirements for **ELT-MIR** are adopted from the METIS study without significant change from their instrument specification. Imaging and spectroscopy at the diffraction limit of the telescope 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 required. *LMN*-band operation is planned for the low-resolution spectrograph and imager, 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). Indeed, the highest Strehl ratios are predicted for on-board SCAO using the science targets as natural guide stars. For the initial ELT-MIR configuration, only the on-board SCAO mode will be implemented. However, it is clear that the ELT-MIR should be designed with operation with a full laser guide star AO system for complete sky coverage as a future upgrade, to ensure advantage over competing facilities.

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 at the VLT, MOSFIRE at Keck). The phase A studies explored the scientific possibilities of high multiplex spectroscopy over the 10-arcminute telescope field via three different studies: EAGLE— a multi-IFU spectrograph with AO-enhanced spatial resolution and spectral resolving power 5000 and 10 000; OPTIMOS–DIORAMAS — 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— 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 start to be defined from 2012 onwards.

Two high spectral resolution instruments were studied — CODEX in the optical wavelength range and SIMPLE in the NIR wavelength range. The scientific requirements of these two instruments are expected to remain as for the phase A study, with high stability and a fixed spectral format remaining as important top level goals. For an optical ELT-HIRES, based on CODEX, resolving power R > 100 000, high throughput and stability allowing radial velocity measurements in the cm/s regime are key requirements. For the NIR-HIRES, similar spectral resolving power (R > 100 000) is required to meet the science cases. An additional requirement is for high angular resolution to meet science cases such as those on the structure of protoplanetary discs or on the IMF in galaxies. Thus AO is an important scientific requirement for the NIR ELT-HIRES, which also has the technical advantage of reducing the cryostat size. The requirements for the **ELT-HIRES** capability will ultimately be selected based on one of these two concepts or a combination of both. Refinements to the scientific requirements will be evaluated as new instruments are commissioned on existing telescopes. Of particular interest are ESPRESSO (for the optical HIRES) and GIANO on the Telescopio Nazionale Galileo (for the NIR HIRES).

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. Additionally, important inputs to the instrument specification are expected following the commissioning of SPHERE on the VLT.

1.2.2 OTHER REQUIREMENTS FOR THE ROADMAP

In addition to the requirements of the previous section, a number of others emerge from both further scientific discussions with the SWG and practical considerations.

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 will be tried on-sky in 2012 in VISIR. 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. This will take most of 2012, allowing a selection of the MOS and HIRES instrument capabilities in 2013 — predominantly on scientific criteria. 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. *Instrument projects should start every two years beyond first light.*

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.

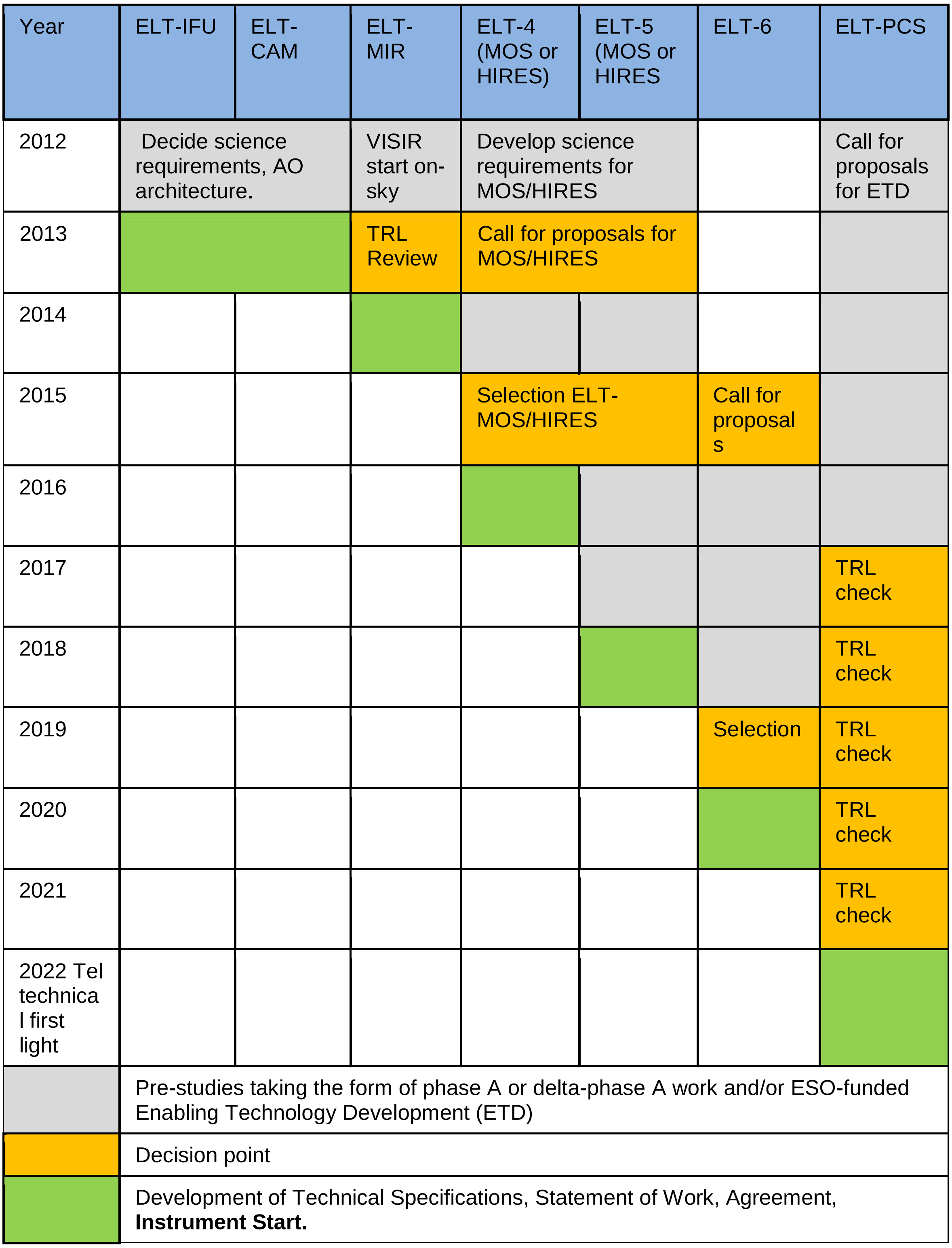
d. *Flexibility should be maintained to allow new concepts and changing scientific priorities.*

This has driven considerations from the beginning and has been stressed by both the SWG and STC in the past. 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. In addition, the precise scientific requirements for ELT-MOS and ELT-HIRES remain to be defined.

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.



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.**

Table 1.2. The E-ELT instrumentation roadmap.

Table 1.3 shows the roadmap key events year by year.

Year	Key Milestones
2012	Development of specifications and AO architecture for first-light instruments. VISIR start on-sky. Aquarius performance to be evaluated. Develop science requirements for MOS and HIRES spectrometer. Commence technology development for ELT-PCS.
2013	ELT-MIR is reviewed for technology-readiness. Key areas are (1) performance of the Aquarius detector and (2) development of sky-chopping. A decision is made regarding the scientific capabilities required for a MOS, and for a HIRES spectrograph. A call for proposals is then issued based on these requirements. Further delta-phase A design is then carried out and enabling technology development initiated. First-light instruments (ELT-IFU,ELT-CAM) start.
2014	ELT-MIR project starts, subject to 2013 review. Ongoing ELT-MOS and ELT-HIRES studies.
2015	The allocation of ELT-MOS and ELT-HIRES as ELT-4 or ELT-5 is made based on technical readiness. A call for proposals is made for ELT-6. Responses may include reworked designs that were not previously selected, or entirely new instrument concepts. A subset will be selected and funded as further phase A studies.
2016	Start ELT-4. Continue technology development of ELT-5.
2017	Possible start date for ELT-PCS.
2018	Start ELT-5.
2019	An instrument will be selected from completed phase A studies as ELT-6.
2020	Start ELT-6.
2021	Six instruments under construction at this point.
2022	Latest envisioned start for ELT-PCS.

Table 1.3. The key roadmap events.

1.2.3 INSTRUMENT DELIVERY SCHEDULE

The following table shows the instrument commissioning dates. These are selected to have spaced delivery dates and construction periods of approximately eight years. These dates will become contracted delivery dates with consortia and projects will be structured to meet the delivery schedules.

	ELT-IFU	ELT-CAM	ELT-MIR	ELT-4	ELT-5	ELT-6	ELT-PCS
Commissioning	2022	2022	2023	2024	2026	2028	2025–30

Table 1.4. Commissioning.

The current schedule of deliveries will, depending on whether a coudé instrument is selected, fill all available Nasmyth ports. However, this will not be until 2028–30. A visitor port will therefore be available for at least the first six to eight years of telescope operation.

1.2.4 INSTRUMENT DEPLOYMENT ON TELESCOPE

Figure 1.1 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).

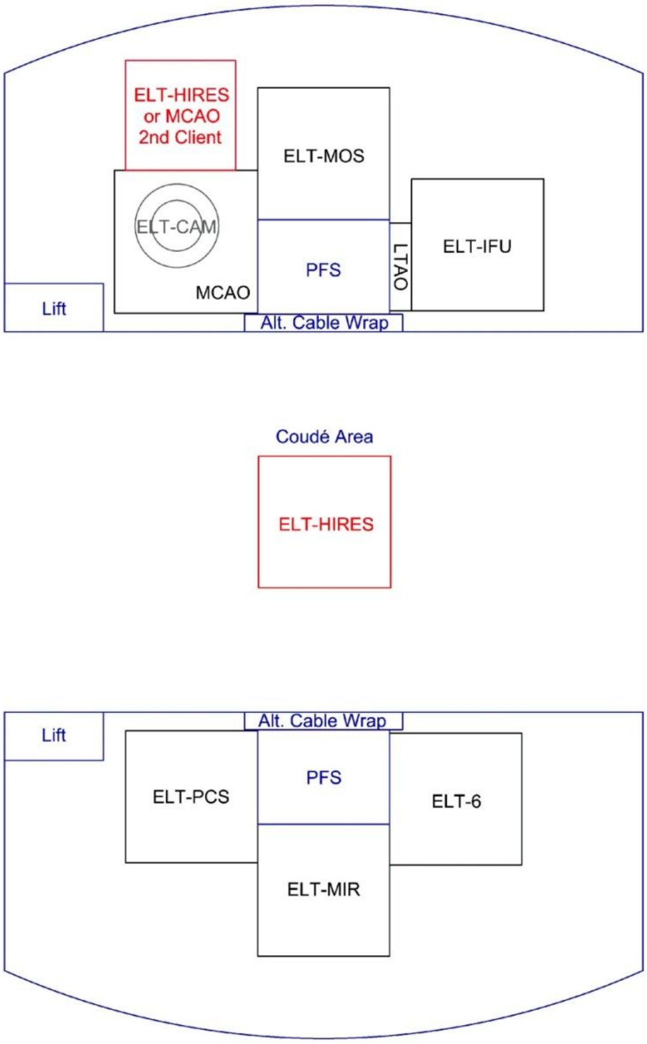


Figure 1.1. A possible arrangement for the instruments on the Nasmyth platforms and coudé area.

The ELT-IFU is shown in the figure being fed by an LTAO module. As already discussed, 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 (FoV) 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 a signature in polarimetric observations. If located at a lateral port, a polarimetric calibration unit may be needed for ELT-PCS at the intermediate focus of the telescope.

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 1.1.

1.2.5 ENABLING TECHNOLOGY DEVELOPMENT ROADMAP

The Instrument roadmap is supported by a parallel Enabling Technology Development Roadmap that is designed to support the instrument selection process outlined above. As the Instrument Roadmap evolves, the ETD Roadmap will evolve to match the new requirements.

The main input to the ETD roadmap comes from the results of the phase A studies. The final reports of the studies identify the important R&D project areas for each instrument concept. Naturally, the R&D requirements of the instruments proposed range between those with significant development programmes critical for construction of a successful instrument, to those requiring only minor developments of non-critical, performance-enhancing components.

The ETD roadmap will be subject to frequent, possibly major, revision during the course of the instrument construction due to the changing scientific priority of various capabilities/instruments, the speed of development of key technologies and the possible introduction of new “disruptive” technologies that revolutionise instrument development. Thus the list below summarises our understanding today of the development needs of the instrument suite and is subject to future review.

While remaining flexible and responsive, the principal consideration for the ETD roadmap is that it must support the Instrument roadmap by ensuring that any novel component reaches a Technology Readiness Level* that allows instrument selection and construction to proceed with manageable risks to performance and schedule. This level has typically been TRL 3 for VLT instrumentation and will also be the basis for the E-ELT. Development of technologies to TRL level > 5 is expected during the project. The way in which this goal is achieved is determined by the category of development, according to the following scheme:

Category	Description
A	Components of TRL ≥ 3 where the scope of the work is such that the developments can be carried out within the project. These developments and the resources required to deliver them are identified in the management plan for the construction phase of the project. Funding for this is included within the instrument construction cost.
B	Components of TRL < 3 with short development timescales. These developments and the resources required to deliver them to TRL-3 are to be identified by instrument teams in their responses to the Call for Proposals for the phase A or delta-phase A study. Funding is allocated from the enabling technologies work package on a case-by-case basis as part of the contract negotiations for the (delta-)phase A study.
C	Components of TRL < 3 with long development timescales that are critical to an instrument concept and must be completed before instrument selection. Funding is allocated from the enabling technologies work package after a Call for Proposals for ETD, or award of a Single Source contract if appropriate. Where there is no highly performing fall-back option for a given technology, a higher TRL may be required. The key example of this is the MIR detectors for ELT-MIR. Also included in this category are common developments that will be exploited by more than one instrument.

Table 1.5. Description of components per category of development.

In addition to the funding planned by ESO within the Instrument budget, ESO will provide guidance and support when possible to the national or International initiatives bringing additional resources to the E-ELT R&D and Enabling Technology Programmes.

Key technologies relating to the instruments on the Instrument roadmap are listed in the tables below, Category A developments in Table 1.6 and Category B and C in Table 1.7.

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* ESO TRLs are similar to the NASA scale and run from 1 to 9 with TRL 1 being just a basic concept through to TRL 9 being fully proven through real deployed systems. At TRL 3 a proof of concept has been demonstrated through analytical and/or experimental work.

Technology	Instrument
Novel focal plane WFS	LTAO
Demonstration of pseudo open loop control	LTAO/MCAO/ELT-MOS
Real time Cn2 profile monitoring	LTAO/MCAO
Slanted Volume Phased Holographic (VPH) gratings	ELT-HIRES
Laser frequency comb (optical and NIR)	ELT-HIRES
Fibre scrambling	ELT-HIRES
High stability cryostat	ELT-HIRES
NIR VPH	ELT-MOS, ELT-IFU
Novel roof-pyramid WFS	ELT-PCS
Testing Fresnel and chromatic effects in an optical system	ELT-PCS
Improved deconvolution algorithms	ELT-PCS
Polarimetric error budget, verified by test	ELT-PCS

Table 1.6. Category A developments as identified from the phase A concept studies.

For the Category B and C developments, milestones by which these are required for the resource planning for the E-ELT Instrumentation are listed. Category A developments are under the control of the instrument projects and the milestones will be determined within the project. Category B and C developments will be supported in part or in full from the enabling technologies work package.

With the exception of the long-term development of the 4k x 4k science detectors, the two first-light science instruments (ELT-IFU, ELT-CAM) require marginal amounts of R&D and those required will be incorporated into the normal project phases. Common technology developments are required for the AO modules.

ELT-MIR has one long-term development requirement, which is now coming to fruition through the development of the Aquarius detectors for VISIR. Selection of the instrument depends upon the success of this project. Within the instrument project, understanding the ultimate sensitivity reached with this instrument will depend upon further demonstration of the technique of on-instrument chopping to be carried out during the instrument developments.

The majority of the technical developments outlined in the studies of the five ELT-HIRES and ELT-MOS instrument concepts shall be carried out within the instrument construction phases or a delta-phase A for the instruments. The exceptions are the developments required to support the Multi-Object Adaptive Optics (MOAO) system planned for the NIR ELT-MOS. These are longer-term developments that will be the subject of a separate Call for Proposals.

Finally, ELT-PCS has a substantial, long-term R&D programme required to develop this ambitious instrument to TRL 3 before official start. The pre-construction phase for this instrument is estimated (based on the EPICS study and the development timescales for SPHERE) to be three to four years.

Technology	Category	Instrument	Required by Milestone	Notes
LGS WFS detectors	C	MCAO, LTAO, ELT-PCS, ELT-MOS	MCAO/LTAO FDR	Development of fast read-out, low-noise detectors, 1680 x 1680 pixels
Real-time computer	C	MCAO/LTAO ELT-PCS, ELT-MOS	MCAO/LTAO FDR	Computing power, of order of 300 GMAC/s
Deformable Mirror (DM) developments	C	MCAO	MCAO FDR	~ 400 mm diameter, ~ 50 × 50 actuators and the pitch of ~ 8 µm
Detector stability	C	ELT-HIRES	ELT-HIRES FDR	Important for the optical HIRES
84 x 84 actuator DM with 6 µm stroke	C	ELT-MOS	ELT-HIRES FDR	Based on EAGLE requirements
XAO-DM and control electronics	C	ELT-PCS	ELT-PCS start	Development of DM to ELT-PCS spec — high actuator density
WFS camera	C	ELT-PCS	ELT-PCS start	increase in speed of the existing hardware (by a factor ~ 2) and introduction of the deep-depleted CCDs for better red sensitivity
Speckle nulling study	B	ELT-PCS	ELT-PCS start	Required to understand the contrast reached by ELT-PCS
Optical de-rotation of the Integral Field Spectrograph (IFS) without introducing Fresnel effects	B	ELT-PCS	ELT-PCS start	Required to increase the performance of ELT-PCS
Aquarius detector	C	ELT-MIR	ELT-3 selection	VISIR on-sky tests
4k x 4k science detectors	C	ELT-CAM/ELT-IFU	PDR of ELT-IFU and ELT-CAM	At quite advanced TRL, funds for testing within ESO planned
Robotic filter/grating exchange	B	ELT-MOS	Selection of ELT-4	Important for the current optical slit mask ELT-MOS concept.
Small diameter (< 100 µm) fibres for high resolving power	B	ELT-MOS	Selection of ELT-4	Important for the current fibre-optical MOS concept

Table 1.7. Category B and C developments as identified from the phase A concept studies.

1.3 INSTRUMENT MANAGEMENT PLAN

1.3.1 INSTRUMENT PROCUREMENT

ESO will manage the E-ELT instrument procurement on behalf of its community and will maintain in-house the technical and management capabilities required to carry out this function. For the VLT, ESO developed and provided standard components (electronics, software and cryogenics) and detector systems, as well as undertaking responsibility for oversight of the external contracts. This model is followed for the E-ELT instrument contracts.

External instrument consortia will receive a Guaranteed Time Observing allocation (GTO) to compensate them for both contributed staff effort and any cash contribution to the projects. One change from the VLT process is that GTO compensation for staff effort will be specified at the time of the Call for Proposals and will not normally be negotiable. Cash contributions from consortia towards procurements will be compensated using a standard formula.

It is expected that the E-ELT instruments will be sufficiently complex, costly and demanding of staff resources so that no single institute, including ESO, will be able to handle their successful construction alone. Therefore the normal project organisation is envisioned to be as follows:

- A consortium will be selected for construction based on either competitive tendering or single-source procurement;
- The instrument project will be defined via an agreement between ESO and the consortium, and by technical specifications and a Statement of Work;
- Project work packages will be distributed amongst a consortium of Institutes in the Member States and ESO, with responsibilities defined in a Memorandum of Understanding (MOU);
- A PI for each instrument will be defined;
- A lead technical institute for the project will be specified. This lead institute will be responsible for top-level project management, system engineering and the Assembly and Integration Team and will have a demonstrated track record in successfully delivering VLT-class instrumentation;
- ESO will have an oversight role via regular progress reviews and major milestone reviews, and will act as the customer.

Instrument	Procurement Plan
ELT-CAM	As first-light instruments, and considering their necessary integration with adaptive optics, discussions regarding instrument-architecture and specifications must be started in 2012. Due to the revised telescope design and depending on the AO approach adopted, some Phase A design may also need to be repeated. ESO will therefore plan to contract instrument construction with the existing MICADO and HARMONI consortia, subject to successful negotiation.
ELT-IFU	
ELT-PCS	Competitive tendering for enabling technology development and instrument construction will be applied.
ELT-MIR	Provided technology readiness can be demonstrated in 2013, a mid-IR imager/spectrometer will be delivered as ELT-3. Since the METIS consortium contains most member-state institutes with mid-IR instrument experience (it is essentially the JWST-MIRI team) ESO will plan to contract directly with that consortium.
ELT-4	Competitive tendering for enabling technology development and instrument construction will be applied.
ELT-5	Competitive tendering for enabling technology development and instrument construction will be applied.
ELT-6	Competitive tendering for enabling technology development and instrument construction will be applied.

Table 1.8. Procurement plan for each instrument.

For instruments built by external consortia, it will be essential that consortium leadership in the project brings adequately demonstrated expertise in project management, product assurance, system engineering and AIT facilities. The organisation of responsibility and allocation of work packages within consortia will be the first step in reaching an agreement for instrument construction. Should agreement not be reached, ESO reserves the right to award the instrument construction to another consortium, or to re-tender.

The basis for E-ELT instrument procurement will be to adopt a competitive approach whenever reasonable. Proposals will then be solicited for the design and construction of an instrument defined in a set of Technical Specifications and a Statement of Work. A basic procurement principle is that all competing instrument proposals should be at a similar level of design before a selection is made. This may require extra studies to be carried out (and hence extra time).

In the case of instruments where a single consortium may contain most, if not all, of the relevant expertise in Europe, ESO will negotiate a contract directly with the consortium. This may also apply in the case where the required instrument schedule does not allow for an extended period of competitive tendering, such as the first-light instruments.

Based on these principles, ESO plans to implement the procurement strategy given in Table 1.8 for the instruments currently indicated in the roadmap.

ESO may lead a selected project when the instrument characteristics specifically match ESO in-house expertise, and when internal effort is available. This will be done within a consortium, with external institutes responsible for subsystems, and competitive tendering will be used to select these. Any decision for ESO to lead an instrument project will be taken by the Director General.

1.3.2 ORGANISATION OF ESO INSTRUMENT MANAGEMENT

The construction of instrumentation for the E-ELT will be managed by the ESO Instrumentation Division as a major work package within the E-ELT construction project. As such, the Instrumentation Division will participate fully in the E-ELT project work and be under the authority of the E-ELT project management team and project governance.

The E-ELT instrumentation work itself breaks down to the following work packages and work package managers for the construction phase.

Work Package	ESO Manager	Task
ELT instrument programme management	M.Casali	Management of programme
Preparatory work		
Instrument specification development	S.Ramsay	Development of initial instrument specifications prior to consortium selection.
Instrument enabling technologies	H.U. Käufl	Development of technologies critical for future instruments, prior to instrument consortium selection.
Instrument infrastructure	J.C.Gonzalez	Development of infrastructure required for instrumentation including cryogenic system and interfaces.
Instrument standards and standard subsystems	M.Casali	Review and definition of instrumentation standards
Instrument Construction		
Instrument 1 contract	Not yet allocated	Management of external construction contract
Instrument 1 ESO deliverables	Not yet allocated	Management of ESO internal deliverables
Instrument 2 contract	Not yet allocated	Management of external construction contract
Instrument 2 ESO deliverables	Not yet allocated	Management of ESO internal deliverables
Instrument 3 contract *	Not yet allocated	Management of external construction contract
Instrument 3 ESO deliverables *	Not yet allocated	Management of ESO internal deliverables
Instrument 4 contract *	Not yet allocated	Management of external construction contract
Instrument 4 ESO deliverables *	Not yet allocated	Management of ESO internal deliverables

Table 1.9. Instrumentation work packages and managers for the construction phase.

** Contract and ESO deliverables work package pairs continue in this pattern for future instruments.*

1.3.3 PRODUCT ASSURANCE AND SUCCESSFUL DELIVERY OF INSTRUMENTATION

The E-ELT will be the largest and most expensive optical–IR facility for ground-based astronomy ever built. Observing time will be highly competitive and highly valued. It is therefore important that new and higher levels of reliable performance and low downtime are achieved for the instruments. For this reason, lessons learned over the period of VLT instrument construction must be reviewed and used to devise best practice guidelines to be applied to E-ELT instrument construction.

A framework for product and quality assurance for the E-ELT is given by E-MAN-ESO-156-0139 issue 5 and this forms the basis for ESO interactions with industry; this will be partially applicable to instrument projects. However, the construction of instruments with consortia of Member State institutes also presents additional problems and advantages and to this end we will apply best practice based on lessons learned over the last ten years of instrument construction for the VLT/I. A particularly critical phase occurs in the project start-up period when the work breakdown structure is developed, work packages are allocated to institutes and the scientific and technical leadership team is defined. An experienced ESO Product Assurance (PA) team will be set up to work with the consortia in this phase. Both parties must be satisfied with the final project structure in order to proceed to a construction contract.

ESO will also be responsive to comments and suggestions from the community regarding improvements that should be made to ESO instrument construction working practices. Meetings will be arranged with senior managers from experienced institutes, in order to uncover areas of difficulty for the community and to generally improve internal ESO processes.

1.3.4 MILESTONES AND REVIEWS

Major project phases and review milestones will be explicitly indicated in the instrument agreements with consortia, and will be specified in each Statement of Work. The purpose of major reviews is to examine progress, recommend changes and advise on continuation of the instrument project to the next phase. Major review milestones will also be major payment milestones for consortia. In addition, in order to smooth cashflow, payments will also be made at other times based on agreed deliverables.

1.3.5 ESO AS CUSTOMER AND MEMBER OF A CONSORTIUM

ESO will take the role of active customer in all instrument projects. This means, in addition to the usual roles of monitoring progress and organising major milestone reviews, ESO will also keep a strong technical and managerial oversight team to comment in detail on design choices, interface requirements, and conformance with observatory standards. This approach has been developed following experience with the VLT instrument programme where it has become the standard model, welcomed by both ESO and instrument consortia. The effort for this managerial and technical oversight has been included in ESO instrument FTE (Full-Time Equivalent) planning.

It is expected that in many instrument projects ESO will also be responsible for delivering certain subsystems, especially detectors and controllers. In these cases it is important that the relationship with the consortium is clear and follows good project management practice. ESO will therefore be a signatory to the consortium memorandum of understanding as an associate partner, and will participate in the project in the same way as any other institute — with a work package and deliverables, though without any GTO compensation. Tasks will include providing reports to the consortium project management, attending progress reviews and other work normally associated with a work package. Internally, ESO will keep work packages associated with this task separate from those of ESO as customer, and the two will be managed by different members of staff.

1.3.6 INSTRUMENT COSTS

100 M€ are available within the construction budget for the E-ELT for the capital costs of instrumentation and related subsystems including enabling technologies, and the staff costs at ESO. Community effort for instrument construction will be compensated by Guaranteed Time and is not accounted for in the instrumentation budget. The budget plan is based on the roadmap (Table 1.2). ELT-IFU and ELT-CAM are proposed as the first-light instruments and their costs are included within the plan along with the costs for the adaptive optics systems required to deliver the science cases for these instruments.

The estimated costs for individual instruments are based on those provided by the study consortia in the deliverable phase A documents describing the development and management plan. In preparing the E-ELT instrumentation plan, ESO has considered these predicted costs in the light of the expected technical changes during the development of specifications in 2012. The instrument costs include 20% contingency unless the phase A consortium suggested a higher contingency, in which case the higher figure is used. Research and development costs for individual instruments are included within the instrument work packages once the instruments are selected. Preparatory enabling technology developments, required before an instrument can be selected, are costed as a separate job, and will be funded and managed by ESO. They will be subject to revision as part of the process of reassessing the instrument requirements and further developing a detailed enabling technology plan.

The cost of the first four instruments in the roadmap will be accounted within the E-ELT construction proposal. Subsequent instruments will be resourced from Operations. This separation is purely for accounting purposes and there will not be any breaks or delays in the roadmap corresponding to this changeover, as shown in (Table 1.2).

The ESO experience with VLT first and second generation instruments is that large cost overruns (> 10%) for ESO have been rare. This is partly because ESO is protected against external staff effort overspends by the nature of our agreements with consortia. The agreements do not automatically compensate funding agencies in Member States if total staff effort used exceeds initial estimates. The funding of excess staff effort is therefore a problem that must in general be dealt with by the consortia and the funding agencies themselves. On the other hand, an excess in procurement spend does generally produce further financial support from ESO. This split in responsibility for overspends helps to spread the risk across all the stakeholders and partners.

1.3.7 EFFORT IN THE COMMUNITY AND AT ESO

The construction of the instrumentation for the E-ELT will overlap with a continuing and robust programme of instrumentation development for the La Silla Paranal Observatory (LPO). It is reasonable to ask therefore whether this would place undue strain on staff resources in Member State institutes. Figure 1.2shows an effort model based on a plausible instrumentation plan for LPO, and the Instrument roadmap for E-ELT including technology development. It shows a reasonably constant effort profile with time. In fact in the years 2013–2017 the effort used should decrease slightly as second generation VLT instruments complete and E-ELT instruments are starting up. A significant factor is that although the total ESO spend on all instrumentation (VLT/I + E-ELT) will increase during E-ELT construction, a much greater fraction of the total E-ELT instrument cost is expected to go to industrial procurements rather than as staff effort in universities and institutes.

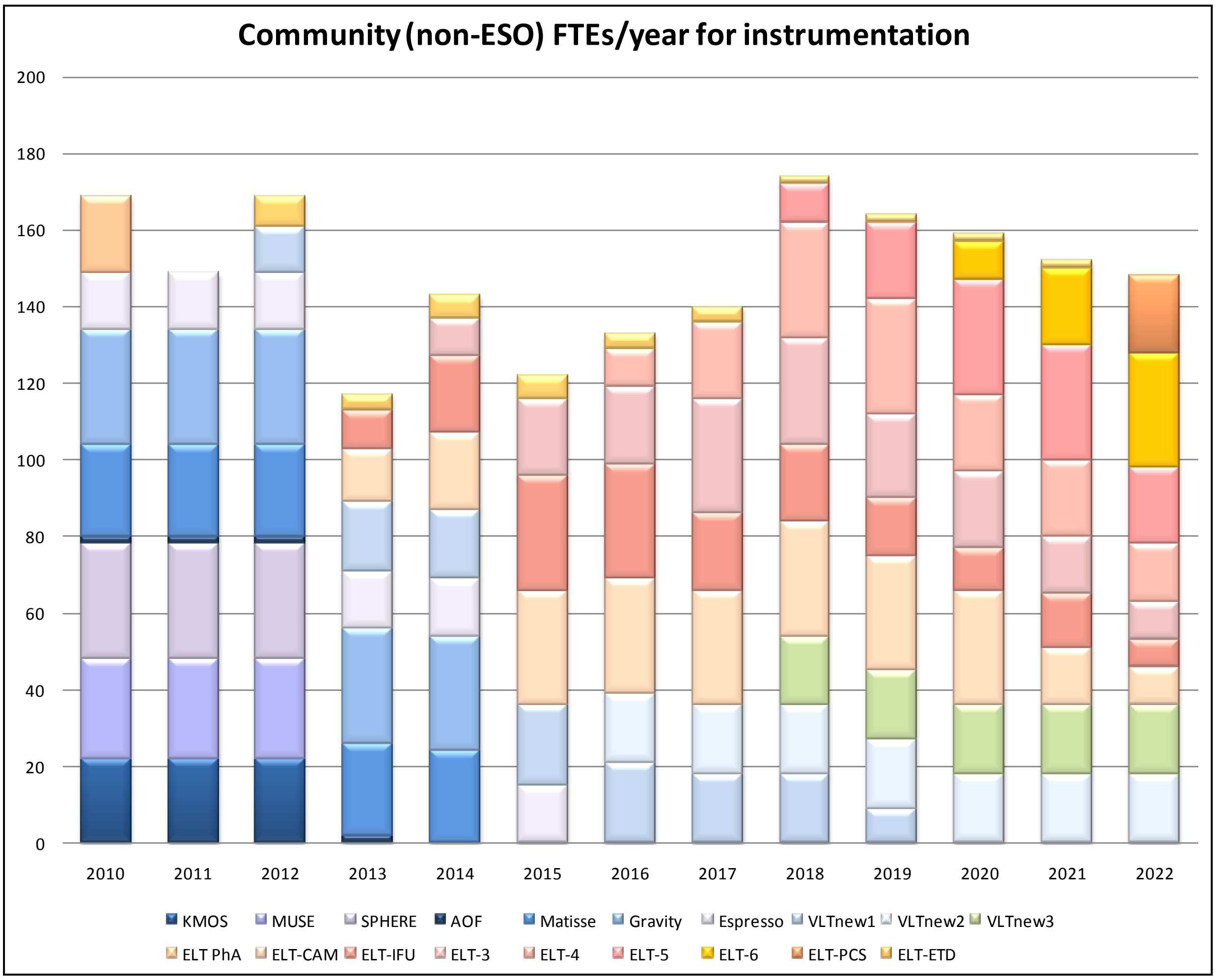

Figure 1.2. Community effort model.

ESO *internal* effort planning has also been done for the period 2012–22 and encompasses both the E-ELT instrumentation roadmap as presented here and a strong continuing LPO programme. Some difficulties with staffing occur in the years 2014–15, but overall the programme can be executed with existing Instrumentation Division and Directorate of Engineering staff. An important tool for ESO in managing the instrument programme is the ability to vary the mix of internal-ESO/external-consortium/external-industry work. If ESO is very stretched for effort we are able to outsource more. This has a cost impact of course in either GTO or cash, but does provide some flexibility to ensure progress during difficult periods.

1.4 APPENDIX: PHASE A STUDIES OF INSTRUMENTS AND AO MODULES

1.4.1 A.1 INTRODUCTION

The phase A instrument studies were carried out with consortia of ESO and external institutes with the goal of addressing the observing capabilities of highest scientific priority for the telescope. The final reports included the most important science cases for which the instruments would be used, the technical concept for the instrument, the expected performance, cost, FTE effort and a construction schedule.

The studies are described briefly in the sections that follow. The post-focal AO modules are described first followed by the instrument studies in the order reviewed.

1.4.2 A.2 THE ATLAS POST FOCAL LASER TOMOGRAPHY AO MODULE STUDY

ATLAS is a LTAO system providing atmospheric turbulence correction on a 30-inch diameter FoV in the wavelength range of the telescope. It complements the telescope GLAO by higher-order AO correction, giving a diffraction-limited Point Spread Function (PSF) down to the *H*-band, and offers great improvements in sky coverage over SCAO. The science FoV is free from any ATLAS optics making it particularly suited to instruments that prioritise high throughput or low emissivity over correction of a large field of view.

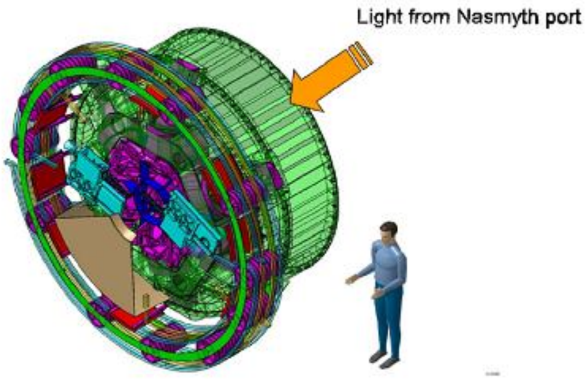

Figure 1.3. The ATLAS post-focal laser tomography AO module.

In the initial concept, ATLAS is a facility that may be duplicated for different Nasmyth ports in order to feed different “client” instruments. In the phase A study, the performance of ATLAS was considered to provide the following instruments with an AO-corrected beam: HARMONI, METIS and SIMPLE. The wavefront correction is made using the telescope adaptive mirror M4 and the wavefront sensing is assured by six laser guide star visible WFS and two natural guide stars infrared WFS. The six LGSs, mounted at a 4.3-arcminute diameter, 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 42-metre telescope. The two NGS WFS are required to measure the low-order mode perturbations not sensed by the LGSs. To maximise the sky coverage to close to 100%, the two IR NGS arms are equipped with 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 correct telescope windshake and low order modes. ATLAS is mounted on the telescope instrument rotator, has a cylindrical volume of 4000 mm x 1000 mm and weighs 1.5 tonnes.

Performance	SC (pole)
52 % SR in K	92 %
40 % SR in K	96%
35 % SR in K	97%
13 % SR in K	100 %

Lambda	900	1250	1650	2200	4800	10 500
EE in 10 mas	10.3	21.1	26.1	26.4	13.7	3.9
EE in 20 mas	15.1	32.1	42.5	48.5	37	14.3
EE in 40 mas	18.2	37.8	53.6	63.8	61.0	35.1
EE in 60 mas	22.4	40.5	56.3	67.8	69.1	54.2
EE in 80 mas	23.2	42.4	58.2	70.2	80.1	63.8
EE in 100 mas	25.6	44.8	59.5	71.7	84.6	67.5
Strehl ratio	5.5	18.8	35.3	52.7	90.5	96.9

Table 1.10. ATLAS sky coverage versus Strehl Ratio (SR) in K*-band (left) and Ensquared Energy (EE) versus wavelength (right).*

1.4.3 A.3 THE MAORY POST-FOCAL MULTI CONJUGATE AO MODULE STUDY

MAORY is a MCAO module providing three-dimensional atmospheric turbulence correction over a 2-arcminute diameter FoV in the wavelength range 0.8–2.4 µm. The correction is implemented by means of three deformable mirrors optically conjugated at different altitudes in the atmosphere. One of the three is the telescope M4, conjugated to the ground layer; the other two deformable mirrors are located in the MAORY instrument and conjugated to 4 km and 12.7 km. The wavefront sensing is assured by six LGS WFS and three NGS infrared WFS. The important properties of the delivered optical beam are near-diffraction-limited correction and a consistent PSF delivered over a substantially wider field of view than with LTAO or SCAO techniques. For the phase A study, a design for MAORY was explored in which the corrected beam could be directed to one of two output ports and so could supply two science instruments. The beam relayed by MAORY has the same focal ratio and exit pupil position as the beam from the telescope.

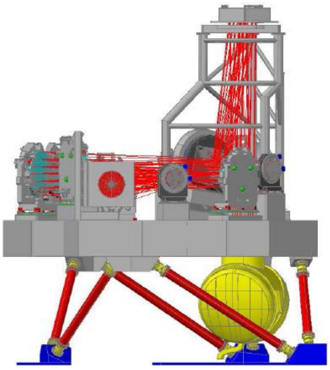

Figure 1.4. The MAORY post-focal multi-conjugate AO module.

The mechanical layout above shows that the red beam is directed from the optics tower into an upward looking instrument. An instrument of up to 5 tonnes can be mounted on the rotator provided by MAORY in this gravity invariant location. The second port would feed a free-standing instrument with higher mass limits. In the phase A study, the performance of MAORY was considered for two client instruments — MICADO and SIMPLE. An important driver on the MAORY design is the science requirement from MICADO for astrometric accuracy of 50–100 mas, which was demonstrated to be met. The volume of the instrument is L x W x H = 7400 mm x 7200 mm x 8000 mm and it weighs 12.7 tons. The review of the phase A design concluded that there were possibilities for some simplification of the optical design. Reducing to one, rather than two, optical relays is thought feasible and would reduce the number and size of large optical components and therefore the cost and risk of the module. The evaluation of the performance when including only a single DM will also be revisited during the specification development phase. Finally, if the spectroscopic mode were to be included in the camera, the scientific impact on sensitivity of the warm AO system would have to be evaluated, traded against the technical impact of cooling this large system.

Minimum Strehl ratio averaged over MICADO field of view (53 arcseconds × 53 arcseconds)			Sky Coverage
λ=2.16 µm	λ=1.215 µm	λ=0.9 µm	
0.54	0.14	0.03	39%
0.52	0.13	0.03	50%
0.50	0.11	0.02	60%
0.48	0.09	<0.01	70%
0.42	0.06	<0.01	80%

Table 1.11.Sky coverage vs. *performance at the Galactic pole for seeing of 0.8-arcsecond FWHM (Full Width at Half Maximum).*

Ensquared Energy 50 mas × 50 mas					
FoV position (arcseconds)	λ=2.16 µm	λ=1.65 µm	λ=1.215 µm	λ=1.021 µm	λ=0.9 µm
0	0.53	0.37	0.19	0.12	0.10
30	0.49	0.33	0.15	0.10	0.08
60	0.41	0.24	0.10	0.07	0.07

Table 1.12. Ensquared energy in an square aperture of 50 mas x 50 mas averaged at three radial distances from the centre of the field for seeing = 0.8-arcsecond FWHM.

1.4.4 A.4 The CODEX Instrument Study

CODEX is a high stability, high resolution (*R* ~ 130 000) optical spectrograph optimised for the wavelength range (0.37 µm–0.71 µm) which has the goal of achieving a Doppler precision of 2 cms^{-1} over a 30-year timescale to meet the science goals of the instrument. The CODEX science team developed in detail the case for a direct measurement of the accelerating expansion of the Universe, and the instrument was designed to explicitly address this top science case for the E-ELT. By the same token (ultra-stable radial velocity measurements), Earth twins in the habitable zone around solar-type stars become detectable, demonstrating that the E-ELT will, in several respects, address exquisitely this hottest of science fields. Both cases figured prominently amongst the DRM cases. An additional case showed that the E-ELT, equipped with a high-resolution spectrograph, would enable a significant advance in the field of nucleochronometry, i.e., galactic archaeology. The fourth showcase of the team was the exploration of the intergalactic medium. By analysing the line-of-sight towards distant quasars, intervening absorption systems can be analysed and not only the structure, but also the element enrichment of the Universe understood out to the earliest epochs. Last but not least, the CODEX science proposed to test fundamental physics by taking the test of the stability of fundamental constants to new limits: a precise measurements of atomic transitions back 90% of the age of the Universe allows a precise test of whether our physical laws have varied, even only slightly, since early times, opening a whole new perspective in physics.

The CODEX design draws heavily 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 natural location for the instrument is in the coudé room of the E-ELT where it will be housed in a temperature stable environment. It is a single object spectrometer (0.82-arcsecond aperture) requiring no adaptive optics, although image stabilisation in the coudé train may be necessary to maintain the required image quality. A laser frequency comb will provide stable, simultaneous wavelength calibration over long timescales. The input to the spectrograph is a single large fibre for the object and a second for the calibration source or sky. A highly anamorphic pupil (x 12) is formed and sliced into six slices which are fed into the spectrograph by a three-mirror anastigmat used in double-pass. The echelle grating is based on that in UVES and is a mosaic of four 408 mm x 200 mm 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. Cross-dispersion is achieved using slanted VPH gratings that are being tested in prototype. The resulting spectrum has *R* ~ 120 000 with four-pixel sampling, an order height of ≥ 170 pixels and separation of ≥ 30 pixels. The focal plane will have 9k x 9k 10 μm pixels.

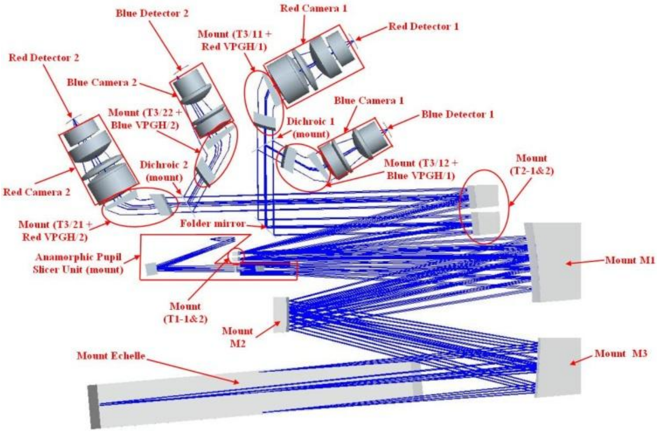

Figure 1.5. The optomechanical concept of the CODEX spectrograph.

1.4.5 A.5 THE EAGLE INSTRUMENT STUDY

EAGLE is a multi-IFU spectrometer for the NIR wavelength range that uses an on-instrument MOAO system. The EAGLE science case focuses on the study of high-redshift galaxies. Such an instrument on the E-ELT will enable surveys of the earliest (and rapidly growing) galaxies. The goal is to exploit the spatial resolution of the E-ELT to understand the star formation history during the epoch of growth of structure and assembly of galaxies. Pushing the E-ELT to its limit, EAGLE would enable the spectra of the very first galaxies to be obtained at redshifts 8–10, close to the epoch of reionisation of the Universe and providing unprecedented insight into this epoch. Integral-field spectroscopy of galaxies with active galactic nuclei will be possible from nearby to significant lookback times and will allow us to better understand the link between the growth of the central massive black hole and the bulge of the galaxy. Closer to us, it will be possible to obtain spectra of individual stars in nearby galaxies, for the first time beyond the Local Group of galaxies, allowing both detailed chemical and kinematic studies, critical for the understanding of galaxy evolution. EAGLE would also be able to address some of the most prominent questions in our own Galaxy. It would allow a detailed study of the gas and stars in the inner parsec of the supermassive black hole at the centre of the Milky Way, helping to uncover its formation and growth history as well as providing new insights into star formation in the very inner regions of the Galaxy.

Key to the scientific performance of EAGLE is the MOAO system that delivers the required image quality in the direction of the sources to be observed by sensing and reconstructing the atmosphere above the telescope using 6 LGS WFS and 5–6 NGS WFS. The correction required at the field position of the object to be observed is calculated and the correction for the atmosphere is applied by a combination of the telescope M4 and the 84 x 84 actuator deformable mirrors in the optical path to the spectrometers. The selection of this AO concept was tied closely to the science case for the instrument. EAGLE MOAO achieves a sky coverage above 80% for *R* < 17 stars and delivers moderately high encircled energy in pixels suited to the size scales of the high-redshift EAGLE targets (requirement: > 30% EE in 75 mas). EAGLE was studied for the preferred location at the *f*/18.85 Gravity Invariant Focus (GIF) of the telescope. To meet the science requirement on field size, the full 10-arcminute field of the telescope is directed to the GIF by a large M6. A consequence of this is that the pre-focal station guide probes are vignetted by M6 and so EAGLE must reproduce the signals required to control M4 and M5 with the instrument wavefront sensors. This functionality is designed into the EAGLE adaptive optics system. The selection of the clustered objects is via pick-off mirrors that are placed robotically in the focal plane. The light from each of the 16–20 sources is then directed towards the spectrograph via an optical system for path difference compensation (due to field position) and a deformable mirror controlled by the MOAO system. The beams from two targets are combined in one glass image-slicing IFU. In total, there are 8-10 spectrometers based on VPH gratings, each with a 4k x 4k detector array, providing low (*R* ~ 4000) and high (*R* ~ 10 000) spectral resolving power. EAGLE is partly cryogenic — the pick-off and AO systems are at room temperature, whereas the spectrographs are cooled with liquid nitrogen to 190 K. For a future instrument based on the EAGLE concept, substantial revision of the design and significant prototyping are required. Removal of the gravity invariant focus means that a delta-phase A study will be needed to find a new concept for delivering the EAGLE science case and performance on the Nasmyth platform.

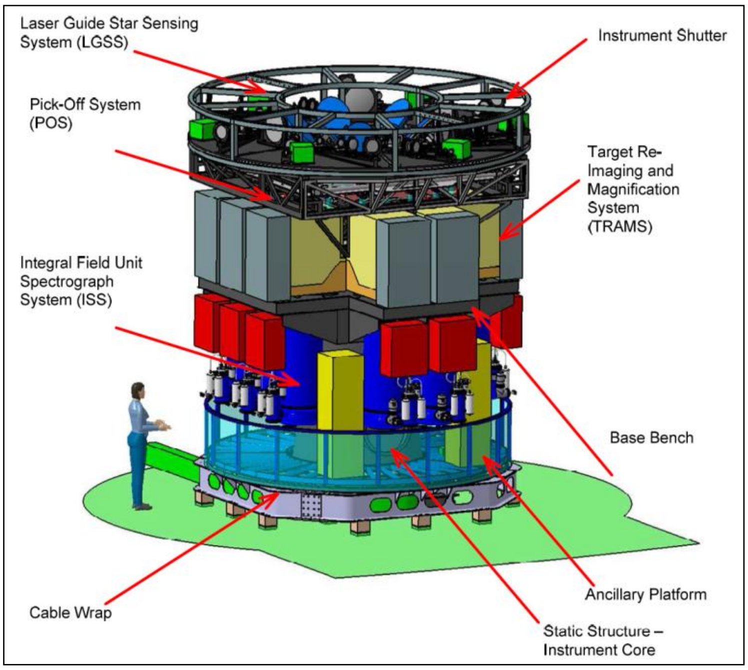

Figure 1.6. The architecture of the EAGLE instrument. Light is directed into the top of the instrument as shown. The whole system is mounted on a mechanical rotator.

1.4.6 A.6 THE EPICS INSTRUMENT STUDY

The EPICS instrument is essentially designed to image exoplanets directly, one of the ultimate goals of the E-ELT. The EPICS science team explored several science cases around this topic and answered in detail what will be possible with the E-ELT. Young, self-luminous planets in star-forming regions or young clusters will be prominent targets as they can be imaged all the way into the solar system near the snow-line, and this out to the distance of the nearest star-forming regions (300–500 light-years). At closer distances (< 30 light-years from the Sun) an instrument such as EPICS on the E-ELT will be able to image mature planets of the mass of Neptune or a super-Earth, potentially in the habitable zone of their star. A first characterisation with low-resolution spectroscopy of their atmospheres will be possible and O_2 dominated atmospheres (signs of life?) will be detectable. In an interplay with other instruments detecting planets by radial velocity or in the mid-infrared, EPICS will be able to follow up and image the most interesting candidates directly. The combination of instruments on the E-ELT will allow for many planets a first characterisation and thus strongly support the development of our planet formation theories.

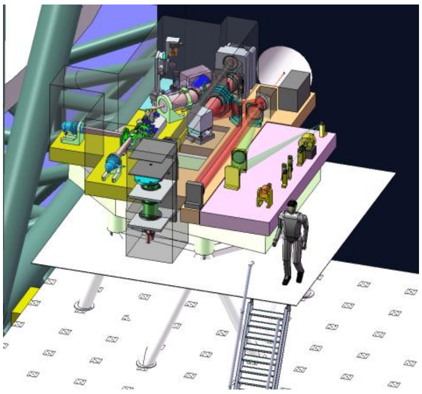

Figure 1.7. A schematic overview of the major components of EPICS mounted on the Nasmyth platform.

The EPICS concept combines extreme adaptive optics with the capabilities of two (possibly three) science instruments to achieve these goals. 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 differential detection methods including polarimetric imaging and integral field spectroscopy. The final step in achieving these contrasts is in the data reduction and post-processing. EPICS is a bench-mounted instrument which can be located on the Nasmyth platform; the preferred location is the straight through port. 10% of the light is used by an on-instrument SCAO system that provides signals for the telescope M4. The common optical path contains an atmospheric dispersion corrector and the high-order deformable mirror for the XAO module. The science beam may be directed into either the integral field spectrograph or the EPOL imaging polarimeter. The baseline for the integral field unit is a lenslet design based on the SPHERE design; there are 343 x 343 lenslets for a 0.8-arcsecond 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 detectors. The only cryogenic element is the detector since the wavelength range is restricted to 0.6–1.65 μm. The EPOL field is 1.37 arcseconds x 1.37 arcseconds; each channel is equipped with a 4k x 8k CCD. A third science instrument — a differential speckle imager — is also part on the continuing work on conceptual design and prototyping. The XAO system uses an innovative roof-pyramid wavefront sensor to measure the signals to control a 210 x 210 actuator deformable mirror of ~ 300 mm diameter.

1.4.7 A.7 THE HARMONI INSTRUMENT STUDY

HARMONI is an integral field spectrometer covering a broad wavelength range (0.47 μm–2.45 μm) designed for operation with the LTAO system. It is a multimode instrument covering a wide range of observational conditions and scientific programmes. The HARMONI team highlighted the E-ELT strong science cases that high-spatial resolution, integral-field spectroscopy will enable. One of the most interesting cases is the one complementing the exoplanet cases of other instruments, with the possibility to obtain spectroscopy of the typical Jupiter-mass exoplanets detected with 8–10-metre-class telescopes. This will allow researchers to fully characterise this type of exoplanet by determining their age, mass and temperature. By expanding this case to higher mass, it will be possible to study the low-mass regime of star formation and to understand the transition between planet and brown dwarf formation. Further, the high spatial resolution of the instrument will probe the vicinity of intermediate-mass black holes in star clusters and dwarf galaxies, thought to be possible seeds of supermassive black holes at high redshift. The combination of high spatial and medium to high spectral resolution will further allow the study of resolved stellar populations in nearby galaxies with the goal of better understanding galaxy evolution throughout cosmic time.

Similarly, HARMONI complements the sciences cases outlined by the EAGLE science team with higher spatial resolution for single objects and with extension to the visible wavelength range. The scientific case for HARMONI calls for three spectral resolution modes (R ~ 4000, R ~ 10 000 and R ~ 20 000). Four selectable plate scales (4 mas, 10 mas, 20 mas and 40 mas) are matched to the size scale of the astronomical objects to be studied with the resulting field size (5 arcseconds x 10 arcseconds, 2.5 arcseconds x 5 arcseconds, 1.25 arcseconds x 2.5 arcseconds, 0.5 arcseconds x 1.0 arcsecond respectively) being derived from consideration of the source sizes, the expected PSF (whether seeing limited or delivered by an AO system) and the demands of obtaining good sky-subtraction in the near-infrared. To achieve the large fields with fine sampling, HARMONI partitions the input focal plane into four subfields that feed four integral field units. The output of the IFU is two pseudo-slits that form the input to two spectrographs. Thus for the full-field, there are eight spectrographs in total. VPH gratings are the baseline for this component — ten gratings are mounted in a wheel for the NIR. The detector is a 4k x 4k NIR detector. For optical spectroscopy (0.47–0.8 µm) the expected performance of the AO at this wavelength implies that the 40-mas pixel scale is adequate in all cases. Since there is no need for rapid beam-switching for sky-subtraction, one quarter of the field is sufficient (5.0 arcseconds x 2.5 arcseconds). Therefore, one of the IFU channels is equipped with two optical spectrographs and wheels containing five VPH gratings to cover the visible wavelength range; the detector is a 4k x 4k CCD. To reduce the thermal background, the complete optical train for HARMONI is liquid nitrogen cooled and contained in a 4-metre diameter cryostat mounted statically on the Nasmyth platform. The field rotation for the small input field is compensated by an optical de-rotator in the instrument fore-optics. A secondary guiding system, also in the common fore-optics, corrects for any relative motions of HARMONI and the telescope beam using measurements of a natural guide star selected within a 19-inch beam. HARMONI is designed for use with the LTAO system and with GLAO. A SCAO system using the telescope M4 has been designed and could be built to substitute for the LTAO system, though with limited sky-coverage, in the case that HARMONI were to be developed on a shorter timescale than the LTAO.

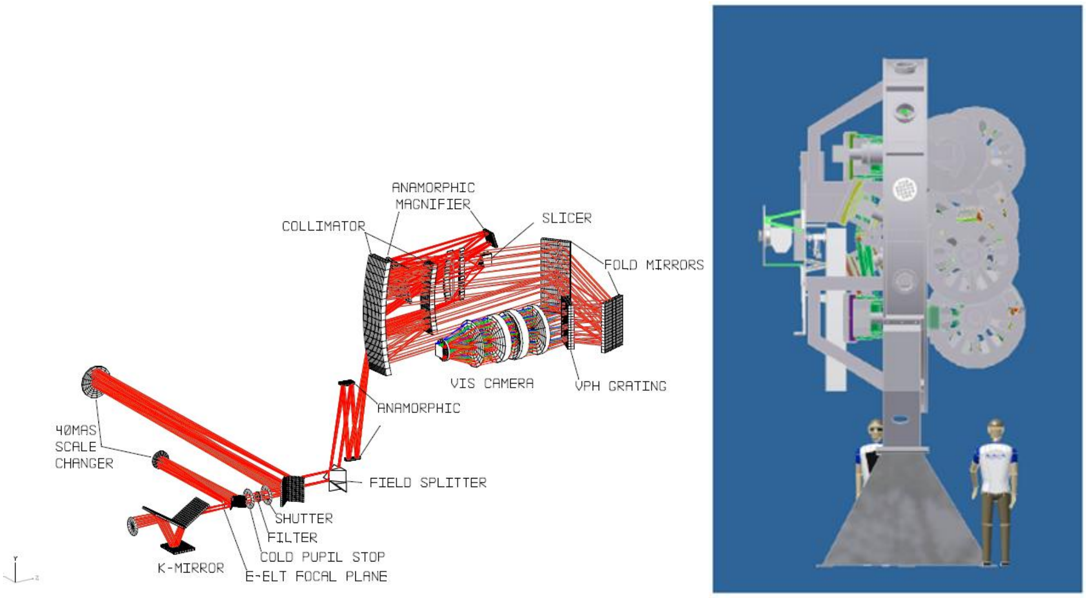

Figure 1.8. The optical path of a single channel from the K-mirror that de-rotates the field to the detector. This is for one of the two visible cameras. Light from the telescope passes through the scale changer in the fore-optics, then is subdivided at the field splitter. The beam is collimated before entering the slicer and finally focused onto the spectrometer 4k x 4k array.

The main risk to technical readiness of the instrument is the complexity the size of the cryostat and the number of mechanisms. To deliver HARMONI as a first-light instrument, careful consideration will be given to simplifying the optomechanical concept while maintaining the key scientific drivers that include the operation at visible wavelengths and the high spectral resolution spectroscopy. The possibilities include reducing the number of spectrographs to reduce volume and mass of the instrument. This may be achieved by a revision of the optical design or by reducing the field of view. The latter would affect the sky-subtraction scheme currently planned for the instrument (nodding along the IFU) with the potential to limit the sensitivity ultimately achieved. Further work with SINFONI data and experience with KMOS (to be commissioned in 2012) will improve our understanding of NIR sky-subtraction with IFUs. Further work is required regarding the strategy for implementation of the adaptive optics module. During the phase A studies, it was not possible to investigate the full integration of the instrument with the AO module. This may result in substantial simplifications of the AO module design and alleviate one of the risks to performance identified during the design phase, namely that there would be differential flexure between the instrument and the AO module.

1.4.8 A.8 The METIS Instrument Study

METIS is a workhorse instrument for the thermal infrared (2.9 µm–14 µm) region offering nine different observing modes -imaging in the *LM*- and *N*-bands, long-slit spectroscopy with moderate resolving power (*R* ~ 5000) for the *LM*- and *N*-bands; integral field spectroscopy at high resolving power (*R* ~ 100 000) in the *LM*-bands; coronagraphy and polarimetry. The METIS science team analysed the breakthrough science in the mid-infrared that will become possible with the E-ELT. The E-ELT with an MIR capability will excel in protoplanetary disc research, probing inside 1–10 AU of forming exoplanetary systems and understanding their origin and diversity. Furthermore, the MIR is the wavelength of choice to image young, self-luminous giant planets and to study the molecules present in their atmospheres as well as their weather. METIS on the E-ELT will characterise a large number of young exoplanets. With its very high spectral resolution in the mid-infrared, METIS will also allow the study of our the Solar System in more detail than ever before, from cometary volatiles to the surface of Kuiper Belt objects. METIS promises a strong push in our understanding of stars and planets, but its science cases are not limited to the local Universe. Indeed, MIR wavelengths can penetrate the heavily obscured inner regions of nearby galaxies and offer a unique opportunity to study the interplay of heavy star formation and active galactic nuclei, and ultimately between the supermassive black hole and the surrounding interstellar medium.

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 that sends correction signals to the telescope M4/M5. The infrared beam then passes through a Dicke switch which acts as an internal, fast chopper, through the optical de-rotator and then may be directed into the modules containing the high-resolution spectrograph, the *LM*-imaging plus low-resolution spectroscopy or the *N*-band imaging plus low-resolution spectroscopy. The fast chopper is a novel concept for this instrument: chopping is more usually achieved with a telescope secondary mirror — a possibility not open to the E-ELT due to the size of the M2. The whole optomechanical system is at a temperature of 80 K, with the exception of the *N*-band spectrograph which is cooled to 30 K. The METIS detector system is based on the AQUARIUS MIR detectors currently being implemented for VISIR on the VLT. As mentioned above, METIS is equipped with an on-instrument SCAO system. An interesting outcome from the study was that diffraction-limited image quality in the MIR can be delivered using just the telescope M4, with wavefront correction signals provided from an on-board SCAO system. The full science performance is met when METIS is coupled with the ATLAS LTAO system offering high sky-coverage.

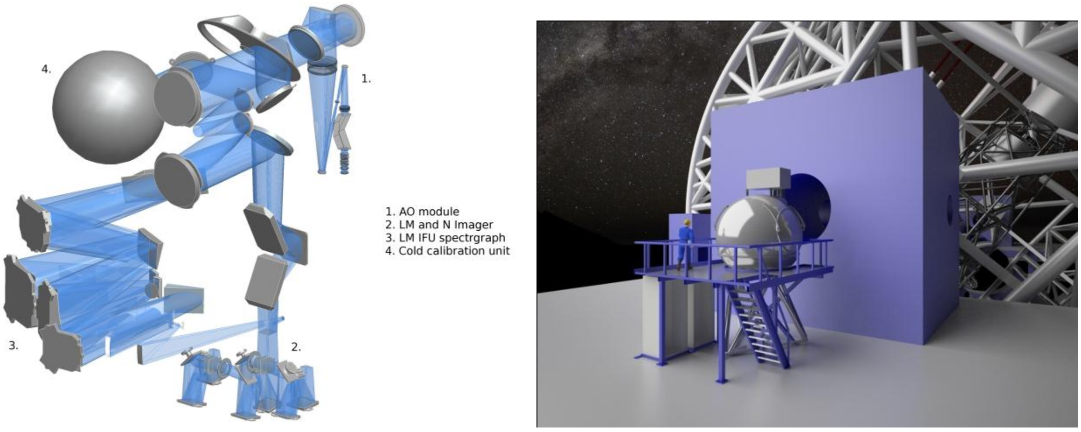

Figure 1.9. The optical layout of METIS (left) showing the two science modules — the imager with low-resolution spectroscopy and the high-resolution spectrometer. The on-board AO module is shown. This complete system is inside the METIS cryostat shown (right) at the straight through port on the Nasmyth platform.

1.4.9 A.9 The MICADO Instrument Study

MICADO is an infrared (0.8–2.5 µm) camera designed to exploit the diffraction limit of the telescope. The MICADO science team studied the science case for such an instrument and drew attention to astrometric science cases. With a diffraction limit of 5 milliarcseconds at 1 µm wavelength, astrometry at the 100 to 50 microarcsecond level becomes possible. This, in turn, opens a new parameter space that can be exploited for many exciting science cases.

Two of the most prominent examples are: the kinematics of stars only ~ 100 Schwarzschild radii from the supermassive black hole in the centre of the Milky Way, orbiting the black hole with orbital velocities of 0.1*c* (*c*: speed of light), allowing the detection of the effects of special and general relativity. The other example is the kinematics of star and globular clusters in our Milky Way as well as of dwarf galaxies in the Local Group, offering a whole new understanding of dynamical effects from intermediate-mass black holes to dark matter halos. Beyond astrometry, MICADO is designed to obtain exquisite photometry of dense, resolved stellar populations at the highest possible spatial resolution. From the science team's studies, it is clear that useful colour–magnitude diagrams will be obtained out to distances unachievable today, complementing the spectroscopy of individual stars and allowing the disentangling of the multiple stellar populations in many nearby early- and late-type galaxies. What is today often referred to as near-field cosmology (a detailed history of the star formation history of the Universe) will get a totally new meaning with the E-ELT.

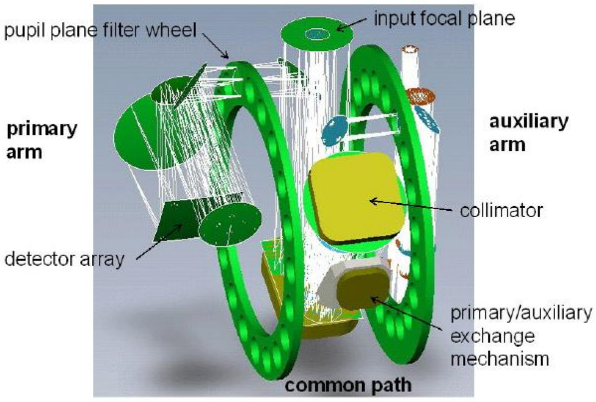

Figure 1.10. The two arms of the MICADO instrument — the primary arm with the 53 arcseconds x 53 arcseconds camera and 16-detector focal plane; the auxiliary arm with the additional scientific modes including spectroscopy, higher resolution imaging at 1.5 mas per pixel and options include high time resolution imaging, polarimetry. A simple fold mirror is used to select between them.

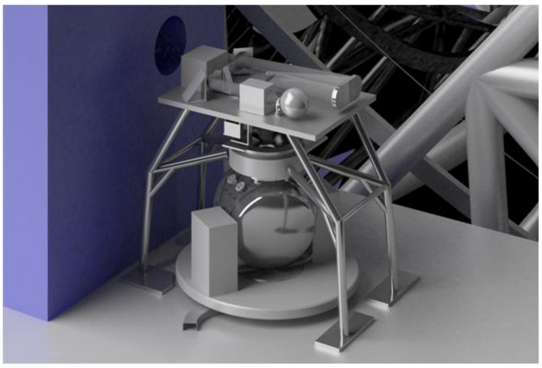

Figure 1.11. MICADO mounted on the Nasmyth platform under the SCAO module that is proposed by the team as an interim measure until the LTAO system is complete. The interface is identical. MICADO operates in this gravity invariant location, rotated by a mechanical rotator on the Nasmyth platform.

The optomechanical 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 50 µas and so the primary arm has fixed optics with the only mechanism being a filter wheel providing a selection of 20 filters. The field of view of this arm is 53 arcseconds x 53 arcseconds with 3-mas sampling (Nyquist sampling the diffraction limit at 1.0 µm). 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 upward looking cryostat. 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 (1.5 mas pixels) and 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.

In the conceptual phase, MAORY was considered to feed MICADO. Since the MAORY schedule predicted at phase A is longer than that for MICADO, an SCAO module was included in the MICADO baseline design in the later stages of the study. This delivers high Strehl images (> 70% on-axis at m_V = 12) and a 27 arcseconds x 27 arcseconds corrected field, of course to be restricted to fields with a bright guide star. A phased delivery of the detectors was proposed by the consortium as an option for matching a phased AO delivery while assisting with the project costs/cash flow.

1.4.10 A.10 THE OPTIMOS–DIORAMAS INSTRUMENT STUDY

OPTIMOS–DIORAMAS is an imager and slit mask-based multi-object spectrometer for the wavelength range 0.37 µm–1.4 µm. The OPTIMOS–DIORAMAS team concentrated their efforts on studying the high-redshift galaxy survey and characterisation capability of the E-ELT. Multi-slit instruments such as the one proposed are very powerful in exploring from redshifts 1 to 6 essentially the entire period of galaxy formation and evolution. The OPTIMOS–DIORAMAS team proposes an ultra-deep imaging survey (down to AB magnitudes of 30, an order of magnitude deeper than possible today). A complementary spectroscopic survey would discover the first building blocks of galaxies at redshifts $z > 6$ and trace the mass assembly of galaxies since this earliest epoch of galaxy formation. The oldest stellar populations, expected in quiescent galaxies, can be traced well beyond a redshift of $z \sim 2$ with the E-ELT — and so can the population and frequency of galaxies with active galactic nuclei. Finally, 3D tomography of the intergalactic medium at $2 < z < 3.5$ can be studied through quasar absorption lines and the large-scale distribution of galaxies at redshifts $z > 2$. In summary, the E-ELT will be able to explore the formation of galaxies and the large-scale structures in the Universe in an unprecedented way.

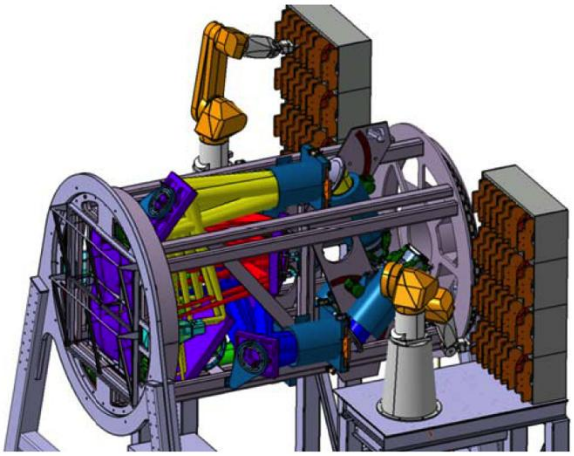

Figure 1.12. A view of the OPTIMOS–DIORAMAS system with the cabinets for the filters and gratings and robotic exchange mechanisms (to the right). At the left of the figure, the mask exchange mechanism can be seen. The cylindrical structure is the rotating part of the instrument.

The realisation of this wide-field MOS is as follows. A 6.78 arcminute x 6.78 arcminute field is split into four quadrants at the telescope focal plane and feeds four spectrometers — two optimised for the wavelength range 0.37–1.0 µm using three 4k x 4k CCD detectors and two optimised for the range 0.6–1.4 µm using three 4k x 4k HgCdTe detectors. In the overlap wavelength range (0.6 –1.0 µm), OPTIMOS–DIORAMAS can survey a field of 44 arcmin^2; outside this range the field is 22 arcmin^2. The design is optimised for high-redshift science and, in particular, redshift surveys.

An ultra-deep imaging survey is a goal of the science case. For spectroscopy, the multiplex may be as high as 480 in the optical and with the lowest spectral resolution ($R \sim 300$); in the NIR, a multiplex gain of 160 is foreseen ($R \sim 3000$). The 0.8 mm thick steel slit masks are 780 mm x 780 mm, weigh 3 kg and are laser-cut on site. The baseline slit width of 0.5 arcseconds is designed to exploit the performance of the LGS GLAO system although the instrument can be used in seeing-limited conditions with some slit losses or some reduction in resolving power. At the detector, the slit width is sampled by ten pixels. The use of an atmospheric dispersion compensator is not essential if the zenith angle of operation of the instrument is restricted. The spectrographs and focal plane are part of the rotating structure of the instrument, relying on active flexure compensation. A novel aspect of the DIORAMAS design is the use of a robotic arm to exchange the filters for imaging or the gratings for spectroscopy, thus removing the need for large gratings wheels. A mixture of transmission gratings and VPHs are used. The instrument has a mass of 24 tonnes in a volume 6 m x 6 m x 6.5 m.

The long wavelength cut-off of the instrument (either 1.4 µm or 1.6 µm) must be decided during the specification development phase. The gain in performance in extending to 1.4 µm is minimal given the atmospheric window between the *J*- and *H*-bands; however extending to 1.6 µm would have implications for the thermal background, possibly requiring the cooling of substantial sections of the instrument. This issue was not addressed during the study and it could substantially affect the mechanical design. The DIORAMAS instrument concept uses a novel robotic filter/grating exchange arm that should be tested in prototype before finalising the instrument concept.

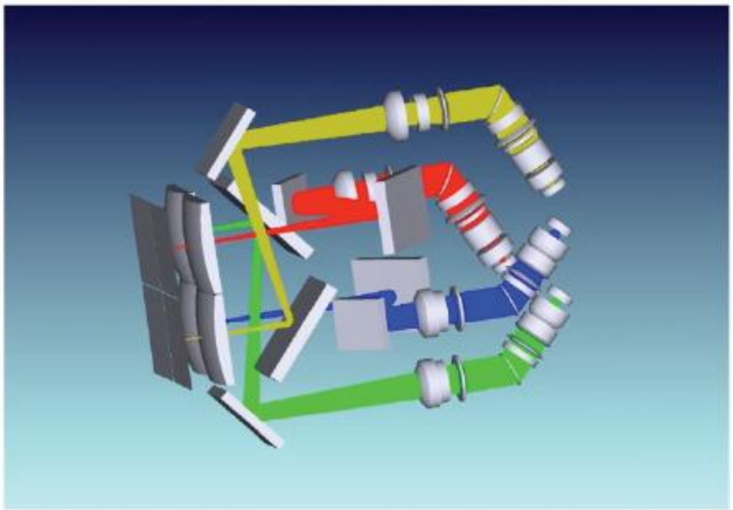

Figure 1.13. The optical layout of OPTIMOS–DIORAMAS in spectroscopic mode showing the four optical paths that make up the instrument — two optimised for the 0.6–1.4 µm range and two for the 0.37–1.0 µm range.

1.4.11 A.11 THE OPTIMOS–EVE INSTRUMENT STUDY

OPTIMOS–EVE is a fibre-based optical to NIR *H*-band 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 10 arcminutes in diameter. The OPTIMOS–EVE science team collected a number of high profile science cases for a multi-fibre optical–NIR spectrograph. With such an instrument, it will become possible to search for exoplanets out to our nearest dwarf galaxy neighbours at the same level as they are found today with 8–10-metre-class telescope in the solar neighbourhood. As in the near-field cosmology cases described above, spectroscopy of individual stars in nearby galaxies can be extended to optical wavelengths and thus the detailed star formation histories traced. With respect to the distant Universe, the instrument is set up to track the first star-forming galaxies and sources of re-ionisation of the Universe at redshifts from 5 to 13. The integral field properties of such a spectrograph would be ideal to detect ionised gas around distant galaxies, complementing the neutral gas studies performed with ALMA. Finally, the high spectral resolution would allow a precise tomography of the intergalactic medium at high redshifts, to e.g., probe the matter distribution and the geometry of the Universe.

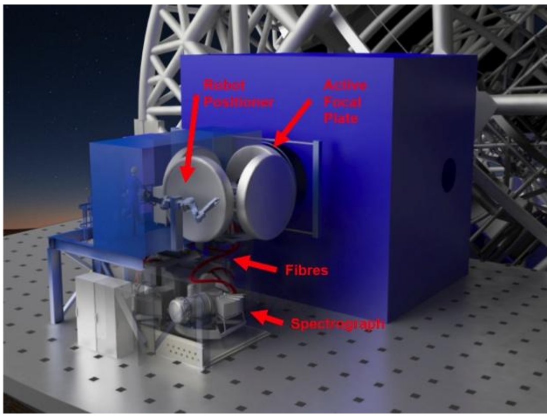

Figure 1.14. A schematic showing OPTIMOS–EVE on the Nasmyth platform, straight-through port. The spectrograph optical elements are mounted below the focal plates and the exchange mechanism.

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. 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 the multiplex is 70 and 40 respectively. In addition to the single-object mode, 30 fibre-bundle IFUs, each with a field of view of 1.8 arcseconds x 3 arcseconds and one large IFU with field of view 7.8 arcseconds x 13.5 arcseconds, are available for use with the lower spectral resolution mode. The fibres are split between the two spectrometers optimised for the optical and two optimises for the infrared. This allows simultaneous observations across the full wavelength range, the operational aspects of which are to be further explored as the instrument design progresses.

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 elements. A total of ten gratings are required to cover the full wavelength range and all spectral resolving powers. Most of the OPTIMOS–EVE optomechanical system is operated at a temperature of 193 K in a cold chamber located in the platform under the focal plate system. As with OPTIMOS–DIORAMAS, an ADC is not necessary for OPTIMOS–EVE provided that only a restricted range of zenith angles is used. The accuracy of sky-subtraction with the fibres is expected to provide the ultimate limit to the sensitivity for this instrument and is an area that would benefit from further study.

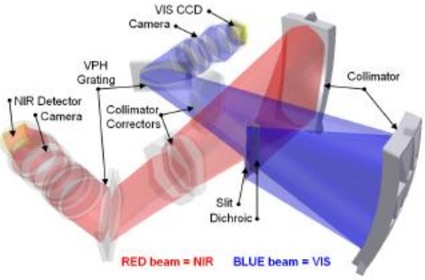

Figure 1.15. The optics of OPTIMOS–EVE showing the split of the infrared and optical light into the two optimised cameras. The beam is folded by the VPH grating.

1.4.12 A.12 The SIMPLE Instrument Study

The SIMPLE science team looked into the breakthrough science enabled by a very high spectral resolution (*R* ~100 000) NIR spectrograph. The most exciting case is certainly the possibility, with SIMPLE on the E-ELT, to obtain detailed spectroscopy of the atmospheres of exoplanets observed in transit in front of their star. Around low-mass stars, with planets on short orbits, it will be possible to identify and chemically characterise the atmospheres not only of Jupiters, but also of ocean planets of

Neptune mass, or even rocky super-Earths. Ultimately, this might be the first chance to detect biomarkers (e.g., O_2) in exoplanet atmospheres.

The combination of enormous light-collecting power, high spatial (adaptive optics assisted) resolution and very high spectral resolution opens up a much larger parameter space to be explored. An instrument such as SIMPLE will also enable fantastic progress in precise chemical characterisation of cool main sequence stars in the inner Galaxy or of star clusters out to the distance of the nearest galaxy groups and clusters. Absorption systems along the line of sight of quasars will be traced to $z > 4$, where metal lines can be used to explore the chemical pollution of the first stars (so-called Pop III).

The SIMPLE instrument concept is a fixed-format cross-dispersed échelle spectrometer delivering complete coverage from 0.84–2.45 µm in a single exposure with spectral resolution R = 130 000.The spectrometer aperture is a 27 mas x 450 mas slit in the primary mode and can be used in a long (4-arcsecond) slit mode by selecting between one and six orders using a spatial filter. For high stability and reliability, the spectrometer has a minimum number of moving parts with just two cryogenic mechanisms: the slit mechanism and the post-slit viewer in a continuous flow liquid nitrogen cryostat. 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 SIMPLE beam is picked off from 2500–3000 mm from the telescope focus, so SIMPLE is easily located at any of the telescope ports or behind any of the post-focal AO modules. The instrument pre-optics contains a secondary guiding system to maintain alignment between SIMPLE and the telescope axis, the field de-rotator 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 with sampling of 2–3 pixels. The total mass of the instrument is 7700 kg in a volume of 4 m x 4 m x 5 m. The vacuum vessel is a cylinder 1.8 m x 2.3 m. The instrument is mounted on a mechanical rotator.

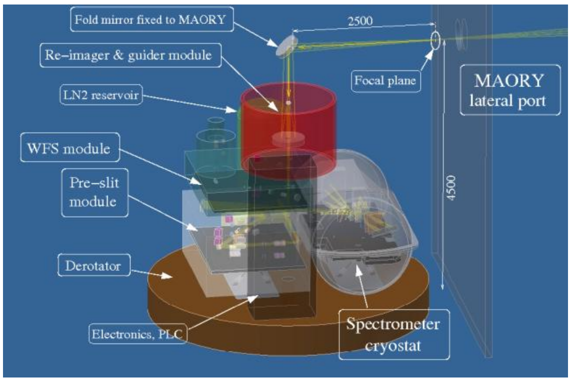

Figure 1.16. The SIMPLE layout showing the beam picked-off from the re-imaged (by the MCAO) telescope focal plane.

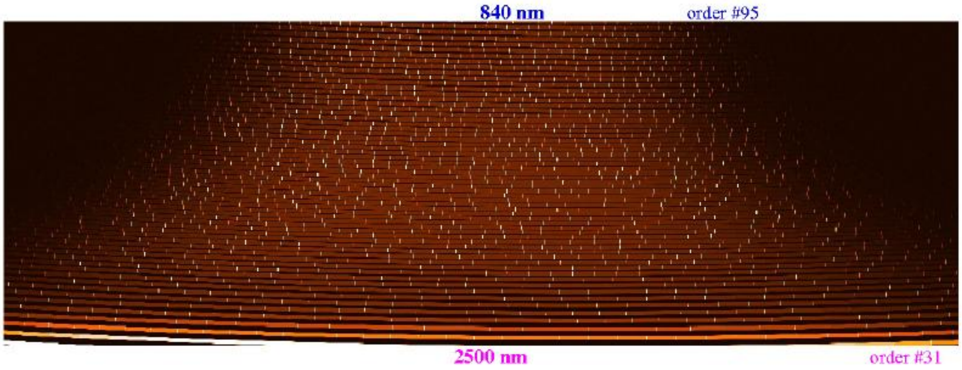

Figure 1.17. The SIMPLE echellogram on 3 x 4k x 4k arrays.