ELT

Working Group #2: Instruments

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CHANGE RECORD

Issue	Date	Section/page Affected	Description of the change
0.5	24.02.2006	all	Draft in Word format, information from twiki
0.8	28.02.2006	all	Final pre-release draft
1.0	28.02.2006	several	Updated sections 1, 3.3, 5.2; Minor edits in others
1.1	20.03.2006	Section 5	Minor edits in other sections, updated Fig. 10
1.2	03.04.2006	All	Expanded tables, minor edits for consistency
1.3	25.04.2006	All	Minor edits, first public release.

Note: The present version is intended to facilitate the exchange of information with the other WGs and the Project Office. Full consistency and completeness of the information collected from various sources cannot be guaranteed at this point. We plan to update the document taking into account comments from the other WGs and the community by November 2006. To this end we welcome input to Colin Cunningham (crc@roe.ac.uk) or any other member of the Working Group.

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Terms of Reference

In order to pursue ESO's highest strategic goal of international leadership in the era of ELTs (Council resolution of December 2004) and in response to the OWL Concept Design Review, ESO will form 5 Working Groups consisting of experts drawn from the ESO staff and the community. The Working Groups are:

WG-1 Science
WG-2 Instruments
WG-3 Site Evaluation
WG-4 Telescope Design
WG-5 Adaptive Optics

The **general** terms of reference of all Working Groups will be:

- To synthesize and collate ELT capabilities in the specified topic area, noting existing community studies and ongoing efforts
- To propose a basis for prioritising capabilities in the specified topic area, a list of key tradeoffs and an initial prioritisation of an ESO ELT capabilities
- To conduct an initial meeting in January 2006 and a concluding meeting in February 2006
- To submit a report of synthesized requirements to the ESO DG by 28 February 2006

The **specific** terms of reference of each Working Group will be:

WG-2 Instruments:

• To categorize instruments according to ELT size, listing possible capabilities, complexity, demands on the Telescope and AO.

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1 Executive Summary

The Instrumentation ELT Working Group has drawn together work done to date on instruments for ELTs, and generated a list of key issues and requirements from the instrumentation point of view for the telescope and AO teams to consider in optimising the specification and design of a European ELT. As we iterate towards a telescope concept for detailed study, it is essential that the trade-offs in cost and performance take full consideration of the instruments, their interaction with the AO systems and the science priorities. It is vital that the telescope and systems are not designed in a way which prevents efficient and affordable scientific exploitation of the facility over its lifetime. We expect approximately 5 instruments to be developed in each of the first and second generation ELT complement over the first 10 to 15 years of operation. With a projected total cost for the first suite of instruments of the order of 100 - 150 M€, it is evident that the cost of the instrumentation will represent a significant fraction (10 to 20%) of the project cost to completion, and of the operating cost over the observatory's lifetime.

Following the recommendation of the OWL review and ESO's decision to work towards a 30-60 m telescope, it has become apparent that the scientific priorities and capabilities will change considerably at the lower end of this range compared to those for a 100 m telescope. In particular, it is likely that more emphasis will be placed on seeing limited instruments, particularly at visible wavelengths where adaptive optics challenges are acute. A submillimetre imager will become less attractive as the aperture decreases, and an ELT has less of an advantage over dedicated submm telescopes. Perversely, more emphasis on seeing limited observation will put greater pressure on instrument mass-budgets and space-envelopes, due to the fact that linear dimensions will scale with aperture, unlike diffraction limited instruments, which will retain the same dimensions as the aperture increases – as long as the field-of-view is reduced commensurately to maintain the information density on the focal plane.

We have preliminarily identified 12 instruments to cover the parameter space of possible observations with an ELT and used them to explore the requirements they set on telescope design, Adaptive Optics and the site. From this detailed exercise we have extracted the main drivers from the instrumentation viewpoint. We have outlined a possible phased plan of implementation of ELT instruments and used it estimate the necessary budget and manpower effort. Finally we have identified the synergy with the FP6 ELT Design study and the next steps in the ELT observatory definition.

Areas for critical trade-offs:

With Science Team: Consider where priorities lie and what compromises could be made in FoV, wavelength range, possible instrument suite, telescope aperture, thermal IR and polarisation performance.
With Telescope Team: Emissivity, cleanliness, symmetry for polarimetry, accessibility to instruments, back-focal distance, focal ratio, scientific field, development path towards built-in deformable mirror. Focal stations - accessibility, additional cost on instruments of non-gravitational stability, instrument exchange
With AO Team: Alignment of AO systems and instrument suite. Performance estimates. Physical implementation of AO in telescope or instruments.
With Site Team: Altitude and ambient temperature for near-IR, mid-IR and sub-mm operation.

Recommended Next Steps:

- Further develop the science case for the range of telescope aperture from 30-60m, and develop a compliance matrix with the science and AO teams
- Trade-off study of the optical layout, including emissivity, polarisation, throughput and future AO development paths
- Trade-off study for instrument platforms with regard to flexure, image rotation, pupil rotation, adaptive optics, laser guide stars and maintenance
- Develop cost drivers for the instrument suite traded against other systems costs
- Ensure appropriate end-to-end test facilities are available in Europe
- Push towards a global development programme for critical instrument technologies

2 SCOPE OF REPORT

This report draws together the work which has been done on Instrumentation for ELTs through the Euro50 study [RD02], the OWL studies [RD03, RD04] and the FP6 ELT Design Study [RD01]. Added to this information are the opinions and experience of the Working Group. It forms the starting point for trade-offs with the Telescope and AO systems and debate with the Science teams on what is possible and what cannot be done within an expected European ELT budget. It can be regarded as a 'toolkit' to be used in conjunction with the outputs of the other Working Groups to allow the project to be progressed towards an optimal system.

The content of this document will continue to evolve during the next phase of the European ELT project, and by making it public to the community, we expect to engender lively debate and use that to inform more comprehensive and definitive versions of the document.

The document starts by describing current and recent work on instrumentation for ELTs, including the OWL and Euro 50 studies, the studies within the Framework 6 ELT Design Study, and the work on instrumentation being done for the North American ELTs. It then goes on to suggest a comprehensive set of generic instruments which cover the parameter space and science case for an ELT. It is not suggested that all these instruments be built to these specifications and scope, they are developed to help us test the capabilities of the telescope, Adaptive Optics and site. For each 'instrument' we provide:

- a brief science rationale
- a table of requirements on the systems – including what we regard as critical issues which will drive the telescope and AO design
- a discussion of technology readiness, complexity and cost issues

We then discuss a phased instrument development plan, issues on cost and procurement, and requirements for integration and test in Europe. We then summarise the key drivers on the telescope and systems from the instrument perspective. Finally, we make recommendations for next steps.

3 STATUS OF ELT INSTRUMENTATION STUDIES

3.1 Instrumentation for Euro50

Euro50 is a concept for an adaptive optics based 50 meter Gregorian telescope. It is the conclusion of a ten years of evolution of a concept for an Extremely Large Telescope which originated from the Lund University Group led by Arne Ardeberg and Torben Andersen,
Moving from initial concepts, back when the very idea of a 25-60 m telescope was regarded as rather outlandish, a detailed and analyzed concept was developed and presented in 2003 [RD02]. There were no specific instrument feasibility studies made, but the basic instrument parameter space for an AO telescope of 50m diameter was identified and some general points on an instrument plan were drawn. The following instrument/observing mode categories were assessed:

* Near-Infrared Instruments for the Adaptive Optics Regime
* Near Infrared Instruments for the Seeing Limited Regime
* Thermal Infrared Instruments
* Seeing Limited Instruments for the Visible Range
* Prime Focus Observations

These are discussed in the Appendix 1 to this document.

The OWL Instrument Concept Studies

In October 2005 ESO completed a Concept Study for a 100m telescope called OWL (Over Whelming Large telescope) for the keen night vision of the homonymous bird [RD03]. As a complement to the telescope design, ESO coordinated in 2004-2005 eight instrument concept studies with institutes in the ESO member states. Six of the studies were led by P.I.s from different European Institutes, and two were coordinated by ESO.

In the selection of the initial instrument concepts, ESO was inspired by the science cases for a generic 50-100 m ELT as developed by the EC OPTICON Network [RD01] and by preliminary studies on the OWL scientific goals. The selected instruments offer various imaging and spectroscopic modes of observing and operate in different wavelength bands from the blue to sub-millimetre. The instruments, the wavelength of operation, their main capability their main science goals and the institutes involved in the study are presented in Table 1.

Table 1. OWL Instrument Concept Studies

Instrument	Wavelength range	Main Capability	Primary Science Goals	Institutes
CODEX	400-700 nm	High velocity accuracy, visual spectrograph	To measure the dynamics of the Universe	ESO, INAF-Trieste, Geneve Obs., IoA Cambridge
Quant EYE	400-800 nm	Photometry at 10^{-3} - 10^{-9} second resolution	Astrophysical phenomena varying at sub-ms time scale	Univ. of Lund and Padova
HyTNIC	1100-1600 nm	High-contrast diffraction-limited imaging	Imaging of massive planets, bright galactic and extra-galactic sources	LISE- Collège de France
EPICS	600-1900 nm	Camera-Spectrograph at diffraction limit	Imaging and spectroscopy of earth-like planets	ESO + external experts
MOMFIS	800-2500 nm	Near IR spectroscopy using many deployable IFUs	Masses of high z galaxies, regions of star formation, GC stars	CRAL, LAM, OPM
ONIRICA	800-2500 nm	NIR Imaging Camera field up to 3 x 3 arcmin	Faint stellar and galaxy population	INAF Arcetri & Heidelberg MPIfA
T-OWL	2.5-20 μm	Thermal, Mid Infrared Imager and Spectrograph	Search, study of planets, high redshift Hα galaxies	MPIfA Heidelberg, Leiden Univ., ASTRON, ESO
SCOWL	250-450-850 μm	Imaging at sub-millimeter wavelengths	Surveys of dusty regions, of extragalactic fields for star-forming galaxies	UK ATC

The instrument study teams were asked:

- To identify the primary science drivers for each instrument and use them to define the instrument requirements
- To develop an instrument concept and to evaluate its performance on OWL.
- To compare them with what it is expected in the next decades from major ground-based and space-born facilities like ALMA and the JWST
- To identify the need of special developments or enabling technologies and to derive a first estimate of the cost
- To address the dependence on telescope diameter in the range 50-100m and to underline any critical aspects of interfacing with the telescope and the AO system.

This first study exercise of possible OWL instruments saw the active involvement of more than 150 astronomers and engineers from 20 institutes in 9 European countries. The instrument teams delivered their final study reports in October 2005 [RD03]. These are listed below.

This sample of instruments covers the different modes of operation for OWL well, and excercises fully the capabilities of the telescope. The list is however by no means exhaustive of all potentially unique observations to be done with an ELT of the OWL class. High resolution spectroscopy in the near infrared, intermediate resolution spectroscopy of faint sources over a wide spectral range, astrometry at diffraction limit are examples of interesting modes not explored in this phase. Wide Field Multi Object Spectroscopy at Blue-Visual-Red wavelengths was also considered not relevant for a 100m telescope, but will have to be discussed if the diameter of the European ELT is significantly smaller.

The instrument studies provided important feedback to the telescope design, specifically on the interface between the telescope-adaptor and the instruments. These are being taking into account in the current design activities for a European ELT. Since the dependence on telescope diameter was explored in the course of the instrument studies, many of the results and performance estimates will remain valid for a smaller telescope diameter. The instrument concepts will need to be updated when the new telescope properties and instrument interfaces are available.

List of the OWL Instrument Concept Study reports [RD03]:

- Pasquini et al,"CODEX: Cosmic Dynamics Experiment", OWL_CSR-ESO-00000-0160, October 2005
- Dravins, Barbieri et al. "Quanteye", OWL_CSR-ESO-00000-0162, October 2005
- Ragazzoni et al. "ONIRICA: OWL NIR Imaging Camera", OWL_CSR-ESO-00000-0165, October 2005
- Cuby et al "MOMFIS: Multi Object Multi Field IR Spectrograph"; OWL_CSR-ESO-00000-0164, September 2005
- Lenzen, Brandl et al "T-OWL, Thermal Infrared Imager and Spectrograph for OWL" , OWL_CSR-ESO-00000-0161, October 2005
- Dent, Egan et al "SCOWL: Submillimeter Camera for OWL"; OWL_CSR-ESO-00000-0163, September 2005
- Hubin, Kasper, Verinaud et al "EPICS: Earth-like Planet Imaging Camera and Spectrograph", OWL_CSR-ESO-00000-0166, October 2005
- Larderie, Borkowski, Labeyrie "HyTNIC : Hyper-Telescope Near Infrared Camera"; OWL_CSR-ESO-00000-0167, October 2005

3.3 FP6 ELT Design Study: Instrumentation Work Packages

The instrumentation work packages under the FP6 Design Study started in April 2005 with a study of Atmospheric Dispersion issues for ELTs and their instruments. The Small Studies are now under way, and will lead into more detailed Point Designs on a subset of the instruments considered in the Small Studies. The following diagram show haw this work is now expected to be coordinated with the activities of the ELT Working Groups and the Telescope Reference Design Phase.

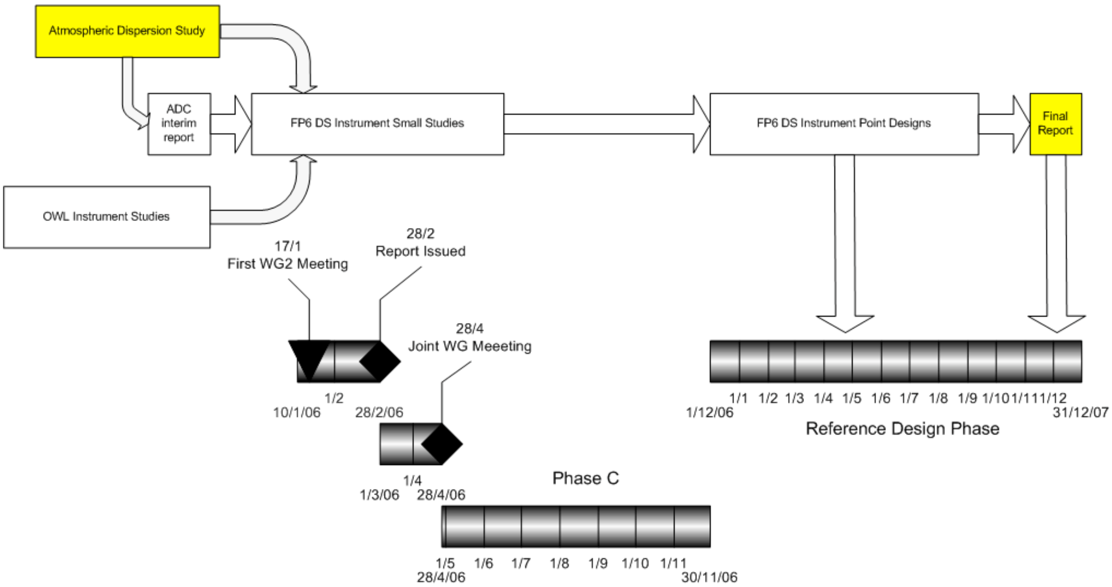

Figure 1: Time line for FP6 Instrument Studies and ELT Working groups

3.3.1 Atmospheric Dispersion Correction

The ADC study conclusions are:

The refractive index of the atmosphere varies with wavelength, causing Atmospheric Dispersion (AD). We examine its correction in the context of the very high angular resolution expected of AO-corrected Extremely Large Telescopes (ELTs). *All* refraction effects (such as seeing) are also intrinsically chromatic, and their full correction is impossible with purely reflective AO systems. We examine all such effects known to us, to see if their uncorrected chromatic analogues will affect the performance of 30- to 100-m ELTs. In what follows our terminology generally follows Hardy, 1998, section 9.3.3, with some alternative labels.

- **Atmospheric Dispersion (AD)**, the variation of atmospheric refraction with wavelength and zenith distance (ZD), must be corrected to a fraction of a percent. This is probably possible for near-diffraction-limited (NDL) telescopes of up to 100m diameter, perhaps for λ >500nm, more certainly for λ >1μm, over moderate bandpasses ($R=\lambda/\Delta\lambda\sim5$), ~arcmin fields of view and zenith distances (ZDs) to at least 45 degrees. We outline designs for visible-band and near- and thermal-IR ADCs offering Strehl ratios approaching 0.8 on 30-, 50- (and in the IR) 100-m telescopes.
- ***Chromatic Error* (Dispersive Seeing)**, the chromatic analogue of "normal" seeing. This should not be a significant problem even for a 100m ELT unless the outer scale length of atmospheric turbulence (L0) is unusually large (of order 1000s of metres).

- ***Dispersion Displacement Error*** **(Dispersive Anisoplanatism)** is a chromatic beam displacement analogous to angular anisoplanatism. If strong, high, turbulence layer(s) are present, NDL performance ($S \geq 0.8$) may only be possible for a restricted ZD range and/or restricted bandpasses.
- ***Diffractive effects*** of atmospheric turbulence must exist, but are unlikely to be of significance even for the largest ELTs.
- ***Differential AD*** over the ±1' FOVs typically predicted for "wide-field" AO systems does not appear to pose problems, except perhaps for broad-band spectrometers operating at maximum spatial resolution at the shortest wavelengths on the largest ELTs.

Conclusions: Atmospheric Dispersion does not appear to present insurmountable problems for achieving the hoped-for performance of even a 100m ELT. ADCs on ELTs can probably deliver the level of correction needed for the Science Programme. However:

- At least 2, possibly up to 4, different "full field" ADC units, optimised for different applications, will be needed. ADC should therefore be an instrument-specific (or at least, a wavelength-specific) function.
- Providing ADCs for each pickoff on wide-field (>10', say) ~non diffraction limited instruments (e.g. using Multi-Object AO) may be difficult in the visible where ADC diameter must be >D/~200.
- Departures from perfect atmospheric stratification may be significant in determining AD and may not be reliably predictable from surface data. An AD sensor should therefore be developed, to quantify AD anomalies and, possibly, for closed-loop control of ADCs.
- Site properties have an important impact on AO performance in the presence of AD:
- If the outer scale length of turbulence (L0) exceeds ~1km Chromatic Error (dispersive seeing) will be significant for the largest ELTs.
- Because of Chromatic Displacement Error (dispersive anisoplanatism) the presence of high-altitude turbulence layers will limit observations requiring extremely high-performance AO to ZDs < 45degrees, and/or to narrow bandpasses.

3.3.2 Small Studies

The project identified a Representative Instrument Suite ("RIS": see below. 8 instruments are currently included). This suite is approximately matched to the Science Case defined by the ELT Science Working Group (SWG). One of the Small Studies also initiated a study and survey seeking "mould-breaking" Innovative Instrument Concepts which might radically change current practice to the benefit of ELT science (for example, a photon-counting energy-resolving IR detector). The RIS provided preliminary Functional Requirements Documents for each conceptual instrument. The project is now developing a "demonstration of concept" Preliminary Outline Design for each of the instruments in the RIS. When complete, these will be reviewed to verify a match of each to the ELT Science Case. The project will then select a representative subset of (Currently 3) of these for more detailed Phase B "Point Design" studies to demonstrate feasibility and identify demands on technology development, site selection, the telescope design and on AO systems which will be made by these instruments.

The Representative Instrument Suite is an ensemble of hypothetical instruments intended to enable most of the science programmes outlined in the ELT Science Case. The RIS should also offer general-purpose capabilities for addressing problems which have not yet been thought of or which may arise from the actual use of the ELT or of other future facilities. Note that this suite is representative, not comprehensive as the instrument set described later in this report intends to be.

The RIS for the FP6 design study comprises:

1. High-resolution Spectrometer (HISPEC): This has been subdivided into separate visual (c.f. the ESO-OWL "CODEX") and NIR instruments.
2. High Time-Resolution Instrument (HiTRI)
3. Mid-IR Instrument (MIDIR): This is closely analogous to the ESO-OWL "T-OWL" instrument.
4. Multi-Object Multi-field Spectrometer-Imager (MOMSI)
5. Planet Finder:. This is closely analogous to the ESO-OWL "EPICS" instrument.
6. Sub-millimetre Common-User Bolometer Array-3 (SCELT), again, closely analogous to the ESO-OWL "SCOWL" instrument.
7. Wide-Field Spectrometer (WFSPEC)

Table 2: Summary of Representative Instrument Suite for FP6 Small Studies

Instrument (=ESO study)	Wavelength range (FOV)	Main Capability (AO mode)	Primary Science Goals	Institutes
HISPEC-V (=CODEX) High-resolution visible spectrometer	400-700 nm (seeing disk)	Ultra-high precision & stability visible-band spectroscopy (Seeing limited)	Measure dynamics of the Universe Evolution of fundamental constants RV detection of Earth-like planets Dynamics of the ISM	ESO, INAF-Trieste, Geneve Obs., IoA Cambridge
HISPEC-IR High-resolution IR spectrometer	1000-5400 nm -(Diff Ltd 32 x 32 IFU) -(seeing disk)	IR spectroscopy at resolutions up to 1 km s^{-1} (SCAO + seeing-ltd?)	Spectrally resolve proto-planetary discs & YSOs Planetary atmosphere physics	UKATC, ESO
HiTRI High Time-Resolution Instrument	400-1000? nm (sub-arcsec: a few diffraction discs?)	Intensity & polarisation variability at all timescales to nsecs (SCAO)	Physics of compact objects at all masses Quantum Optics	NUI-Galway
MIDIR (=T-OWL) Mid-IR Imaging spectrometer	3–27? μm (images 7x7" spectra 7" slit, IFU)	Mid Infrared Imaging & Spectroscopy with R=300, 3000 (IFU) & 50,000 (SCAO in Mid-IR)	Formation and evolution of proto-planetary systems Studies of high-z AGNs and GRBs Studies of the IR-luminous centers of nearby galaxies	MPIA, Leiden, ASTRON, ESO, UKATC
MOMSI (very approx ~MOMFIS) Multi-Object, Multi-Field Spectrometer-Imager	800-2500 nm (~100mas IFU - FOVs, ~2' patrol FOV)	Near IR imaging and spectroscopy with R=5000 and 20000 using many deploy-able IFUs (MCAO or MOAO)	Photometry & spectra (metallicity, dynamics) of resolved stellar populations in nearby galaxies Ditto for bright stars in Virgo Dynamics & composition of high-z galaxies	UKATC, Durham, ESO
PlanetFinder (=EPICS)	600-1900 nm (few arcsecs)	Coronagraphic imaging & Spectroscopy at diffraction limit (XAO)	Detection & characterisation of planets by imaging and spectroscopy Detection of nearby earth-like planets	ESO, Durham, Oxford, UKATC
SCELT (=SCOWL) Submm Camera for ELT	250-450-850 μm (up to 10'?)	Imaging at sub-millimeter wavelengths (no AO, but subarcsec image quality w/out visible WFSs?)	Debris disc detection to sub-solar-system masses Clump mass functions in galactic SFRs to sub-stellar masses Star-forming history of $\geq L_{M\text{-}Way}$ galaxies throughout the universe	UK ATC, ESO
WFSPEC Wide-field Spectrometer	600-2500 nm (tbc) 5' patrol field	Widefield multi-object (10-30) visible-near IR spectroscopy (LTAO, MOAO)	Origins of large-scale structure Redshifts at high-z	CRAL, LAM, OPM

3.4 Instrumentation Plans for Other Extremely Large Telescope Projects

There are currently two non-European Extremely Large Telescopes (ELTs) under detailed study and development. The Thirty Meter Telescope (TMT) is a public-private collaboration of American and Canadian partners whose aim is to build a 30m class, highly-segmented, telescope within the next decade. The other project, the Giant Magellan Telescope (GMT), is a joint effort of six institutes and universities to build a 20-25m facility employing a small number (7) of 8-m class primary mirror segments. The GMT is also pursuing a very aggressive schedule.

Consideration of the growth in complexity and development time of instrumentation for large telescopes leads to the conclusion that, in order to meet their ambitious completion dates, both the TMT and GMT must begin instrument procurement immediately. In fact, both projects already have mature instrumentation plans tailored to the scientific needs of their respective communities. These plans firmly recognize that for ELTs, it is foolhardy to develop the telescope without a solid concept of the instrumentation, and vice-versa. The role of adaptive optics in this synergy cannot be neglected.

In this section, we briefly review the TMT and GMT telescope designs, and describe their respective plans for both instrumentation and adaptive optics. Both facilities are currently at important design milestones, and these plans will naturally evolve. Up-to-date information on TMT and GMT is available at http://www.tmt.org and http://www.gmto.org, respectively.

3.4.1 TMT: The Thirty Meter Telescope

The Thirty Meter Telescope project follows the recommendations of the 2001 Decadal Survey of the US National Academy of Sciences. That document argued that a 30 m class telescope, led by the USA and funded by a public-private partnership, should be the highest priority for the American astronomy community in the first decade of the 21st century. The TMT Observatory represents a coming-together of three, independent efforts to build an Extremely Large Telescope: CELT, the California Extremely Large Telescope led by Caltech and UC; GSMT, the Giant Segmented Mirror Telescope coordinated by NOAO; and VLOT, the Very Large Optical Telescope proposed by the Canadian astronomical community.

TMT will be a thirty-meter class telescope with a very fast, f/1 segmented primary mirror and a concave, Gregorian secondary. An articulated tertiary mirror will deliver the final, f/15 beam to a range of instruments. The TMT reference design recognizes the need for large, gravity-stable platforms for both instrumentation and adaptive optics: in fact, the Nasmyth platforms are almost as large as the primary mirror.

The TMT Instrumentation / Adaptive Optics Suite

The TMT Instrumentation Working Group adopted the strategy to fund state-of-the-art, yet currently feasible and realistic instrument concepts. This clearly represents a balance between ensuring that there will be instruments ready for first light, and supporting innovation, which may offer significant discoveries.

In January 2005, the TMT Observatory issued a call for proposals for studies of 8 different instruments identified as high priority by the Scientific Advisory Committee. Eventually, they received sixteen different proposals representing the efforts of over 200 scientists and engineers in the USA, Canada, and France. The following section outlines each of the instrument concepts, with a focus on the role of adaptive optics in each.

TMT First Generation Instruments

IRIS: Infrared Imaging Spectrograph
- integral field unit (IFU) spectrograph imager
- 0.8-2.5 µm wavelength, 10" FoV (imaging) 2" FoV (IFU)
- spectral resolution R=4000 for J,H,K, broad and narrow band imaging
- fed by the NFIRAOS narrow-field AO system
- study team led by J. Larkin (UCLA) and K. Taylor (Caltech)

WFOS: Wide Field Optical Spectrograph
- multi-object, visible-wavelength spectrograph
- 0.3-1.1 µm wavelength, (goal: 0.3-1.6 µm), 75 sq. arcmin FoV (goal: 300 sq. arcmin)
- spectral resolution 500-5,000 (goal: 150-6,000)
- seeing-limited or GLAO operation
- study led by R. Abraham (Toronto)

MIRES: Mid-IR Echelle Spectrometer
- mid-infrared, high resolution spectrograph
- 8-18 µm wavelength (goal: 5-28 µm), 10" FoV
- spectral resolution R=5,000-100,000
- fed by the NFIRAOS narrow-field AO system, eventually MIRAO – mid-iR AO
- study team led by J. Elias (NOAO) and A. Tokunaga (Hawaii)

IRMOS: Infrared Multi-Object Spectrograph
- near-infrared spectrograph with multiple, deployable integral field units
- 1-2.5 µm wavelength, 2" FoV per IFU, at least 10 IFUs exploring 5' diameter FoV
- spectral resolution R=2,000-10,000
- fed by MOAO – multi-object adaptive optics system
- 2 studies: S. Eikenberry (Florida) & D. Andersen (Victoria)
  R. Ellis & K. Taylor (Caltech)

PFI: Planet Formation Imager
- high-contrast coronagraphic imager
- 1-2.5 µm wavelength (goal: 1-5 µm), contrast 10^6 (goal 10^7), 1-2" FoV
- spectral resolution R<100
- employs high-order extreme AO
- study led by B. Macintosh (Livermore)

NIRES: Near IR Echelle Spectrograph
- near IR diffraction-limited, high resolution spectrograph
- 1-5 µm wavelength, 20" FoV (TBC)
- spectral resolution R=20,000-100,000
- fed by the NFIRAOS narrow-field AO system
- study led by (TBC)

HROS: High Resolution Optical Spectrometer
- seeing-limited, high resolution spectrograph
- 0.31-1 µm (goal 0.31-1.3 µm), 1" slit
- spectral resolution R=50,000
- seeing limited or GLAO operation
- 2 studies: S. Vogt & C. Rockosi (Santa Cruz) and C. Froning (Colorado)

WIRC: Wide-Field Infrared Camera
- wide field, diffraction-limited near infrared imager
- IR wavelength TBD, 30” FoV
- broad and narrow band filters
- fed by Multi-Conjugated Adaptive Optics (MCAO)
- no study to date.

TMT Adaptive Optics Systems

NFIRAOS (pronounced “nefarious”)
- narrow field of view, first light facility
- 30” field with 150-200 nm RMS wavefront fidelity
- approximately 60x60 subapertures
- 6 laser guide stars, 25 W per beacon
- natural guide star tip-tilt-defocus sensor within 2’ FoV

MIRAO – Mid-Infrared Adaptive Optics
- feeds instruments at 7-20 µm (goal: 3-20 µm)
- 10” FoV
- 1-3 laser guide stars, 1 natural guide star
- approximately 15x15 to 30x30 subapertures
- goal: adaptive secondary to reduce emissivity

MCAO – Multi-Conjugated Adaptive Optics
- feeds WIRC
- upgrade to NFIRAOS
- correction layers at 0 and 12 km

MOAO – Multi-Object Field of View
- feeds IRMOS
- 20 positionable patches of 5” each, within a 5’ FoV
- micro-mirror (MEMS) deformable mirrors
- approximately 100x100 subapertures per field

Extreme AO System
- feeds Planet Formation Imager (PFI)
- very high-order micro-mirror (MEMS) deformable mirror

3.4.2 GMT: The Giant Magellan Telescope

The Giant Magellan Telescope Project seeks to build a 20-25 meter effective diameter optical/infrared telescope targeted to a broad range of astronomical research. The facility will be located in northern Chile, likely sharing the infrastructure of the Las Campanas Observatory. The GMT project builds on a rich heritage of large telescope innovation by its partners: The Carnegie Observatories, University of Arizona, University of Michigan, Massachusetts Institute of Technology, University of Texas Austin, Texas A&M University, Harvard University, and the Smithsonian Astrophysical Observatory.

The GMT optical design represents a natural evolution of current-generation, large telescopes, such as the MMT, Magellan, and particularly, LBT. Like the TMT, the Giant Magellan Telescope will be a compact Gregorian with a very fast primary mirror focal ratio (f/0.7). Unlike other ELTs, however, the GMT primary will consist of a very small number (7) of large (8.4 m) circular segments: six identical off-axis aspheres and a central, on-axis segment. The secondary mirror is entirely adaptive and consists of seven individual membrane segments, one per primary mirror. The combination of low segmentation and one-to-one mapping between primary and secondary drastically simplifies the control system, and should help make the telescope robust.

The GMT Instrumentation / Adaptive Optics Suite

Conceptual designs for first generation GMT instrumentation have been developed, and will form part of the telescope conceptual design review that took place in the last week of February 2006. The goal of these studies is to demonstrate the feasibility of instruments that address the science needs of the user community, as well as to identify design requirements for the telescope structure and to establish approximate costs.

GMT First Generation Instruments

GMACS – Visible Wavelength Multi-Object Spectrometer
- 0.35-1 µm wavelength, 18'x9' FoV
- spectral resolution R=3500 (red) 1200 (blue), other resolutions available
- fed by natural seeing, GLAO
- study led by S. Shectman, OCIW

Near-IR Multi-Object Spectrometer
- 1.0-2.5 µm wavelength, 7'x7' FoV (imaging), 5'x7' FoV (spectroscopy)
- spectral resolution R 1500, 3200, IFU under development
- fed by natural seeing, GLAO
- study led by D. Fabricant, SAO

Optical High Resolution Spectrometer
- 0.4-0.95 µm wavelength (goal: 0.32-1.0 µm), single object FoV
- spectral resolution R=30,000 (goal: 50,000)
- fed by natural seeing
- study led by P. MacQueen, UT Austin

Mid-IR Imaging Spectrometer
- 3.0-25.0 µm wavelength, 30" FoV
- spectral resolution R=1500
- fed by LTAO
- study led by P. Hinz, University of Arizona

Near-IR High-Resolution Spectrometer

- 1.2-5.0 µm wavelength, single object FoV
- spectral resolution 25,000-100,000 (JHK) and 100,000-150,000 (LM)
- fed by natural seeing, LTAO
- study led by D. Jaffe, UT Austin

Near-IR Extreme Adaptive Optics Imager

- 0.9-5.0 µm wavelength, 30" FoV
- spectral resolution 5-5,000
- fed by ExAO
- study led by L. Close, University of Arizona

GMT Second Generation Instrument Concepts

- Bragg fibre OH suppression spectrograph
- narrow band tunable imaging filters
- deployable IFUs

GMT Adaptive Optics Systems

GLAO – Ground Layer Adaptive Optics

- feeds Optical, Near-IR MOS
- exploits 160 m conjugate of adaptive secondary
- natural guide stars within 10-20' FoV
- laser guide stars for smaller 2-5' fields

LTAO – Laser Tomography Adaptive Optics

- feeds Near-IR High-Res Spectrograph, Mid-IR Imaging Spectrometer
- multiple laser beacons + natural guide stars
- all-sky diffraction limited down to 1 µm

ExAO – Extreme Adaptive Optics

- feeds Near-IR Extreme AO Imager

MCAO – Multi-Conjugated Adaptive Optics

- second generation capability

MOAO – Multi-Object Adaptive Optics

- second generation capability

4 REQUIREMENTS ON TELESCOPE, AO AND SITE

4.1 A comprehensive suite of ELT instruments

As a first step to derive requirements from the instruments on the telescope, the associated AO and the site of the observatory we have identified a wide list of instruments (see Table below) which should be considered for an European ELT. The assumed baseline is a telescope diameter of 42m (and a possible range 30-60m) with 3-6 mirrors before the instrument focus (including 1-2 adaptive mirrors). The scope is to consider initially all possible observing modes to be offered at the telescope and to associate to them a corresponding set of requirements. The chapters on the individual instruments each contain a specific requirements table for the respective instrument. A more detailed explanation of the entries in these tables is given in appendix 2. This exercise is not performed in an absolute vacuum: we have kept in mind the spectrum of programs in the ELT science case and benefited from the feasibility and concept studies carried out for the 50m EURO telescope, for OWL and for the TMT.
The relevance of different scientific goals of the project will eventually set the priority among the instruments and consequently on the requirements derived from them.

No	Name	Wavelength Range	Modes	Comments
1	High Resolution Visual Spectrograph	UV – 1000 nm	Echelle Spectroscopy	CODEX at OWL and SS, HROS at TMT
2	Visual Imager	UV – 1000 nm	Imaging	Scientifically worthwhile? Seeing-enhanced?
3	Multi-Object Visual Spectrograph	UV – 1000 nm	Medium Resolution Spectroscopy	WSPEC as SS, WFOS at TMT
4	High Time Resolution Instrument	B, V, R, NIR	High Time Resolution Imaging	QuantEYE at OWL, HTRI as SS
5	Polarimeter	B, V, R, NIR, MIR	Imager, Low Res Spectrograph	Polarimetric modes in other instruments also possible
6	Multi-Object NIR Spectrograph (high spatial resolution)	1000-2500 nm	“Small” Field MO Spectroscopy	MOMSI as SS – approaching diffraction limit, consider LTAO, single target in central field
7	Multi-Object NIR Spectrograph (wide field)	1000–2500 nμm	“Wide” Field MO, field spectroscopy	MOMFIS at OWL, WSPEC as SS, IRMOS at TMT
8	Planet Imager and Spectrograph	V, R, J, H (?)	Imager, Area Spectrograph, Polarimeter ?	EPICS at OWL and SS, Planet Formation Instrument at TMT
9	Wide Field NIR Imager	1000–2500 nm	Imager	ONIRICA at OWL, Split in two instruments with different sampling and field?, WIRC at TMT
10	High Resolution NIR Spectrograph	1000-5000 nm	High Res Spectroscopy	SS, NIRES at TMT
11	Mid-IR Imager and Spectrograph	3 - 20 μm	Imager, Medium- and High Resolution Spectrograph	T-OWL at OWL, MIDIR as SS, MIRES at TMT
12	Sub-mm Imager	Sub-mm bands	Sub-mm Imager	SCOWL at OWL, SCELT as SS

Table 3: A comprehensive suite of ELT instruments studied by the working group

The full process of selecting a telescope design including the associated AO system, and an high priority set of instruments which goes with it, will require a further iteration with the science case team, and it is beyond the time frame of this report.

While the listed instruments do cover well the observing parameter space, they do not necessarily represent the optimal solution which should be finally adopted. As an example going through the OPTICON science cases, there are number of really strong cases (incl. z=10/re-ionization) asking for an intermediate resolution Visual-Red- NIR spectrograph (R~10000) with highest possible throughput. In the current suite of instrument we have defined, such an instrument would either be a high resolution mode of one of the multi-object/multi-IFU instruments or a low-resolution mode of the high-resolution spectrographs. In both cases compromises have to be made on cost of the throughput. It will be important to take into consideration this aspect in the final choice of an instrument suite.

4.2 High Resolution Visual Spectrograph

4.2.1 Introduction and Observing Modes

High resolution spectroscopy is one of the observing modes which has the largest predicted advantage at a telescope of large diameter. The two most used high resolution spectrographs at 8-10m telescopes
(HIRES at Keck and UVES at the VLT) have produced in less than a decade more than 450 refereed papers which had a revolutionary impact on many field of astrophysics, from the study of planets around stars to stellar population in the Galaxy and in nearby systems to the study of IM at very large redshift. A similar impact is expected by the next step in telescope development. The huge collecting power of an ELT will provide sufficient photons to achieve significant S/N at very high spectral resolution for relatively faint sources. In first instance this will imply access to targets at larger distances than with 8-10m or, for the same magnitude, higher accuracy in the spectroscopic measurements. In the regime where the detector noise dominates, the limiting flux for a given exposure will improve with the diameter to the power of two.

A Visual High Resolution Spectrograph was studied in the framework of the OWL Instrument Concept Studies [RD03] (see section 3.2). The study of CODEX did show the enormous potential of combining an high resolution spectrograph like UVES or HIRES at an ELT with the stability properties of the radial velocity vacuum spectrograph HARPS installed at the ESO 3.6m. The CODEX concept is that of a single target instrument, providing high spectral resolution by slicing the image of the target and feeding it to separate spectrographs. The fixed format, wide spectral coverage is provided by an echelle grating and VPHG cross-disperser.

The CODEX study is being updated to the coupling of a 42m telescope within the framework of the FP6 Instrument Small Studies (see section 3.3).

4.2.2 Science Drivers

In the referenced study of CODEX at OWL the following programs were pinpointed as of highest scientific priority:

- measurement of the variations in the expansion of the universe as a function of redshift over large time scales.
- variability of fundamental constants
- detection of exo-planets from radial velocity studies of companion stars
- Li^6 in stars, Li^6/Li^7 in the Intergalactic Medium and Big Bang nucleosynthesis

The scientific goals of the above programs can be achieved with an ELT of 42m. Losses in collecting power – with respect to OWL- will have to be partly compensated by improvements in the instrument efficiency (it is easier to design a more efficient instrument coupled to a smaller telescope) and by an increase in the integration times.

In the OPTICON Science Case for a European ELT [RD01], the science cases which would require a high resolution visual spectrograph are discussed in the following sections:

- planets from radial velocity measurements, section 3.1.5.1
- stellar chemical composition, section 3.3.2.5
- stellar populations up and beyond Virgo, section 4.2.3, 4.2.4
- cosmic differential expansion, section 5.1.2.2
- fundamental constants, section 5.4

4.2.3 Outline Specifications and Instrument Concept

The table outlines under “Required” the specifications derived from the CODEX science cases and under “Goals” additional, tentative modes which would permit to enlarge the scientific case of the instrument, essentially to fainter targets at the expense of the spectral resolution and stability requirements. Compatibility of the additional modes with the baseline concept has not been explored and it requires proof of feasibility.

Instrument Parameter	Required	Goal
Wavelength range	400-700 nm	350–900 nm
Spectral resolution	150,000	Additional mode 40,000
Pixel sampling (dispersion direction)	3	2
Wavelength calibration repeatability	10^{-11} over time scales >10 years	
Total peak efficiency	≥ 10%	

Table 4: Specifications for a High Resolution Visual Spectrograph

The concept of a High Resolution Visual Spectrograph is based on well-established principles adopted on spectrographs such as UVES on VLT and HARPS on the ESO 3.6m telescope. These principles are:

- Fibre feed for highest input-beam stabilisation, further improved by optical scrambling systems
- Cross-dispersed echelle spectrum combined with a white pupil mount for high resolution and optical efficiency, as well as compact design
- Intrinsically stable opto-mechanical design with no moving parts in the optical path after the fibre feed
- Active environmental control, in particular of the temperature and the pressure (e.g. vacuum operation), in order to avoid instrumental drifts

The implementation of such a spectrograph at an ELT sets however strong constraints on the size of the instrument since, for a similar design, the instrument scales with the diameter of the telescope’s primary mirror. This assumes that no efficient adaptive optics systems will be available in the visible wavelength range, which would be able to reduce the image diameter for a given encircled energy by a significant factor. In order to take into account this fact and at the same time keep the efficiency of the instrument and its size reasonable, the following approach was adopted in the instrument concept:

- To cover the full desired FOV, i.e. the star-image size in the focal plane of the telescope and some reference sky, the pupil of the telescope is sliced and fed to a number of relatively "small" spectrographs, 5 in the OWL concept study. This modular concept allows adapting the instrument design in a very simple way (by using fibre bundles) to any telescope diameter.

- Simple “tricks” (pupil slicing and anamorphic optics) were adopted to use the detector area in the most efficient way

The advantage of the chosen approach is that all design elements, even if new in their application, are well known and present low development and cost risk. The most challenging point concerns the stability requirements, which are very demanding and many times higher than ever achieved with present instrumentation. An in-depth analysis of the HARPS performances shows however that, by optimizing its operation, a stability of 10^{-10} is already achieved on short term (~1 night) and could even be achieved on time scales of years.

4.2.4 Requirements and Pressures on Telescope, AO & Site

The main requirement from this type of instrument on the telescope design is the need of a spacious, gravity-invariant, thermally very stable instrument room. This almost necessarily leads to a laboratory in the telescope foundation or close to it.

In the spectral range of operation of this instrument one cannot expect significant improvement from the AO. It is however essential to achieve the full best seeing image quality and to have a high guiding accuracy (rms <0.03 "-tbc) which the telescope might provide with the proper combination of active optics and GLAO.

Since the High Resolution Visual Spectrograph has no demand on adaptive optics (apart from their role in providing stability in guiding and optical quality at the best seeing value), it is an instrument which can deliver unique science results from day one of the telescope operation.

There are no special requirements on the site.

TABLE 5: REQUIREMENTS ON TELESCOPE, AO & SITE - High Resolution Visual Spectrograph

No.	Requirement	Value or Value Range	Rationale	Index [1]	Major Driver on Telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	Ideal: 320-950 nm ; Goal: 350- 950 nm ; Required : 400-700 nm;	More science if spectral range larger, but at a high cost. UV possibly constrained by telescope mirror coatings.	C	On Telescope coating
2	Telescope final focal ratio	No strong constrain	Since the beam has to be injected in a fibre, f-ratio not critical	N	
3	Scientific Field Size (Diameter)	Required: 5 arcsec; Desirable: 10 arcsec	Parallel sampling of the sky spectrum is a requirement, hence the field requirement. A multi-object instrument operating over a larger field is not compatible with the concept explored so far within the OWL study. It would imply lower resolution, lower spectral coverage, lower radial velocity accuracy. Essentially a different set of science goals.	C	
4	Field flatness			N	
5	Linear field size	Not critical			
6	Image quality	FWHM = 0.5 arcsec at V	The instrument will operate with an entrance aperture close to the best seeing limit	C	
7	Adaptive Optics System	GLAO or LTAO (?)	A low _order system which provides an improvement >10% in the EE with respect to seeing down to visual- blue (?) wavelengths (in the seeing range 1.5- 0.8 arcsec FWHM especially) would be highly desirable to increase efficiency, but likely difficult to achieve. Would a fast tip-tilt system make sense?	D/C	

8	Stability of the FP scale	Not critical		N	
9	Thermal Background (telescope)		Not relevant in the spectral range of operation	N	
10	Stray-light in focal plane	Fainter than 22 magV/arcsec^2	It could be a problem if brighter and variable		
11	Differential Refraction		Not relevant for this instrument	N	
12	ADC	Working range 350-900 nm up to ZD 60 degrees	Given the small field it should be easier to insert it in the instrument. It is a must, calls for a slow beam and some back focal distance. ADC must be before fiber entrance.	C	
13	Max. Zenith Distance	Down to 60º ZD	To be more flexible in scheduling and to have access to part of the other hemisphere	D	
14	Type of telescope focal station	Laboratory-type room in basement of telescope or close to it	From the first concept study the instrument is likely to consists of a battery of identical vacuum spectrographs. The requirements on thermal and mechanical stability would be very high and not achievable with a sole active correction system. In the case of CODEX a room of 10 x 20 x5 m with a 0.1 K stability and outside the main structure of the telescope was proposed to host the spectrographs.	C	Special Focal Station
15	Back focal distance		No particular constrains on this parameter from this instrument given the small field	N	
16	Instrument attachment	It will not be attached to the adaptor-rotator	Guiding could be tricky if not on-axis.	N	
17	Max Mass of Instrument -not rotating and/or rotating	A few tons (7-15 ?)	A first value from a feasibility study only- not rotating	C	
18	Max Volume occupied by the instrument	See requirement # 14			Volume instrument room
19	Telescope pointing/guiding	Pointing to better that ± 2"; speed < 5min to any point of the visible sky; ready to observe; Guiding accuracy < 0.05" rms ??	Centering accuracy 0.01" (required for accurate radial velocity only, tbc) Slewing speed for fast varying targets of opportunity desirable. Consequences of guiding accuracy on instrument still to be studied.	C	Planet searches require observations of many targets per night
20	Telescope Chopping	Not required		N	
21	Maximum brightness level of stars to study	m(V)= 6 (tentative, extrapolated from UVES).	Effect on operation of the acquisition camera to this limit to be evaluated in feasibility study	N	
22	Calibration Requirements	Dedicated room in telescope area might be required	The calibration unit will be a critical subsystem. It might employ a laser comb which will have to feed the instrument entrance slit/fibre. Interface to telescope?	C	

	IMPACT ON OPERATION, SITE				
23	Operation mode	Service	Fully acceptable and preferred option	D	
24	Typical Integration Time	20-30 minutes (max 60 min)	Set		
25	Special supply	Coolant- LN2-	for CCD detectors if cryocooler not used		
26	Various atmospheric properties of the site	Low relative water content and strength of OH emission are an advantage. Median seeing <0.8" (better average seeing implies significant reduction in the cost of spectrograph	Water spectral features contaminate spectrum at visual and red wave.	D	
27	Latitude of the site	< 30 N; > 40 S	Relatively neutral to a Northern or Southern Hemisphere location. Synergy with ALMA desirable but not critical	N	
28	Altitude of the site	> 2000m	Not critical. Higher altitude desirable for UV.	N	
29	Percentage Photometric nights	Not critical parameter		N	
30	Percentage Clear nights	> 80 % (spectroscopic, 10-20% transmission variations admitted)	Important part of the science cases will be based on surveys and opportunity targets requiring many "spectroscopic" nights .	C	

[1] **Classification of requirements:**

C for critical to the realization of the instrument and/or its scientific goals
D for desirable or preferred
N for neutral

4.2.5 Technology Readiness & R&D required

In the CODEX study critical elements were identified, which need to be developed to build the spectrographs, to obtain the desired performances and to contain the costs. These are:

- Grating mosaics of 200x1700mm dimension (2 times the UVES mosaic) have to be procured
- An ultra-stable wavelength calibration and reference source has to be conceived and built. (a prototype laser comb is under development)
- Global Efficiency and image-scrambling performances of the fibre feed system
- Cost of CCD detector per square cm has to be reduced to keep the detector system share of the budget to a reasonable level

4.2.6 Cost and Complexity Issues

The hardware cost of CODEX coupled to a 60m telescope and based on 5 parallel spectrographs (entrance aperture 1 arcsec) was estimated at 23 M€. This includes 1 M€ for the cost of a dedicated laboratory and a full prototype to be tested at the VLT. A reduction of the number of spectrographs and hence a substantial reduction of the cost is expected if the diameter of the telescope is significantly smaller than 60m. A preliminary breakdown of qualified manpower in the scientific institutes for the project (obtained from an extrapolation of the values for the VLT instruments) led to around 100 person years.

4.3 Visual Imager

4.3.1 Instrument Modes

This instrument has a single imaging mode.

4.3.2 Science Drivers

Scientific Field Size

As with the wide field IR camera, there is no magic field requirement derived from a science case – in general the bigger the better. So this is derived here on the basis of building a feasible camera. A core consideration here is the physical size of a focal plane which can be built. E2V are planning to produce 4kx4k devices soon, which will be 3-4 side buttable and have 12-15 micron pixels. Omegacam (VST) uses 32 2kx4k CCDs at a detector cost of 2 M€. It is possible that CMOS may overtake CCDs at some time in the future, but for the moment it is not clear when this would happen. An ambitious, but probably achievable focal plane could therefore be envisioned to use ~100 new 4kx4k devices. Such a square focal plane would be 60 cm on a side, or 85 cm in diagonal. This is quite close to the maximum linear field at the telescope focal plane, which allows two approaches to optical imaging.

- Direct imaging onto the focal plane via a field corrector is feasible. The achieved square angular field on sky is then 0.6 / (Diameter/f-ratio). This solution does lead to enormous pixel wastage however. 15 micron pixels at an f/12 focus of a 42m would have pixel scales of 6 milliarcsec, so the seeing disc will contain 4000 pixels, so binning would certainly be used. At f/12 the sky background will be similar to that on current 8m telescopes and exposure times will be similar.

- Re-imaging could be another option. If a final camera at f/1 (eg. Schmidt-type) could be made, pixel scales of 100 to 60 mas/pixel would result for telescopes from 30 to 50m respectively, sampling the seeing quite adequately. The final focal plane would then require only a single 4kx4k device! The exposure time to be background limited would be shorter by a factor of 144 however.

In practice, the best option may lie between the two extremes. That is, include re-imaging with a moderate final f-ratio, to give both an achievable camera and sensible focal plane.

4.3.3 Outline Specification

The linear focal plane diameter entering either the field corrector or re-imaging optics places a strong constraint on achievable field of view. This is 4x4 arcminutes for a 42m, f/12. Optical image quality only needs to meet a seeing-limited budget. An ADC will be needed to achieve best image quality in the blue and UV.

4.3.4 Requirements and Pressures on Telescope, AO & Site

A seeing-limited optical imager places few constraints on the site or AO. The primary consideration is good seeing. This would be one of the simpler instruments which could be developed for day 1, and would not require AO to function.

TABLE 6: REQUIREMENTS ON TELESCOPE, AO & SITE – Visual Imager

No.	Requirement	Value or Value range	Rationale	Index[1]	Major Driver on Telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	Goal 350-1050 nm Requirement TBD	Assume maximum wavelength coverage. UV desirability needs consideration.	D	Blue end coating requirement
2	Telescope final focal ratio	<F/19 for 20m, <F/13 for 30m, <F/10 for 40m etc	Combine requirements 3 and 5 to get an effective focal length of <380m.	C	F# and pixel size trade off
3	Scientific Field Size (Diameter)	~0.6/(Diameter/f-ratio) = 4x4 arcminutes for 42m,f/12	Seeing limited imager. Preferably with re-imaging.	D	
4	Field flatness	Not an issue	Field curvature will be corrected in camera optics	N	
5	Linear field size	< 1 metre	Constraints (i) maximum size for first optical element (ii) Instrument total mass must be reasonable and scales as L^3.	D	
6	Image quality	seeing limited optics for 6' field		C	
7	Adaptive Optics System	GLAO	Relies mainly on gain provided by large aperture	D	
8	Stability of the focal plane scale	Not critical	Many objects in field will allow accurate relative astrometry.	N	
9	Background emission from telescope	Not important		N	
10	Straylight from telescope	Minimised as in a properly baffled camera.	Moon will contribute structure to images, as well as a higher scattered light background	C	Trade-off with IR performance
11	Differential Refraction	Not important		N	
12	ADC	Needed	to achieve best seeing limited performance in the blue and UV	C	Not yet studied for seeing limited case
13	Zenith Distance Angle Range of operation	to 60 degrees zenith angle	As long as ADC is incorporated	N	
14	Type of telescope focal station	Fixed instrument	Heavy instrument is best left fixed, but system trade off needed	D	
15	Back focal distance	No requirement	Instrument front element can be close to focal plane. Assumes re-imaging.	N	
16	Instrument attachment	Adapter/rotator		D	
17	Max Mass of Instrument (not rotating and/or rotating)	8 tonnes without Ad/Rot	based on linear field^3 scaling	D	

18	Max Volume occupied by the instrument	15 cubic metres	2.5m diameter and 4m long	D
19	Telescope pointing and guiding	Pointing not important. Tip-tilt field stabilization	Wide field of view	C
20	Telescope Chopping	Not required		N
21	Maximum brightness level of stars to study	Very faint > 20 mag	targets will be stars fainter than currently can be observed with 8m in normal exp times.	D
22	Calibration Requirements	flatfielding		D
	IMPACT ON OPERATION, SITE			
23	Operation mode	Any		N
24	Typical Integration Time	depends entirely on final f-ratio		D
25	Special supply	None		
26	Various atmospheric properties of the site	Highest priority is seeing	Seeing has the biggest impact on S/N ratio	D
27	Latitude of the site	Within ±30 deg of ALMA	to allow multi-wavelength studies	D
28	Altitude of the site	Not important		N
29	Percentage Photometric nights	high		
30	Percentage Clear nights	high		

[1] **Classification of requirement:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.3.5 Technology Readiness & R&D required

For this and other ELT instrumentation projects, the development of large fast camera designs should be considered. Large refractive optical elements may be an issue depending on choice of FoV and F number of feed.

4.3.6 Cost and Complexity Issues

Not a very complex instrument. The main challenge is in procuring the CCDs and mounting them all flat over a large focal plane. The cost should be moderate. Say 4 M€ for the CCDs and 8 M€ total for the instrument. FTEs should be moderate, order 50.

4.4 Multi-Object Visual Spectrograph

4.4.1 Instrument Modes

Multi-object spectrograph operating in the visual optical region. The resolving power is moderate covering ideally R=~500-10000 although a more realistic coverage might be 700-7500. The wavelength coverage would be 320-1000nm. IFU mode is likely to be of less use but if it could be implemented it might provide a useful complement. A non-cryogenic extension to ~1500nm would be beneficial for a number of science cases.

Depending on design it could provide basic imaging facilities with broad-band filters for pre-imaging of variable/moving targets.

4.4.2 Science Drivers

The OPTICON science cases [RD01] for this instrument are not very carefully detailed and are somewhat incomplete. The most relevant are:

- Section 4.1.3 "The High Redshift ISM", which contains little information but which can be to some extent subsumed under the cosmic tomography science case mentioned below.
- Section 4.3 "Extra-galactic massive stars beyond the Local Group". This case lists a FoV of ~1', spatial resolution 0.1"-0.02" and R=1000-10000 operating in V and R with a target density of ~tens/arcmin^2
- Section 5.2.3 "Galaxies and AGN at the end of re-ionization (FoV > 5'x5' - ideally 10'x10' - although with a focus on slightly lower redshift systems this might be less crucial. R=5000-10000. Spatial resolution of 0.1"-0.2".
- Section 5.2.5 "Early chemical evolution of the IGM". Again the particular exposition in the OPTICON science case is not well suited to this instrument but the general goal can be achieved by the "Cosmic tomography" case below.

Besides the OPTICON science cases, the TMT has also assembled science cases for its Wide-Field Spectrograph (WFOS). These complement the OPTICON science cases and are worth an examination here for the constraints they set on the instrument parameters. They also overlap somewhat with the GSMT science cases for a similar instrument.

- "Cosmic Tomography". Subsumes the 4.1.3 and 5.2.5 points of the OPTICON science case. The goal is to probe the IGM through Lyman alpha forest spectroscopy of field galaxies. This allows a 3D map of the IGM to be built up with a scale of ~few 100kpc. The requirements placed on the instrument are R=1000-10000 and wide field (~5'x5'). The research can be done in seeing ~0.8" but will benefit from PSF matched to the intrinsic size of the objects, which in this case is ~0.4" or so.
- "Stellar populations" This is similar to 4.2, "Resolved Stellar Populations" in the OPTICON science case but less ambitious and aims to study giant stars down to the Horizontal Branch in the Local Group. The requirements is R=5000-10000 and a wavelength coverage from ~400 to 1000nm. The surface density is expected to be ~100 arcmin^2 so a large multiplexing capability is clearly beneficial. Select spectral ranges in the blue and red are also of interest so a choice of dichroics might be useful.
- "Dark Matter Mapping" This aims to map the dark matter halo of elliptical galaxies using their globular cluster and planetary nebulae populations. The requirements are R~2000-5000, and a substantial FoV.

The TMT cases are less ambitious than the OPTICON science cases so are driving the design less, but they provide a useful minimum baseline to refer to. One consequence of all the science drivers is that the optimal placement for a dichroic in the telescope is around 560nm because that is where the information content in stars and galaxies at z~0 is at a minimum. But it is also clear that a choice of dichroics will greatly benefit science.

4.4.3 Outline Specification

In the absence of an in-detail European study of a seeing-limited MOS, the following specifications should be viewed as providing a sketch of an instrument that can fulfil the requirements of the science cases. There are two designs for such instruments for 30m class telescopes currently available. One is the multi-slit spectrograph WFOS for TMT and the other is the MOMFOS multi-fibre spectrograph for GSMT. In view of the de-scoping of the European ELT project it is clearly desirable to conduct a more in-depth European study of such an instrument and the FP6 design study of WFSPEC is likely to provide such an opportunity.

The discussion here will be biased towards a slit spectrograph since the WFOS concept has been somewhat more developed but we do not wish to make a decision here on fibre vs slit spectrograph. In fact it may very well be that a fibre spectrograph with a set of pick-off mirrors might provide a significantly smaller instrument than what is envisioned here.

General requirements
The instrument type is well-known and will require relatively small extrapolation from an 8m class MOS, but the space requirements will have to be examined closely. In the case of a slit spectrograph it seems beneficial to divide the instrument into several separate spectrographs to reduce size. This approach has been repeatedly mentioned in the literature and is the one chosen for the WFOS design.

- *If* the focal plane is divided then care must be applied to ensure that it is possible to efficiently tile the sky.
- The layout of the detector area is important and increased efficiency can be achieved if this has the right geometry. A ratio of 1.5-1.9 for dispersion to spatial FoV will be beneficial.
- Nod and shuffle modes would likely be beneficial for this kind of instrument to allow for high precision sky subtraction and high density of targets.
- The spectral resolution should ideally be R~500 to R~10,000 (20,000) with a realistic range being 700-7500. The lower range is likely to be useful for redshift determination of faint galaxies, but we note that the WFOS science cases require R>1000.

Camera
The camera must clearly be fast to avoid too much oversampling of the spectra. The WFOS design calls for a f/1.5 camera, whereas MOMFIS has a target f-ratio of f/0.75 which is rather challenging. The two are likely to bracket the f-ratios considered for a >30m telescope. In passing it should be added that although oversampling should be limited as far as possible, it may open up the possibility of novel cosmic ray removal techniques.

The default would probably be to implement the camera with a blue and a red arm to optimise performance and this raises the question of dichroics. These are likely to be expensive and it would be advantageous to have a choice of dichroics, depending on the science drivers.

Gratings
For the low resolutions, R<~1000, ruled gratings will be used whereas at higher resolutions it will almost certainly be VPH gratings. This raises some questions if the pupil size (as seems likely) exceeds the current maximum sizes (340x240 mm mosaiced VPH gratings have been produced by CSL in Liege). The behaviour of a mosaiced grating is not yet thoroughly understood but is not likely to be a major risk.

Detectors

The required detector real estate is a key challenge for a wide-field seeing limited instrument regardless of the design chosen. A 42m telescope with 13.5 µm pixels will have 23 pixels/arcsec at f/1.5. So for a slit spectrograph with a FoV of 10' this requires about 14k pixels along the spatial axis. Depending on the final instrument design 20-26k pixels will be required along the dispersion axis. This scales proportionally with the telescope diameter. The situation for a fibre spectrograph is essentially the same but a larger structure than what can be held on a Nasmyth platform might be possible. However it is possible that a innovative design using pick-off mirrors feeding a fibre bundle can reduce the requirements on spatial coverage - this should be given high priority in any pre-study as it would likely be the only way an instrument of this kind could be built for telescopes with D > 40m.

Certainly in the case of fibre spectrographs, but also for slit spectrographs it is likely that a nod-and-shuffle mode might be beneficial to ensure good sky-subtraction. It does raise the question of how to nod efficiently and this would require a tip-tilt mirror. It will also increase the mechanical complexity of the detector somewhat as the detector might have to be physically moved to avoid/limit problems with charge traps, as was done for GMOS.

4.4.4 Requirements and Pressures on Telescope, AO & Site

TABLE 7: REQUIREMENTS ON TELESCOPE, AO & SITE – Multi-Object Visual Spectrograph

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	320-1000 nm	To optimize studies of galactic stellar sources and O VI in the high redshift IGM the instrument should push as far towards the blue cut-off as possible.	C	Blue end coatings
2	Telescope final focal ratio	Not critical		N	
3	Scientific Field Size (Diameter)	> 6'	Density of targets. WF sensors in ring outside this.	C	
4	Field flatness	Not critical			
5	Linear field size	Not critical	The beam size will be important within the instrument but the input size is not crucial.	N	
6	Image quality	<0.2" FWHM	Natural seeing (possibly with GLAO) limited instrument	D	
7	Adaptive Optics System	GLAO	This instrument can carry out all science cases without AO but efficiency will be higher with GLAO and the Galactic and nearby-galaxy targets will be more efficient. Distant galaxies are likely not to benefit significantly with PSF<0.4" due to the intrinsic size of objects.	D	

8	Stability of the focal plane scale	Not critical			
9	Background emission from telescope	Not critical, but as low as possible	Optical instrument so thermal background is not likely to be strong constraint.	N	
10	Straylight from telescope	Low level, baffling in telescope	Predominantly faint targets. Baffling will impact ability to do accurate flat-fielding. Baffling in telescope will reduce complexity of instrument somewhat.	D	
11	Differential Refraction	ZD <60°	In the case of a slit spectrograph for long exposures masks will be cut for the middle of the exposure time, ZD <50º is easier.	D	
12	ADC	Essential, classical sufficient. High blue-throughput	Possibly integrated in instrument	C	
13	Zenith Distance Angle Range of operation	60°	Long exposures likely to be common		
14	Type of telescope focal station	Depending on implementation.	Very heavy. If implemented as slit spectrograph it needs a Nasmyth platform, if implemented as a fibre spectrograph Cassegrain or external focal station are also possible. Gravity invariance will be beneficial but not strictly necessary.	N	
15	Back focal distance	>1m	Space for optics. WFOS has BFD ~20m with a physical distance of 1.5m. Implementation as fibre spectrograph will ease these requirements somewhat.	D	
16	Instrument attachment	Fixed, need field rotator		C	Large & heavy load on rotator
17	Max Mass of Instrument (not rotating and/or rotating)	~30 tons	From WFOS feasibility study	C	Very heavy if on the Nasmyth platform
18	Max Volume occupied by the instrument	8m diameter x 10m length ~500 m^3	From WFOS feasibility study	C	Space must be made available
19	Telescope pointing and guiding	<0.4" pointing	Acquire targets	C	
20	Telescope Chopping	Not required			
21	Maximum brightness level of stars to study	Not critical			
22	Calibration Requirements	Flat-field, wavelength calibration, PSF monitoring useful	The need for accurate flat-fields will depend on science cases.	C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	Primarily service	Survey spectrograph, likely to have long programs so well suited for service observing.	D	
24	Typical Integration Time	1/2 hr per exposure, 10-30 ks per mask	The integration time per mask might exceed 100 ks in special cases.	C	

25	Special supply	None			
26	Various atmospheric properties of the site	Good transparency in the blue. Median seeing <0.8"	Cosmic tomography programs will benefit from good blue throughput	C	
27	Latitude of the site	close to equator, possibly <0º	Sky coverage. <0º gives synergy with ALMA and VISTA/VST as target lists will typically be taken from here.	D	
28	Altitude of the site	>2000m	Blue transparency	D	
29	Percentage Photometric nights	>10%	Programs requiring good spectrophotometry	N	
30	Percentage Clear nights	>80%	Survey spectrograph, likely to be in use as often as possible	C	

[1] **Classification of requirement:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

Science from day 1
This instrument can carry out a number of the key scientific goals from day 1 regardless of the AO option offered. It is also relatively low-risk since it is a well-known type of instrument and requires relatively little R&D.

It is also worth noting that the key science projects cannot be done with 8m class telescopes nor with JWST so the instrument will fill a clear niche here.

AO development plan
The distant galaxy studies can be done at almost optimal efficiency from day 1 assuming a decent site with seeing typically better than 0.8 arcsec. However, studies of stars in our galaxy or nearby galaxies and related projects will benefit from improved AO correction.

Given the required FoV, this kind of instrument is however unlikely to benefit from any more advanced AO correction than GLAO. This will probably mean a GLAO system with wavefront sensors around the science field although the final distribution of wavefront sensors (and related loss of science field) will be a trade-off between science cases. However the gains of GLAO are so small that the improvement in image quality obtained by placing WFS within the science field is unlikely to outweigh the loss in field of view.

Telescope structure
This instrument is likely to put significant pressure on the size and weight limitations of the Nasmyth platform. It almost certainly would exceed the limits set for OWL.

4.4.5 Technology Readiness & R&D required

This instrument could be designed to use almost only readily available technology. Interference filters for narrow-band imaging and the grating to use seem to be the areas potentially requiring R&D. It would be very well suited as a first-light instrument.

4.4.6 Cost and Complexity Issues

The instrument would be large and providing a broad range in resolving power might lead to a complex design. The cost of the instrument can be estimated from the TMT WFOS study which gives an estimate of ~30 M$ exclusive of labour costs (~50 M$ including). If we assume that this scales linearly with telescope diameter, the total cost for a 42m would be ~40 M€ exclusive of labour costs. An extension to 1.5µm would add significantly to the cost due to the much more expensive detectors. The estimated man-power requirement is 100 – 200 FTE based on the WFOS feasibility study.

The main complexity would arise from the size and weight of the system so any innovative designs that can reduce this significantly should be high priority in any European study of this instrument.

4.5 High Time Resolution Instrument

4.5.1 Introduction and Instrument Modes

An instrument (QuantEYE) for the study of astrophysical phenomena at high time resolution has been investigated in the framework of the OWL Instrument Concept Studies [RD03] (see section 3.2). QuantEYE was designed to take advantage of the huge photon collecting power of OWL to observe stellar sources through different filters (B, V, R broad bands, a few selected narrow bands and polarizers) at a time resolution of 10^{-3} to 10^{-9}s. This instrument would be unique in providing data on rapidly varying phenomena from astrophysical sources and to investigate photon arrival time correlations. The instrument as proposed is able to monitor the flux from a target in the center of the field and a reference star within a field of ~ 1 arcmin.

In the framework of the FP6 ELT Design Study (see section 3.3), an Instrument Small Study for a High Time Resolution Imager is now under way and will permit an additional investigation of the scientific drivers and design options for an instrument dedicated to high time resolution astrophysics. The study report will be available in the second half of 2006 only. While they are similarities between QuantEYE and this instrument, the HTRI concept is more centered on the study of stellar phenomena showing variations in the 10^{-3} to 10^{-6} second time scale with a capability for imaging over a small field and possibly as a photon-counting Stokes' polarimeter.

4.5.2 Science Drivers

The science goals and the details of the expected performance are presented in detail in the QuantEYE OWL Instrument Concept Study Report and summarized in the OPTICON Science Case [RD01], section B 1.6.4.

In the OPTICON ELT Science Book there is a single scientific case calling for fast photometry with a time resolution of the order of 10^{-3} to 10^{-4} sec (study of isolated neutron stars, section 3.3.3.2). There is a need to identify and develop more scientific programs exploiting this observing mode and to underline the advantage to carry them out at the ELT. This will be done in the framework of the FP6 Small Study.

4.5.3 Specifications and Instrument Concept

The basic specifications of QuantEYE could be summarized as follows:

- parallel observations of the target and a reference star
- minimum spectral range 400-700nm
- possibility to insert broad band, narrow band filters and polarisers
- detector and acquisition system capable of a resolution of 10^{-9} seconds

The resulting instrument concept is based on two pick-up units in the focal plane of the telescope. In each unit the telescope beam is recollimated and the telescope pupil is sampled by a 10 x10 lenslet array feeding a fibre bundle. Each fibre of the bundle is eventually coupled to a 50 mm Single Photon Avalanche Diode (SPAD) detector in a 10x10 dispersed array. One major advantage that should also be mentioned is that this design permits photon-counting with rates of up to approx. 1 GHz, thus fully utilizing the light-collecting power of an ELT. A current technological limit is that the maximum count-rate in one individual SPAD is limited to maybe 10 MHz; by distributing the flux over 100 of them, count-rates of up to 1 GHz become feasible, enabling searches also at the nanosecond-scale. The acquisition system can record the arrival time of each individual photon to better than 100 ps.

4.5.4 Requirements and Pressures on Telescope, AO & Site

This type of instrument has no special demands on the telescope and AO performance and no special requirement on the site.
It exploits the telescope as a photon collecting bucket and does not need AO. As such the High Time Resolution Imager could achieve its scientific goals from the time of first light.

TABLE 8: REQUIREMENTS ON TELESCOPE, AO & SITE – High Time Resolution Instrument

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	400 nm-1000 nm, -->2000 nm desirable	broadband optical studies, limited by current detector spectral response. Extension toward near IR with germanium based photon counting APD's under development a future possibility	C	Blue end coatings etc
2	Telescope final focal ratio	~f/11	to limit the detector imaging area faster ratios would be desirable. f/11 more compatible with foci at smaller telescopes for testing	C	
3	Scientific Field Size (Diameter)	15 arcsec minimum (up to 60 arcsec desirable)	point source studies and availability of a reference star for calibration	C	
4	Field flatness	not critical		N	
5	Linear field size	not critical		N	
6	Image quality	compatible with best seeing of the site	to maximise signal-to-noise . No effective AO is expected at blue-visual wavelengths	D	
7	Adaptive Optics System	GLAO, SCAO	Depending on their performance to ensure best image quality and guiding stability of the telescope . Possible negative effects on flux stability to be investigated.	C	
8	Stability of the focal plane scale			N	
9	Background emission from telescope	not relevant	thermal emission outside the spectral range	C	
10	Straylight from telescope	should be minimized and be temporally stable	can be a limitation for imaging at short time scales of relatively faint sources	C	
11	Differential Refraction	not relevant		N	
12	ADC	essential	for performing broadband optical observations	C	
13	Zenith Distance Angle Range of operation	60º	long integration times on faint targets; access to larger fraction of the sky	D	

14	Type of telescope focal station	Any	instrument will be small and not gravity restrictive	N	
15	Back focal distance	≤500mm	would permit insertion of ADC before the instrument	N	
16	Instrument attachment	fixed to field rotator	possibly not standalone but piggybacked with other instrument	D	
17	Max Mass of Instrument (not rotating and/or rotating)	<500 kg	very small instrument if dedicated to imaging through different filters only		
18	Max Volume occupied by the instrument	guess at 2 m^2	see Req. 17		
19	Telescope pointing and guiding	<1arcsec pointing accuracy . Guiding accuracy <0.1"	No problems in the acquisition of the targets which are relatively bright in normal integration. Required guiding accuracy depend on the optical feed to detector. If the target is acquired through a small, fixed aperture,fluctuations could be caused by light in the stellar profile wings quivering outside the aperture	C	
20	Telescope Chopping			N	
21	Maximum brightness level of stars to study	-1 mag	With nanosecond time resolution very bright stars could be a target	N	
22	Calibration Requirements	flat-fielding, telescope polarisation	need to calibrate polarisation of the telescope, and produce accurate deep flat-fields. Reference star in the same field is desirable	C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	possibly service	TBD		
24	Typical Integration Time	half-night timescale	TBD	C	
25	Special supply	TBD	Possibly cyrogenics.		
26	Various atmospheric properties of the site	Best seeing possible	for diffraction limited imaging in narrow field	C	
27	Latitude of the site	close to equator	to have access to both hemispheres	D	
28	Altitude of the site	not critical	N		
29	Percentage Photometric nights	not critical	good-excellent photometric nights preferred	D	
30	Percentage Clear nights	not critical	N		

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.5.5 Technology Readiness & R&D required

The present QuantEYE design was intentionally made to be technologically conservative, only using small extrapolation from existing technology. The 10x10 array of individual SPADs, fed by optical fibres is just 100 units of precisely such SPADs which are currently operating in the laboratory at Lund. Thus no technological development is required for that particular solution apart from some design work for optimisation and the actual manufacturing. However, as a next step one could consider an integrated, large, imaging SPAD array, and such are not yet commercially available. Other detector devices are being considered within the HiTRI Small Study.

4.5.6 Cost and Complexity Issues

Whatever the final specifications and design, the High Time Resolution Imager at the ELT is a relatively simple instrument from the opto-mechanical point of view. The main cost driver will be the size and expected performance of the detector system. Hardware and software coping with the huge photon rate and their time tagging represent the other crucial subsystems.

In the case of QuantEYE the total hardware cost was estimated at 2.5 M€ (for the case of two heads leading to 10 x10 SPAD arrays). The concept study did include an estimate of ~100 person years for the manpower in the institutes responsible for the project.

4.6 Polarimeter

4.6.1 Instrument Modes

Dedicated polarimetric instruments are rare. However, NIR or optical imagers and spectrographs can be equipped with polarimetric modes. In this report, science drivers and impact on the telescope of differential and absolute polarimetry in the visible, NIR and MIR are summarized.

4.6.2 Science Drivers

Major sources of polarised emission are synchrotron emission, Zeeman effect, dichroic absorption and scattering of light. Hence, the polarisation studies allow for a detailed characterization of the physical processes causing emission and from where the emission originates for a variety of astronomical objects. In addition, differential polarimetric imaging can efficiently enhance the contrast and reveal faint polarised sources (disks, substellar companions) in the vicinity of a bright unpolarised source.

Disks

At visible and NIR wavelengths disks scatter light from the central source rather than being self-luminous. Hence, polarimetry is a vital tool for the study of disks of any kind (debris, gas, circumstellar, circumbinary, circum-AGN). For unresolved disks the scattering polarisation can often reveal important geometric information such as the orientation and inclination. Detailed comparison of observational data to theoretical models at different wavelengths allows us to pinpoint the geometric distribution, the optical properties and size distributions of the dust grains in the disk, and thus help understand growth processes. The highest possible angular resolution is often essential because spatial averaging can decrease the apparent polarisation. Also the high contrast is required to avoid contamination with un-polarised starlight or nuclear light in AGN. Polarisation degrees of the order a few percent to about 30% can be expected in the NIR and visual range.

In the mid-IR, polarimetry provides a very important diagnostic for the properties of dust grains in situations as diverse as AGN, young stellar objects, protoplanetary and debris disks, and comets. Uniquely, polarimetry is capable of separating emissive from absorptive components. Lastly, polarimetry in the thermal IR can also provide information on the structure of magnetic fields. Gemini is supporting Michelle polarimetry, and CanariCam (on GTC) will have excellent imaging and spectropolarimetry. Although the thermal IR on space telescopes is superior to what can be obtained from the ground, JWST will not have a polarimetry mode for any of its instruments.

Mass loss from Evolved stars

Measuring the degree of polarisation of the scattered light reveals the distribution of dust while the polarisation at different wavelengths will provide strong constraints on the grain size and shape distribution. This information is of interest for many types of stars in their late stages of evolution, like supernovae, novae and stars undergoing heavy mass loss such as AGB stars and LBV. Polarimetric parameters are especially important for models of nucleation and growth of dust grains.

AGN

In active galactic nuclei, all different kinds of polarised emission play a role. Polarimetry at different wavelengths allows us to disentangle the different polarisation mechanisms (scattering in the narrow line region or off the torus and dichroic absorption by torus dust). Particularly important for AGN is the fact that many type 2 AGN are in fact partially obscured type 1 AGN, whose characteristics are visible in polarised (scattered) light. In addition AGN jets are highly polarised by synchrotron emission. In the simplest model of pure synchrotron emission one expects (after correction for Faraday rotation) the same polarisation pattern in all wavelength regimes. However, there are differences in the details of the polarised emission at different wavelengths (NIR vs radio), which provide insight into the radial structure of the jet.

Stellar magnetic fields
Stellar magnetic fields are important for the understanding of stellar evolution. Magnetic fields are already an essential ingredient during the collapse and fragmentation of proto-stellar clouds. During the lifetime of a star, magnetic fields are important for the loss of angular momentum, the convection properties and mass loss. Strong magnetic fields are a fundamental property of neutron stars and many white dwarfs. Spectropolarimetric measurements of the Zeeman effect in absorption lines is the most important tool for the investigation of stellar magnetism.

Dust and magnetic fields in galaxies
The dynamics and distribution of the interstellar material in galaxies is closely related to the structure of the large scale magnetic field. The magnetic field is also a key parameter for the physics of the collapse and fragmentation of proto-stellar clouds and the resulting star formation process. The orientation of the interstellar magnetic field can be determined from the polarising (dichroic) absorption of stellar light by dust particles, which are aligned by the magnetic field. Polarimetry provides therefore information on the magnetic field structure in galaxies and the Milky Way on different scales depending on the spatial resolution. Further the dust particles in the ISM can be investigated for a large redshift range providing insight in the cosmic cycling of dust particles.

GRBs and other high energy sources
High energy processes in GRB, neutron stars, X-ray binaries, SNR and other sources produce non-thermal and therefore polarised emission in the visual-NIR range. For these sources the polarisation provides information on variation in the magnetic structure and the homogeneity of the emission region.

4.6.3 Outline Specification

For the impact on the telescope and instrument design one should distinguish between different polarimetric modes: Imaging (spectro)-polarimetry requires besides a polarimetric mode also an adequate spatial resolution and field of view to distinguish between the polarisation of different structures or components of a target. Also for many unresolved sources (spectro)-polarimetry is very useful so that for some applications spatial resolution and field of view are not important. Even fibre optics may be used after the polarisation analysis to guide the light to a spectrograph for spectropolarimetry. High precision polarimetry (precision of 10^{-5} or better) is required for bright targets in order to exploit the light collecting power of an ELT. A high absolute accuracy (of the order 10^{-3} or better) of the polarisation measurement (instrument calibration) is essential for many objects where no reference (unpolarised or continuum) emission is registered simultaneously with the investigated polarised signal. For polarimetry the instrumental polarisation and polarisation cross talk effects introduced by the telescope have to be minimized as far as possible. A rotationally symmetric telescope introduces no polarisation effects (induced instrument polarisation $< 10^{-4}$, essentially no polarisation cross talk) and is therefore ideal from the polarimetric point of view. This favours a Cassegrain-type telescope where the polarisation analysis, e.g. for a small field of view, is made in the Cassegrain focus (or similar). A rotational symmetric telescope/instrument concept is required to achieve a high absolute polarimetric accuracy. If possible, reflections from strongly inclined surfaces (>15 degrees) should be avoided as far as possible. Nasmyth foci or similar designs are problematic but may still be useful, if only the differential polarisation signal (with respect to a continuum or a bright source in the field) is measured and the highest possible absolute polarisation accuracy and stability is not required. Nasmyth instruments with polarimetric mode may still require that the introduced polarisation by telescope mirror M3 can be stabilised and compensated with crossed mirrors and retarder plates (transmissive optics) to a residual polarisation of less than 1%. The non-linearity of the currently available detectors requires such a precision in the compensation of the instrument polarisation.

A good case can be made for including circular polarimetry, and its inclusion in a number of instruments could affect their design (e.g. the need to have 2 retarders in the optical path), although it does not affect telescope design.

The combination of polarimetry with an AO system requires an approach where all polarimetric issues are considered with high priority from the very beginning. An existing instrument concept is often not adaptable in a later stage for the introduction of a sophisticated polarimetric mode.

Sensitivities of 10^{-6} (or better) for fractional polarisation measurements are potentially ideal for detecting the reflected light from unresolved extrasolar planets (and hot-Jupiters are unlikely to be resolved in the foreseeable future), but these sensitivities may only be achievable with a dedicated polarimeter. Such a polarimeter (PlanetPol) has been used it at the WHT to obtain fractional polarisation sensitivities of better than 10^{-6}. It is photon noise limited, is not an imaging device and therefore just needs a big light bucket. Such an instrument could be considered for use on a 50-m class telescope when conditions are not optimal for AO.

4.6.4 Requirements an Pressures on Telescope, AO & Site

TABLE 9: REQUIREMENTS ON TELESCOPE, AO & SITE - Polarimeter

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	400-2400 nm 2.4 to 28 µm	VIS, NIR and MIR to cover wide range of astronomical applications (see science drivers). Polarimetric mode also relevant for sub-mm wavelengths, see section 4.13.1	C	
2	Telescope final focal ratio	>f/10	Need to insert retarder plate in case of Nasmyth focus	C	
3	Scientific Field Size (Diameter)	>10 arcsec	Study of circumstellar disks with diameters above 100 au, Polarimetric imaging of galaxies	C	
4	Field flatness	not important			
5	Linear field size	not important			
6	Image quality	<100 nm RMS for low spatial frequencies < 1/m, <40 nm RMS for higher spatial freq	Required for efficient AO correction	C	
7	Adaptive Optics System	SCAO/XAO	Some science drivers (circumstellar disks, Exoplanets, AGN) require high contrast	C	Strong argument for adaptive secondary, thereby eliminating oblique reflections.
8	Stability of the focal plane scale	Not important			
9	Background emission from telescope	Below sky	no additional background, faint objects	C	
10	Straylight from telescope	< 10^{-4} outside 30 mas	should not dominate over AO residuals & should be unpolarised as far as possible	C	
11	Differential Refraction	no special requirement			

12	ADC	Yes	Required for good image quality for the large spectral bandwidth observations, but need to control polarisation. Large transmissive optics ahead of polarisation modulator may cause problems.	C	
13	Zenith Distance Angle Range of operation	<60 degrees		C	
14	Type of telescope focal station	Cassegrain	Keep telescope polarisation minimal	D	Needs minimum no. of oblique mirrors, and preferably rotational symmetry
15	Back focal distance	>300 mm	Space to insert retarder plate in case of Nasmyth focus	D	
16	Instrument attachment	De-rotator	Field de-rotation to observe faint targets, the use of a 3-mirror derotator or alike is polarimetrically very problematic	C	
17	Max Mass of Instrument (not rotating and/or rotating)	3 tons	Relatively small FoV, diffraction limited, dimensions similar to VLT instruments	C	
18	Max Volume occupied by the instrument	5 m^3	Relatively small FoV, diffraction limited, dimensions similar to VLT instruments	C	
19	Telescope pointing and guiding	Blind pointing better than FoV, no special guiding requirements			
20	Telescope Chopping	not required			
21	Maximum brightness level of stars to study	> mag 0	From bright to very faint	C	
22	Calibration Requirements	Continuum source and insertable polarimetric plates near focus for instrument polarisation calibration			
	IMPACT ON OPERATION, SITE				
23	Operation mode	Service	good seeing required, targets uniformly distributed over sky	D	
24	Typical Integration Time	<5 h time on target, individual exposures tbd	Accurate polarimetry is photon expensive	D	
25	Special supply	LN2	For the dewar		
26	Various atmospheric properties of the site	median seeing < 0.8 arcsec	for good AO performance	C	
27	Latitude of the site	within 40 degrees of equator	For sky coverage	D	
28	Altitude of the site	> 2500 m	Seeing	D	

29	Percentage Photometric nights	> 10%	Not essential	N	
30	Percentage Clear nights	> 80%	Time intensive observations	D	

[1]Classification of requirements:
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.6.5 Technology Readiness & R&D required

Coatings
Coatings on inclined surfaces always need careful consideration from the polarimetric point of view. Multi-surface coatings may introduce strongly wavelength dependent polarisation effects. The coatings on the telescope mirrors M1 and M2 (e.g. for Cassegrain-type telescope) should be homogeneous. One part of the primary mirror having a different coating should be avoided, as this will introduce polarisation effects which are not compensated by the rest of the primary despite the symmetric configuration of the entire mirror. Mirror aging should not be a problem, but different coating types (protective layer) on individual mirrors of a segmented primary may be problematic. Coatings on inclined mirrors, such as mirror M3 for a Nasmyth telescope must be polarimetrically well behaved and under control.

Modulators (half wave retarders)
Different types of transmitting modulators and retarder plates may be used for polarimetric measurements. It should be noted that they have to be combined with a polariser or polarising beam splitter for the polarisation analysis. For high precision polarimetry combined with XAO application, e.g. search of polarised light from planets near bright stars, the optical quality (differential aberrations between the different states) of the modulator is an open issue which has to be investigated (for instance in the VLT PF study).

Detectors
For faint targets only polarimetry with moderate precision is possible due to the limits set by the number of photons and the capabilities of available imaging detectors. Bright targets, for which high precision polarimetry requires fast modulation, currently use non-standard detectors which are only available as custom-made devices. Current ZIMPOL devices that employ charge shuffling with CCDs to enable fast polarisation modulators to be used are promising. More suitable array-detectors for the fast demodulation of a modulated signal (avalanche diode arrays or hybrid CMOS devices) may be available in the future. It seems likely, that substantial R&D is required for such devices that they meet the requirement for an application in astronomical polarimetry.

4.6.6 Cost and Complexity Issues

Polarimetry is often not the primary driver for an astronomical instrument. For this reason many instrument concepts neglect polarisation issues. In later design phases it is then often impractical to change an advanced instrument concept to include also a polarimetric mode, despite the fact that such a mode would be useful and in principle not affect the other (primary) observing modes. For this reason, potential science cases and corresponding concepts for polarimetric instrument modes should be considered as early as possible in the instrument planning in order to not exclude this possibility without compelling reason.

4.7 Multi-Object NIR Spectrograph (high spatial resolution)

4.7.1 Instrument Modes

We use the MOMSI instrument as an example of this type of instrument. MOMSI (Multi-Object, Multi-field Spectrometer and Imager) is intended to exploit the high spatial resolution obtained from an ELT working towards its diffraction limit. With a field-of-view of ~2x2 arcmin, this will require a system of multi-object adaptive optics (MOAO) to correct small fields that are picked-off from the focal plane. We would expect the imaging mode (if included) to pick-off small fields for direct imaging to complement integral field spectroscopy pick-offs.

4.7.2 Science Drivers

The primary driver for MOMSI was originally intended to be that of resolved stellar populations. With the adoption of primary mirrors in the range of 30-60m, some of the most compelling OPTICON science cases [RD01] become less feasible. MOMSI will still be able to make a strong contribution in these areas, but the design is now also driven by cases concerned with e.g. studies of galaxy evolution at high redshift. Example cases are:

- Photometric observations of resolved stellar populations in a wide range of galaxies out to ~10 Mpc, to investigate their star-formation histories, ages and metallicities. Depending on crowding, studies of the luminous populations in the outer regions of galaxies in the Virgo cluster are particularly of interest.
- Examine the stellar kinematics in galaxies at the periphery of the Local Group and beyond, to trace the fossil record and mass-assembly of stars.
- Detailed studies of young stellar clusters in systems such as M82, the closest examples of so-called super star clusters, to better interpret integrated light observations of starbursts at large redshifts.
- Stellar astrophysics in new environments - high-resolution spectroscopy of stars in low metallicity systems such as Sextans A, to drive our understanding of stellar evolution and feedback in very metal-poor environments (and the connection to Population III stars etc.).
- Mass assembly at high redshift - to probe the dynamical structure and chemical compositions of galaxies at z ~ 1-3, to explore their assembly via internal (e.g. star formation) or external process such as merging.
- Interaction of super-massive black holes - with its high spatial resolution MOMSI would be able to study the interaction of black holes, their accretion disks and the inner bulges of the host galaxies.

4.7.3 Outline Specification

The notional field-of-view from the science case is 2x2 arcmin, with 20 pick-offs to do imaging and IFU spectroscopy. The spectral resolution required for the science cases comprises a 'low-res' mode with R ~ 4,000 (i.e. high enough to resolve the OH lines), and a higher-resolution mode with R ~ 20,000. We advocate inclusion of the I-band in addition to J, H and K, which will significantly strengthen the resolved stellar populations part of the science case, i.e. the wavelength coverage is 0.8-2.5 microns. One possible approach for MOMSI could be to include the High Resolution NIR Spectrograph in the same 'smart' focal plane.

The diffraction limit (at 1.65 microns in the H-band) for a 42m telescope is ~10 milliarcsec. At this level of sampling a 0.4"x0.4" IFU pick-off with 40 slices would combine to form an effective slit commensurate with a 2k pixel array. Such a field-of-view is well matched to the typical half-light radii of galaxies at z~3. At 5 milliarcseconds a 2k array in each pick-off would give an imaging sub-field of 10"x10".
The stellar populations part of the science case would benefit from as large a multiplex as possible (although studies of high redshift galaxies may not have sufficient source densities in a 2' field to complement this). We adopt a goal of 20 pick-offs - whether this is feasible with MOAO (and multiple lasers etc.) remains to be proven.

4.7.4 Requirements and Pressures on Telescope, AO & Site

MOMSI is clearly not a first generation instrument - in terms of AO development, MOMSI provides the motivation for studies of wider-fields (~2 arcmin), compared with the Planet Imager and Spectrograph that will drive development of extreme AO in small fields. A stable platform is required that in terms of traditional design suggests a Nasmyth platform. However the space envelope and weight of the instrument with the inclusion of the AO system, and the requirement for compensation of field rotation may warrant consideration of alternative solutions.

A field size of ~290mm or greater is preferred in the focal plane, to give enough physical space for the sub-field pick-off mechanisms. F/12 for a 42m telescope gives 2.44mm/arcsec, i.e. 290mm for a 2 arcmin field. Faster f-ratios lead to a focal plane that is too crowded. Significantly slower f-ratios (>> F/20) give focal planes >> 0.5m that may lead to problems with manufacture of large ADCs (assuming that the ADC is incorporated before the focal plane).

A high site (>2500m) with low water vapour content is preferred for optimum performance in the NIR.

TABLE 10: REQUIREMENTS ON TELESCOPE, AO & SITE – Multi-Object NIR Spectrograph (high spatial resolution)

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	800-2500 nm	IJHK imaging & spectroscopy	C	
2	Telescope final focal ratio	F12-F15	to give adequate focal plane size for pick-offs	C	
3	Scientific Field Size (Diameter)	2 arcmin	patrol field in which sub-fields are picked-off	C	
4	Field flatness	Preferred	pick-offs could work in curved field	D	
5	Linear field size	>290mm	adequate room for pick-offs	C	
6	Image quality	FWHM~10mas @H	toward diffraction limit, good EE for spectroscopy, good uniformity over 10 arcsec for imaging	C	
7	Adaptive Optics System	MOAO with lasers (or very.good MCAO)	main driver is to work close to diffraction limit in IJHK	C	High performance AO
8	Stability of the focal plane scale	<5 mas	high-precision astrometry/photometry	C	
9	Background emission from telescope	< sky background in K, < OH continuum in J & H	thermal properties of telescope need to be considered in design	C	
10	Straylight from telescope	-	requires detailed modelling for small but crowded fields	C	
11	Differential Refraction	not relevant	relatively small fields	N	
12	ADC	prior to object pick-off	AD is large compared to relative scale of pick-offs	C	

13	Zenith Distance Angle Range of operation	0-60 degrees	as wide a range as possible to increase availability of targets	D	
14	Type of telescope focal station	nasmyth	stability of spectrographs, could share patrol field with other instruments, e.g. High Resolution NIRSpectrograph	C	Stability requirement or closed-loop flexure control
15	Back focal distance	~300mm	similar to VLT-KMOS	D	
16	Instrument attachment	rotator	will need field rotation	C	
17	Max Mass of Instrument (not rotating and/or rotating)	> 3-4 tons	similar to VLT-KMOS, but inclusion of AO into system will increase mass upwards	C	
18	Max Volume occupied by the instrument	>2x2x2m	similar to VLT-KMOS, but with higher-resolution spectroscopic mode and inclusion of AO into system will also lead to increase in the space envelope	C	
19	Telescope pointing and guiding	blind pointing to < 2arcsec	good pointing for acquisition of small fields	C	
20	Telescope Chopping	not required		N	
21	Maximum brightness level of stars to study	no strong requirements	most targets will be very faint	N	
22	Calibration Requirements	good understanding of PSF	other usual requirements such as wavecals etc.	C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	service or visitor	short-term programmes & large surveys	N	
24	Typical Integration Time	coadded frames over 1-2hrs	faint targets	C	
25	Special supply	LN2	pre-cooling	C	
26	Various atmospheric properties of the site	low water content/OH emission	median seeing as good as possible for high-degree of AO	C	
27	Latitude of the site	±40° of equator	although part of science case becomes quite hemisphere/latitude critical, depending on location of TMT, max operational zenith distance of telescope etc.	D	
28	Altitude of the site	>2500m	low water content etc.	C	
29	Percentage Photometric nights	>50%	efficiency of imaging programmes	D	
30	Percentage Clear nights	no special constraints	obviously the higher the better	N	

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.7.5 Technology Readiness & R&D required

Pick-off technology has been significantly driven by the Smart Focal Planes project, presenting several options that could be incorporated into MOMSI. In particular the pick-off arms developed for VLT-KMOS will have the additional benefit of a proven technology.

Significant R&D is required to tackle the issues of MOAO.

4.7.6 Cost and Complexity Issues

With its heavy dependence on some system of multi-object (or multi-conjugate) AO, a Multi-Object NIR Spectrograph with high spatial resolution is clearly a very complex instrument. Many of the pick-off and IFU issues could be simply scaled-up from the VLT-KMOS design, but the largest uncertainty in cost comes from the AO system.

4.8 Multi-Object NIR Spectrograph (wide field)

4.8.1 Instrument Modes

Near IR multi IFU between 600 and 2400 nm at a spectral resolution of 4000-10000 and spatial resolution 50 mas ±50%. Packed IFUs provide for contiguous IFU.

4.8.2 Science Drivers

There are two major science drivers for this instrument, one being identified in the OPTICON Book [RD01] as a highlight science case. Namely:

First light - The First Galaxies and the Ionization State of the Early Universe
When and how did the first galaxies form ? Understanding the key parameters of the earliest galaxies (masses, star formation histories, metallicities and their effect on the gas that fills the Universe around them) will give us crucial insight into the precise details of how the Universe evolved during its youth. These questions can be answered with multi-IFU near IR observations of the earliest galaxies in the redshift range 7-10 through their Lyman alpha and UV continuum (for the brightest objects) emission.

Evolution of galaxies: Physics of High Redshift Galaxies and The Assembly of Galaxy Haloes
How has the dark and baryonic matter in galaxies grown from the first cosmological seeds? What were the characteristics of the galaxies that merged in the early Universe to form the galaxies we see today? What is the relative fraction of dark and baryonic mass as a function of redshift, total mass, and radius from the centre of mass of the galactic system? These questions can be answered with a multi-IFU in the near IR on an ELT by mapping the spatially resolved kinematics, star-formation, and chemical abundances of individual massive galaxies as well as measuring the kinematics of their satellite objects.

The instrument serves a wide range of other scientific applications, including single object near IR spectroscopy at moderate resolution. The list below is extracted from the OPTICON book [RD01], and represent cases that could be addressed by this instrument:

- Free floating planets in star clusters or in the field (3.1.8)
- Mass function of black holes and neutron stars (3.3.3.1)
- Microlenses: optical and near-infrared counterparts (3.3.4)
- Extragalactic massive stars beyond the local group (4.5)
- The cosmic star formation rate from supernovae (4.8)
- The future of black hole astrophysics (4.10.2)
- Type Ia supernovae as distance indicators (5.1.1.1)
- Gamma ray bursts as distance indicators (5.1.1.2)

4.8.3 Outline Specification

The requirements from the two main science drivers are:

- Typical number of IFUs : 30-50
- Typical size of individual IFUs : 1 arcsec on a side
- Typical spatial resolution : 50 mas ± 50%

Spectral resolution: > 4000 for OH avoidance. From science requirements: > 1000 for high-z galaxies, 5000-10,000 for galaxy evolution. Ideally, the instrument shall offer flexibility in spectral resolution.

The spatial sampling requires the image quality delivered by telescope and AO to be of the order of 50 mas ±50% - meaning with >50% encircled energy. This requires so-called multi-object adaptive optics (MOAO).

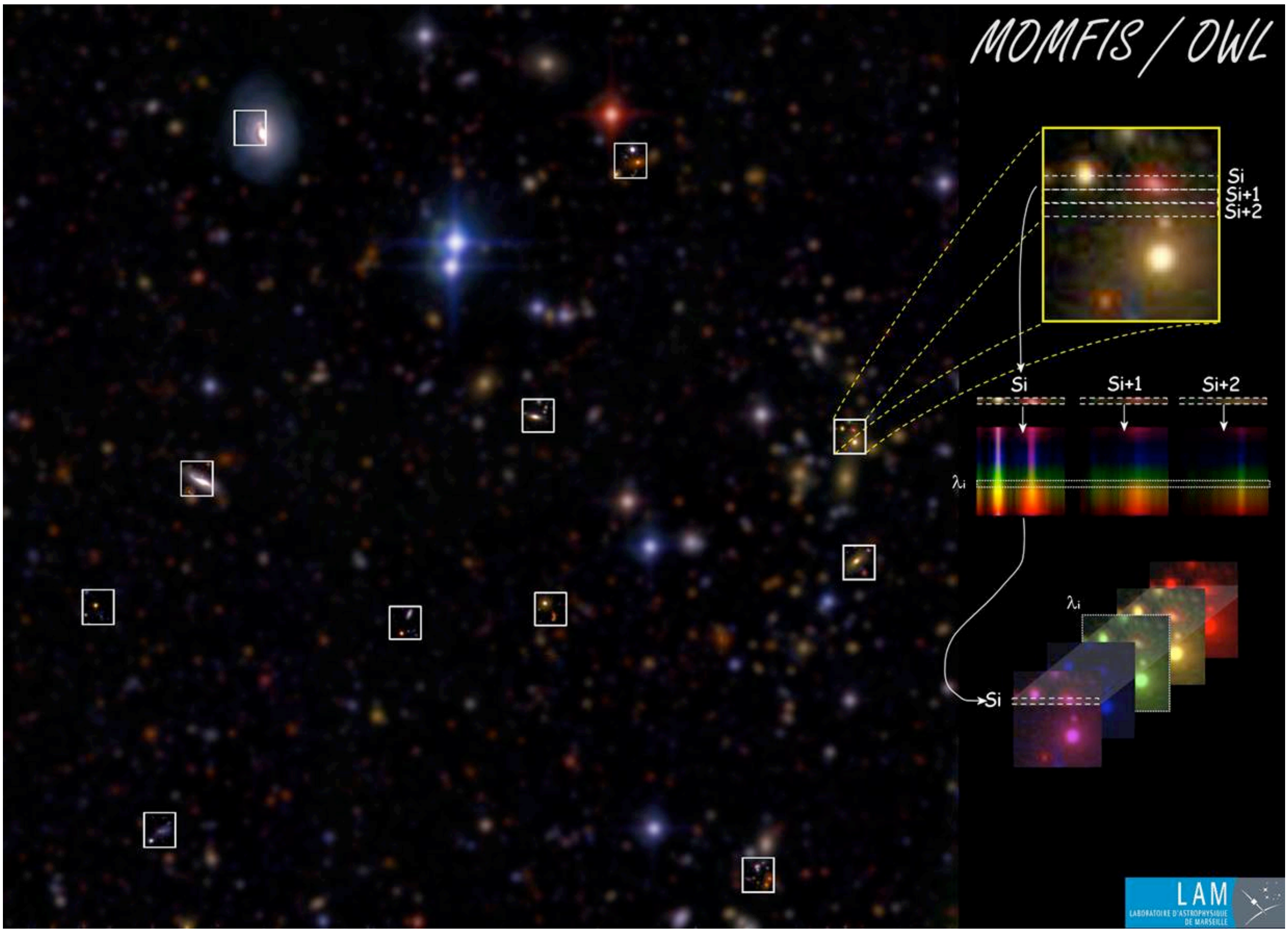

Figure 2: Principle of operation for a Multi-Object NIR Spectrograph

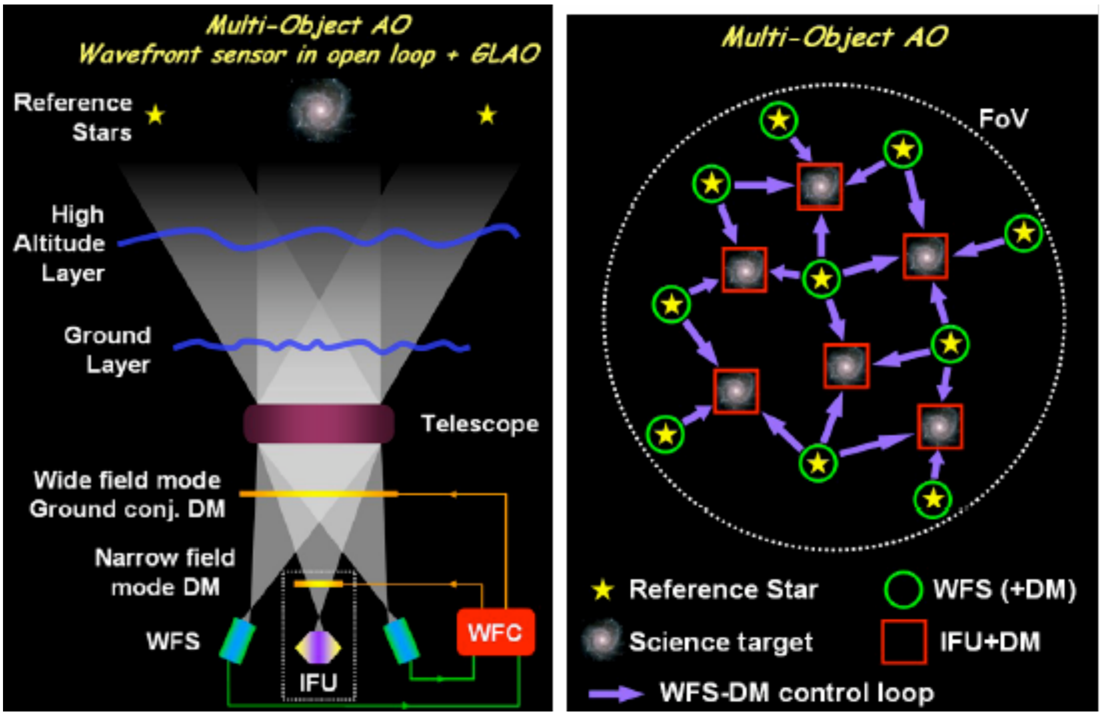

Figure 3: Principle of operation of the MOAO

4.8.4 Requirements and Pressures on Telescope, AO & Site

TABLE 11: REQUIREMENTS ON TELESCOPE, AO & SITE – Multi-Object NIR Spectrograph (wide field)

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	600-2400 nm	High-z and mass assembly science cases require I to K spectroscopy. I band is D, K band is D for high-z, C for mass assembly. YJH are C	C	
2	Telescope final focal ratio	> f/10	Optical relay, opto-mechanical implemantation, tolerance to back focal distance	C	
3	Scientific Field Size (Diameter)	5-10'	Low density of targets	C	
4	Field flatness	No requirement	Can be dealt with, within acceptable limits	D	
5	Linear field size	<2-3m	Overall size	D	
6	Image quality	50 mas (fwhm)	Size of high-z objects, required sampling to resolve velocity fields in z<5 galaxies	C	
7	Adaptive Optics System	MOAO	Assumes GLAO in telescope & 2nd stage / MOAO in instrument. SCAO/LTAO possible initial fallbacks on smaller fields. LGS ultimately required	C	Major AO requirements

8	Stability of the focal plane scale	better than 10 mas/hr	positioning IFUs on targets	C	
9	Background emission from telescope	Low	Affects K band performance	D	
10	Straylight from telescope	Low	No special specification	D	
11	Differential Refraction	Of the order of 20 mas/hr	Can be handled by re-positioning	-	
12	ADC	Required	IR dispersion > fwhm	C	
13	Zenith Distance Angle Range of operation	0-60º	Standard spec	C	
14	Type of telescope focal station	Nasmyth or gravity stable (vertical opt. axis)	Design at large, integration, maintenance, operations.	C	
15	Back focal distance	>500 mm	Design of pickoffs and WFS, overall implementation	C	
16	Instrument attachment	tbc	rotator or decoupled	D	Gravity stable rotator?
17	Max Mass of Instrument (not rotating and/or rotating)	10-30 tons	Crude extrapolation from MOMFIS		Major interface driver
18	Max Volume occupied by the instrument	~100 m^3	Crude extrapolation from MOMFIS		Major driver on inst platform layout
19	Telescope pointing and guiding	Pointing: 100 mas, guiding: 10 mas		C	
20	Telescope Chopping	not required			
21	Maximum brightness level of stars to study	N/A			
22	Calibration Requirements	FF, arcs, PSF, plate scale		C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	Service			
24	Typical Integration Time	tens of hrs	individual exposures 20-30 min (enough to be background limited between OH lines		
25	Special supply	LN2	LN2 for pre-cooling or for regular instrument cooling. Depends on infrastructure at site	C	
26	Various atmospheric properties of the site	Median seeing ~ 0.6"			
27	Latitude of the site		Targets from JWST ok for ELT. Multi-wavelength programmes, so best to be at latitudes of other major facilities. Observability of	C	

			equatorial fields required.		
28	Altitude of the site	>3000m	Colder, less atmospheric dispersion and differential refraction	C	
29	Percentage Photometric nights				
30	Percentage Clear nights	No special constraint	The higher the better	C	

[1]Classification of requirement:
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

Can instrument do useful science on day 1?
Definitely, yes. Considering that the instrument covers a wide range of applications and is not diffraction limited, it can be used from day 1 for first class science, including one of the three OPTICON highlight science cases. The full implementation can be seen as a sequence of upgrades related to AO, a sequence that will strongly depend on the final AO development plan and on technological developments.

In the most conservative case one can consider starting in the seeing limited case, although a more likely one is to consider GLAO and/or SCAO/LTAO since these facilities are foreseen for telescope first light. GLAO will provide for seeing improvement over the large field, while SCAO/LTAO will offer close to diffraction limit images in the central field. Excellent image quality (< 0.05 arcsec) can therefore be achieved from day 1 in the central regions of the field of view where as many IFUs as required can be positioned, with an average image quality of the order of 0.2-0.3 arcsec at IR wavelengths in the rest of the field.

A plausible and equally likely alternative to the above would be to start with low order NGS MOAO. The likelihood of having MEMS DMs with ~1000 actuators within 10-15 years is reasonably high, considering that this is a high priority development for all major astronomical projects on the ground. This 'low order' MOAO would be well matched to the performance that can be expected with natural guide stars. This NGS MOAO could, from day 1, provide images of the order of 0.1-0.15 arcsec at near IR wavelengths. The ultimate goal of reaching an image quality of 0.05 arcsec or so could be achieved in a subsequent upgrade of the instrument a few years after installation with high order DMs and Laser Guide Stars (LGS).

There are therefore several options for the deployment of a near IR multi-IFUs, most of them likely to provide very good image quality (~0.1 to 0.2 arcsec) from the beginning, while the ultimate goal of LGS MOAO will only be achieved as a later stage.

The scientific usefulness of having the instrument in first generation is therefore very clear. In the worst case scenario of seeing limitation it will already provide gains of the order of 1.5 to 2 magnitudes compared to existing instruments on 8-10 m class telescopes which are photon starved for galaxies at z >6 and for detailed physical and dynamical studies of galaxies at redshifts >1.5 or so. In a more ambitious but highly plausible scenario where the instrument could start observing with GLAO/SCAO/LTAO and/or low order MOAO, most of the ultimate science goals could be achieved from day 1, at least in the central field, possibly on a reduced number of IFUs. Note that by closely packing the IFUs, contiguous IFU observations could be performed with excellent image quality from the very beginning, allowing for instance blind searches and/or observations in crowded regions such as clusters, etc.

Requirements on telescope

A nasmyth-type of platform is highly desirable for reasons of size, accessibility, integration and maintenance. A gravity stable platform would help. Any other focal station would increase cost complexity and difficulty of maintenance. However, considering the size of instrument, some sort of embedded metrology could be required. This metrology could help handling flexures or motions in case of a non-gravity stable platform.

- f/ratio. The slower the better. In particular, the possibility to pack the individual IFUs to form single large IFU strongly depends on the f/ratio and on the shape of the pick-off mirrors - should such a solution be retained. Faster than f/15 is highly undesirable.

- Adaptive optics: as above, requires GLAO (woofer DM) in telescope

- Sky coverage: an absolute must. NGS provides for full sky performance but with moderate image quality, ultimate goal is to have full performance over the whole sky which requires operation with several (5-10) LGS.

- Number of telescope mirrors: K band performance will depend on the number of warm telescope mirrors. K band is not the highest priority though, so it may be possible to find some compromises.

Development plan for AO

System level:

Demonstrators are required: principle of operation, wavefront interpolation, woofer/tweeter, performance, LGS operation, optimum configurations, etc.

- system analysis, including simulations
- lab demonstrator - VLT like (existing benches)
- sky demonstrator (VLT)
- lab demonstrator - ELT

Components: nothing specific to MOAO. MEMS with high order correction, wavefront sensors, etc.

4.8.5 Technology Readiness & R&D required

Much of the technology is being developed under the Opticon Smart Focal Planes JRA, but further R&D is required in:

- Optical concepts
- Adaptive Optics. MOAO, already commented above
- Starbugs and smart positioners
- Metrology
- Beam Steering Mirrors
- Low cost image slicers
- Low cost detectors (not really a R&D thing since outside the range of R&D that astronomy can afford)
- OH suppression devices

There is no real show stopper in all of this, or which prevents starting to design an instrument now. Breakthroughs in some of the items above may lead to significant simplifications of the instrument concept and design. A few more years of R&D are required.

4.8.6 Cost and Complexity Issues

Cost is of the order of 30 M€ ± 10 M€, capital cost

Required manpower: of the order of 200 FTEs

Complexity: this type of instrument is more complex than any instrument being built for current telescopes, in particular in the need to integrate complex pick-off devices with MOAO, but it would be possible to design an instrument with phased upgrades corresponding with improved wide-field AO performance.

4.9 Planet Imager and Spectrograph

4.9.1 Instrument Modes

We use the example of the EPICS instrument concept developed for OWL [RD03], and now being progressed within the FP6 ELT Design Study. The concept of EPICS builds on the strengths of the VLT Planet Finder (now SPHERE) instrument proposal. This permits EPICS to be sensitive to a wide range of exo-planets spectro-polarimetric physical properties from the visible to the NIR, thanks to three different instruments based on differential imaging methods. It is envisioned that these instruments work simultaneously for maximizing scientific return.

A total of four spectral channels (3 for science and one for wave-front sensing) are defined, see figure 4. Each scientific channel will be equipped with its own coronagraph.

- The R band is dedicated to the Polarimetric Differential Imager for detecting rocky planets and to the follow-up observations for the detection of O_2.
- The J band will be equipped with a differential imager using pairs of filters that will be sensitive to both CH_4 and H_2O absorption bands.
- The H band will be equipped with an Integral Field Spectrograph. The main features that can be detected in this band are CH_4 and CO_2.
- The I band is reserved for wave-front sensing. This band has been chosen because of the lesser scientific interest for planet detection. Its location, spectrally speaking, between the visible and NIR instruments, is optimal with respect to important atmospheric chromatic limitations for XAO on ELTs. Moreover no light is taken from the scientific channels.

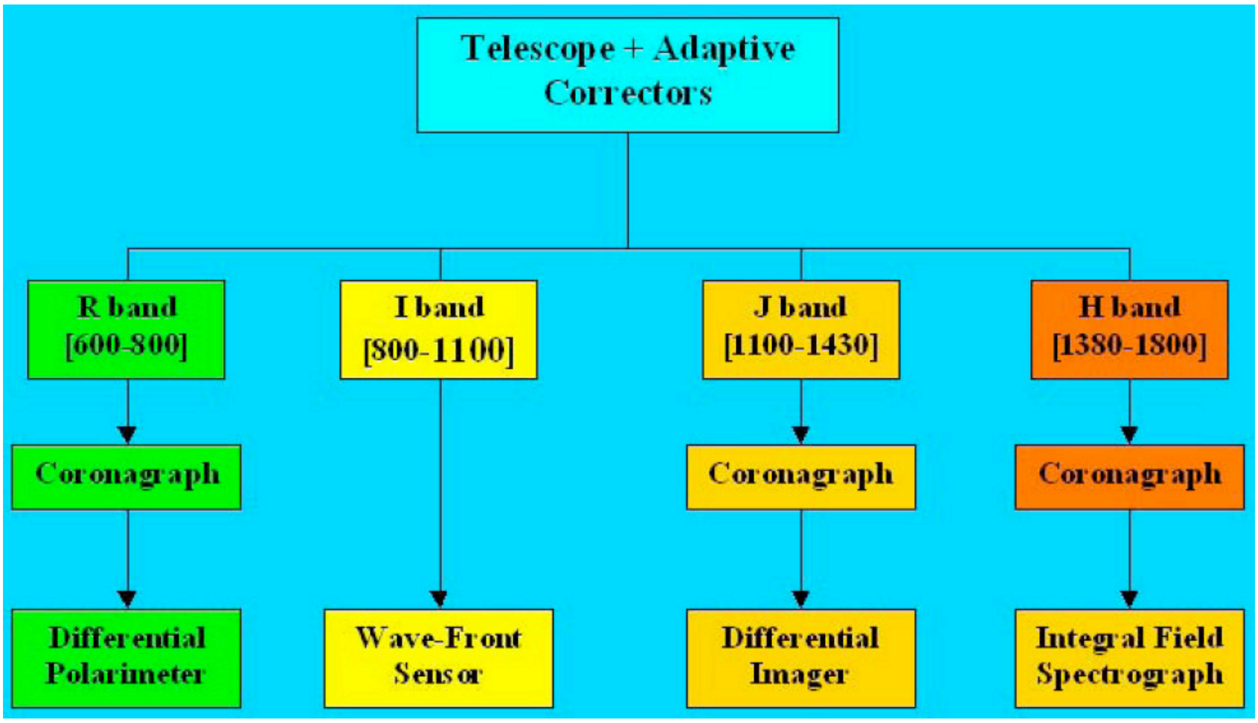

Figure 4: Concept of a Planet Imager and Spectrograph; all wavelengths given in nm.

4.9.2 Science Drivers

The expected direction of exo-planet research including the possible role of an ELT are summarised in the report by the ESA-ESO Working Group on extra-solar planets [RD05]. There are two main science drivers in the field of exo-planet science:

Gas giant planets in a late evolutionary stage

A Planet Imager and Spectrograph at an ELT will permit a significant breakthrough in the detection and characterization of old gas giant planets. Their contrast (the contrast of Jupiter at 5 AU is 10^{-9}) and larger separation, makes them comparatively easy targets, and opens the door to high resolution spectroscopy. In particular, radial velocity measurements and the analysis of atmospheric composition and dynamics of close-in giant planets will be possible. The contrast between a Jupiter mass planet at 0.5 AU and its star is around 10^{-7} approaching the stellar AO residuals. At 10 pc distance from Earth, assuming a G2 star, its magnitude would be around 22.5 and the photon flux at resolution of 50,000 would be about 0.2 photons per second and spectral bin (30% overall quantum efficiency). Therefore, a reasonably high SNR for the high resolution spectroscopy appears feasible in observing times of a couple of hours. The search for gas giants around late-type stars at orbital separations bigger than 5 AU will also be a domain of EPICS since these objects are not easily accessible to radial velocity surveys due to the orbital period exceeding 15 years.

Detection of Rocky planets

One of the most ambitious science objectives of an ELT is the detection and characterization of extra-solar systems in an advanced evolutionary stage. Rocky planets with possibly Earth-like features are the ultimate and most challenging goal of EPICS. The direct detection of exo-planets is made very difficult by the very high relative flux ratio between the star and planets orbiting it and their small angular separation. For example a terrestrial planet orbiting a G-star at 10 pc distance in the habitable zone is 2.10^{-10} times fainter than the star at an angular separation of 0.1 arcsec. These requirements will probably be too challenging even for a 50-m ELT. However, the situation becomes more favourable for the handful of G-stars closer than 10 pc because of the larger angular separation as well as K- and early M-stars where the habitable zone is closer to the star and the contrast is more favourable ($\sim 10^{-9}$ at 50 mas for K-stars, 10^{-8} at 30 mas for M-stars). About 70 of these late-type stars are within 10 pc and observable at moderate zenith angles. Early M stars at 10 pc are around V = 10 setting the AO limiting magnitude requirement.

Other Science

Apart from the planetary science listed above, a large variety of additional important science cases will be covered by EPICS. High contrast and superb image quality are also essential for example for the calibration of the mass-luminosity relation of low-mass stars and brown dwarfs, the study of debris disks and gas-rich disks around young stars, the study of evolved stars and their outflows, the detailed study of solar system bodies as well as a extragalactic science such as determining the morphology of nearby AGNs and the study of the stellar population in the nucleus. Details on these science cases are presented in [RD01].

4.9.3 Outline Specification

This section lists the instrument top level requirements for EPICS that derive from the main science goals. They are to be used by the system group to develop an instrument design that fulfils these requirements assuming a certain set of observing conditions.

General instrument requirements

- The instrument covers the wavelength range 600-1800 nm
- The total field of view in all observing modes is at least 2" in diameter at visible wavelengths and 4" in diameter in the NIR
- The inner working angle in all observing modes working at visible wavelengths is smaller than 30 mas (goal 15 mas)
- The spatial sampling will fulfil at least the Nyquist criterion at all working wavelengths

Observing modes requirements

- There will be a low resolution differential spectroscopic mode covering at least the following bands:
    - CH_4 in J- and H-band, R >15
    - H_2O between the atmospheric bands, R >15
    - CO_2 in H-band, R >15
- There will be a mid (R~1000) and high (R~50,000) resolution spectroscopic mode for the NIR
- There will be a broad band differential polarimetric mode. The absolute polarimetric accuracy will be 1% (TBC)
- The photometric (absolute/relative) precision in all main observing modes is better than 1%
- A Jupiter-like planet at up to 10 pc at a phase angle of 90° is detected in spectroscopic mode at SNR >50 in one night of observation
- An Earth-like planet at up to 10 pc at a phase angle of 90° is detected in all main observing modes at SNR >5 in one night of observation

Adaptive Optics requirements

- The AO control radius is larger than 0.4" at 800 nm (goal 0.8")
- AO limiting magnitude for achievement of TLR: I = 10

4.9.4 Requirements and Pressures on Telescope, AO & Site

Given the need for XAO Planet Imager and Spectrograph does not qualify as a first light instrument for ELT.

TABLE 12: REQUIREMENTS ON TELESCOPE, AO & SITE – Planet Imager and Spectrograph

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	600-1800 (2300 goal) nm	VIS for polarimetry and O_2; NIR for methane and H_2O, giant planets	C	
2	Telescope final focal ratio	> f/10	pupil stabilization close to focal plane, instrument size	D	
3	Scientific Field Size (Diameter)	>4 arcsec (goal 10 arcsec)	terrestrial & giant planets close to central star	C	
4	Field flatness	not important			
5	Linear field size	not specified			

6	Image quality	<100 nm RMS for spatial freq <2.5/m; <10 nm RMS for spatial freq > 2.5/m	low frequency corrected by DM avoid saturation, high frequency to suppress static speckles	C	Major issue
7	Adaptive Optics System	SR: 0.40 (V), 0.64 (R), 0.87 (J), 0.92 (H); star < 10 mag, seeing 0.6 arcsec ;XAO guide stars V <10 mag	not useful without AO	C	Driving XAO
8	Stability of the focal plane scale	1 mas, 20% over FoV	study orbital motion of planet	D	
9	Background emission from telescope	less than sky	introduce no additional background, planets are faint targets - but contrast is critical issue	C	
10	Straylight from telescope	< 10^{-6} of peak outside 30 mas radial distance	should not dominate over AO residuals	C	Critical issue for all optical surfaces/devices and structures
11	Differential Refraction	Observations generally close to zenith < 50 degrees ZD; in small field	avoid chromatic anisoplanatism	C	
12	ADC	as early as possible in telescope optics & as close as possible to pupil plane	differents wavelengths have to follow identical optical path	C	Could be critical driver for ADC - IFU solution possible?
13	Zenith Distance Angle Range of operation	<50 degrees	avoid chromatic anisoplanatism	C	
14	Type of telescope focal station	nasmyth gravitationally stable	avoid aberration induced by flexure	C	
15	Back focal distance	> 500 mm	space may be needed for optical components in front of focus	D	
16	Instrument attachment	fixed on platform	field derotation may not be necessary	C	
17	Max Mass of Instrument (not rotating and/or rotating)	5 tons	small FoV, diffraction limited, dimensions similar to VLT instruments	C	
18	Max Volume occupied by the instrument	6m x 3m x 1.5m; 25 m^3	small FoV, diffraction limited, dimensions similar to VLT instruments	C	
19	Telescope pointing and guiding	<4 arsec (FoV)	pick up target in FoV	D	
20	Telescope Chopping	not required			
21	Maximum brightness level of stars to study	V = 3 mag	nearby stars	C	
22	Calibration Requirements	High accuracy flatfield on pixel scale, PSF calibrator, wavelength cal	high contrast imaging and spectroscopy	C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	service or long term experiment	good seeing required, targets uniformly distributed over sky	D	

24	Typical Integration Time	<5 h time on target individual exposures: 1 to 10 sec	high contrast imaging	C	
25	Special supply	LN2 (or cooler)	cooling of detectors	C	
26	Various atmospheric properties of the site	median seeing < 0.8 arcsec, PWV < 2 mm	required for good AO correction, differential imaging contrast	C	
27	Latitude of the site	Within 40º of equator	sky coverage	D	
28	Altitude of the site	>2500 m	seeing, low PWV	D	
29	Percentage Photometric nights	>10%	not essential	N	
30	Percentage Clear nights	>80%	time intensive observations	D	

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.9.5 Technology Readiness & R&D required

The EPICS XAO system involves several new concepts that need to be proven through numerical simulations and experiments. The ESO parallel simulation code is in constant evolution and there are several plans to increase the ESO AO simulation cluster computing power and also to port the code to super-computing facilities (collaboration with Australia through European FP6). In the frame of the Joint Research Activity 1 of OPTICON, ESO is developing a High Order Test (HOT) Bench for XAO and coronographic experiments.

- Pyramid wave-front sensor: even though very promising this concept is very new and only one system is actually working on the sky. The big advantage in sensitivity is at the expense of non-linearities of the measurements and sensitivity to pupil shape through diffraction effects. We will study optimisation of the pyramid sensor for XAO application and test them with HOT.

- Multi-stage schemes, Woofer-Tweeter schemes: Woofer is a low order DM with larger actuator stroke to correct for the strong low order aberrations, tweeter is a high order DM with small stroke to correct for the weaker high order aberrations. The HOT bench will be composed of two deformable mirrors, a low order curvature mirror (60 actuators) and a high order MEMS mirror (1000 actuators). We will develop and test different control algorithms involving multiple stages.

- New WFSs, focal plane WFS: the extreme contrast needed for exo-planet search calls for new WFS concepts where the correction is optimised by analysing directly focal plane images. As an extension to HOT we plan to test these new concepts, like for example the focal plane interferometers, especially in the frame of high precision control of systematic errors.

- Research on Fast algorithms for Shack-Hartman and for Pyramid sensors. New algorithms are being studied and developed in frame of FP6 WP 9600.

Hardware developments:

- Adaptive mirrors: an important risk area is the availability in the near future of MEMS adaptive mirrors with an extremely high number of actuators (> 10^4). In the frame of OPTICON JRA1, we are developing now a 2K actuators adaptive mirror based on MEMS technology. The next step will be the development of a 10K mirror which is getting close to required number of actuators for EPICS.

- Detectors. CCDs: 512x512 detectors with fast read-out (2 KHz) and low noise (read-out noise less than one electron) are required. Developments of low light level CCDs (L3CCD; technology which effectively reduces RON by electron multiplication during readout) are already part of the OPTICON Joint Research Activity 1.

- Real-time computers with Input/Output communications rates of 10 Gb/s, fast processing elements: Field Programmable Gate Array (FPGA), hardware that provides very low latency processing faster CPU-CPU busses and faster memory. ESO currently develops a scalable RTC architecture for AO called SPARTA which incorporates new technologies like FPGAs. Whether it can meet the demanding requirements of EPICS has to be investigated.

- Coronography. The performance of EPICS relies largely on the interaction of XAO with coronography so that these two sub-systems should be tested together as much as possible. This is an important goal of HOT. Several coronography concepts will be studied and realized in collaboration with LESIA (Observatoire de Paris Meudon) in the framework of the FP6 program and will be tested on HOT.

Developments in instrumentation:

- The experience and results of the SPHERE development phase will be extremely valuable. Important feed-back is expected from extreme adaptive optics developments, coronography differential imaging, polarimetry and integral field spectroscopy.

- Fourier Transform Integral Field Spectrograph. Is not part of the SPHERE project but revealed to have a potential niche for high contrast imaging on ELTs. R&D and prototype development is strongly encouraged.

- Super-polishing: Optical polishing and coating quality: a number of optical surfaces in the EPICS design need to be of extremely good quality. The effect of coating on super-polished surface is an important aspect of this topic. R&D with close interaction with manufacturers is needed. Realization of a prototype of superpolished coated optics (e.g. beam splitter or filter) is strongly encouraged.

Detectors: specific requirements to be studied during phase B.

- Polarimetry: differential errors induced by modulator, studied for SPHERE

- Integral Field Spectroscopy: cross talk and diffraction effects, studied for SPHERE

- Investigation of new detection methods to improve efficiency: speckle elongation, and speckle coherence.

4.9.6 Cost and Complexity Issues

A detailed cost estimate has been done for the EPICS study. The smaller size of the telescope leads to significant savings in the areas of WFS CCD, DM and RTC). The total hardware cost for a planet imager and spectrograph for the ELT is estimated at between 15 and 23 M€. Manpower is estimated at 150 FTE. The Planet Imager and Spectrograph will be one of the more demanding and complex instruments for an ELT.

4.10 Wide Field NIR Imager

4.10.1 Instrument Modes

We propose that there are two imaging modes. HIRES gives a 2' field of view sampled at the diffraction limit with 3.7 mas pixels and a 4 x 4kx4k sparse mosaic of detectors. The second LORES mode has approx 17 mas pixels and requires a 9' diameter field of view. Both modes use the same detector focal plane.

4.10.2 Science Drivers

The OPTICON science case [RD01] lists a number of science areas requiring wide field (e.g. > 1 arcminute) infrared imaging. However, most of these provide little concrete justification for the field of view requested, and in general follow the principle “the wider the field the better”. Among those in this category are 3.1.8: Free floating planets, 3.3.1.1 and 4.4: Star Formation and IMF, 4.8: Massive Clusters. Furthermore, none of these projects can be done with a single pointing of even the largest conceivable field on an ELT. Therefore field size in these cases impacts primarily on the speed with which a science project can be accomplished. In fact projects related to surveying for star formation and free floating planets usually require fields of 100s to 1000s of sq arcminutes and may be beyond the sensible capability of an ELT.

The OPTICON case does provide a number of examples which provide justification for the field size requested and these are worth examining in more detail. A natural benchmark in any discussion of wide field imaging is the near-IR 5 arcminute field of view in JWST. Note that an ELT is only faster than JWST for point sources at JHK if high Strehl ratio can be achieved. This will certainly NOT be the case for wide fields of view.

- 5.1.1.2 Gamma Ray bursts: here the requested 5 arcminute field size is justified in terms of finding objects which are only coarsely positioned using X-rays etc. However, for the first 10 days or so many of these GRBs can be detected by ground-based facilities smaller than 8m. Virtually all of these have wide enough fields to find the decaying optical/IR transient, and identify its position. The ELT can then be used to track the decay to very faint limiting magnitudes - so a wide field ELT is not needed for this.

- 4.8 and 5.1.1.1 Cosmic star formation rate from Supernovae: the requested field size of 2x2 arcminutes is to try to have a reasonable number of supernovae detected in reasonable time. In principle this would best be done with the 5 arcminute field of JWST, though admittedly the project would need a lot of observing time. Field: Wider is Better.

- 5.2 and 5.3.4 The first galaxies, and the history of the star formation rate: these projects require 5x5 and 3x3 arcminute fields respectively, and are based on expected target densities and ELT sensitivities. They must be considered highly uncertain. Again, JWST could be used for the IR imaging and then deployable IFUs to study the individual targets. Field: Wider is Better.

Interestingly, there is one scientific project which definitely requires a field size of one arcminute at least. This is the study of objects and planets within our solar system, where the field size is set by the ability to image Jupiter. If near diffraction-limited resolution could be achieved the images would be truly spectacular.

Conclusion: It is not really clear from the science cases what the minimum "wide field" size should be. In the absence of firm field size requirements from the science case, the maximum field size has been set by plausible instrument constraints (cost, weight etc.)

4.10.3 Outline Specification

HIRES diffaction limited mode	3.7 mas pixels, diffraction limited optics, 1.4x1.4' imaged field, requiring an optical 2' diameter field. Start with GLAO and move eventually to MCAO
LORES seeing limited mode	17 mas pixels, 6x6' imaged field and 9' diameter optical field with GLAO
common focal plane	4x4kx4k detectors, spaced if devices are not buttable, resulting in a 50% filling factor of square 600mm field

Table 13: Specifications for Wide Field NIR Imager

General

Central to the discussion of a Wide Field NIR Imager is the delivered image quality. The entire camera optics may change dramatically depending on whether PSFs will be seeing-limited or GLAO-improved, or contain diffraction-limited cores with significant energy. We are therefore left with three possibilities (i) a diffraction limited camera with usefully wide field (ii) a seeing-limited camera with widest possible field and (iii) a camera that employs both either simultaneously (eg ONIRICA) or interchangeably.

What Pixel Scale ?

Although an extreme AO camera is required for high strehl ratio and high contrast imaging, new techniques such as MCAO promise to provide lower strehl ratios over larger fields (2 arcmin). In these wide field AO applications, even though the central PSF does not contain a large fraction of the light, it is still diffraction limited which means an appropriate pixel size must be used in an Wide Field NIR Imager if the resolution information is not to be lost. It is important to realise that near diffraction limited imaging can be achieved even at low strehl ratios, with some post processing such as deconvolution or image filtering. To Nyquist sample J band with a 42 m telescope requires 3.7 milliarcsec pixels for f/24 with a 42m telescope and 18 micron pixels.

On the other hand, assuming we would like a pixel scale to match best seeing with GLAO, then a 100 milliarcsec pixel scale would be required. On a 42m telescope this requires an F/0.9 final f-ratio, extremely difficult if not impossible to achieve over a reasonable field of view. The result is that we would have to substantially oversample to achieve a more realistic F/3 or F/4. But this may not be a bad thing. For although GLAO gives a uniform PSF over a large field, its gains are modest, and there are some AO modes which may promise substantially greater improvements. By distributing LGSs through the field rather than having them at the periphery, we can achieve substantially better performance over smaller individual regions. If the field is filled with a sparse array of detectors, the correction regions could be the individual detectors, or even sub-regions within detectors.

Field Size

In the seeing-limited or GLAO improved-seeing case, one can make a general point about the field of view in the case of mapping large fields. A 42m ELT is 28 times faster than a VLT if both are seeing-limited. On the other hand the VLT will have imagers such as Hawk-I which has a 56 sq arcminute field of view. Of course, the VLT could be equipped with even larger arrays for survey work in the future. So an ELT needs at least a 2 sq. arcminute field imager just to match the survey speed of the VLT in the seeing limited case, and in practice would want an order of magnitude gain to be worthwhile. This would require a detector field of at least 4.5x4.5 arcminutes. Since detectors will not be 4-side buttable, but probably built up of 4kx4k mosaics, there will need to be substantial dead area in the focal plane, perhaps 75%, so the optical science field will need to be larger – 6x6 arcminutes. This gives a diagonal field of 9 arcminutes. Such a field would also be well-matched to the JWST near-IR camera field.

In fact one could argue that an ELT IR survey mode should not only be much faster than a VLT, but much faster than VISTA. In this case, VISTA's large 1677 sq. arcminutes of sky coverage in a single exposure would require a 12x12' field on a 42m ELT to be 10x faster at surveying.

Detector Constraints
(i) diffraction limited case: Nyquist sampling of J-band with a 42m telescope requires 3.7 milliarcsec pixels. Then a single 4kx4k array focal plane mosaic (eg. HAWK-I) would have a field of view of 14.8 arcsec and forms the natural building block. What kind of mosaic would be sensible? Assuming we want a square field, the number of arrays increases as the square, and progress by a factor of 4 each time. The optical field is calculated by assuming a detector filling factor of 50%. We assume a 50% detector reduction in cost compared to the present.

Mosaic	**Detector cost M€**	**Optical field diameter (arcmin)**	**Linear size (mm)**
2x2 x4kx4k	2	1	300
4x4 x4kx4k	8	2	600
8x8 x4kx4k	32	4	1200

Table 14: Detector Constraints for Wide Field NIR Imager

With cost and linear field escalating rapidly, a good option would appear to be a VISTA-style 4x4 x4kx4k. The field diameter of 2 arcminutes matches well with maximum MCAO fields.

With H-band photoelectron fluxes of ~40 photoelectrons per pixel per second, read noise in a diffraction limited instrument is important. However, assuming a read noise of 10 electrons is achieved, exposures can be well into the background limited regime in 1 minute.

(ii) seeing limited case: there is not a large problem with detectors in the seeing limited case. An f/3-5 camera giving 17 milliarcsec, and a 6x6 arcminute field with 50% filling factor would use the same focal plane as the diffraction limited mode.

Instrument Size and Mass Constraints
If we think of a cylindrical instrument volume, the diameter is proportional to the entrance linear field size L, and hence entrance window size. In the best case situation where the field is segmented into identical cryostats (eg. ONIRICA), we would expect the total cryostat volume and hence mass to scale as L^2. In a more traditional non-segmented optical design the scaling will be as L^3. Now current and planned VLT cryogenic instruments with entrance windows of order 500 mm in size (HAWK-I, KMOS) have instrument weights of ~2 tons. If we take the 100m OWL weight interface of 17 tonnes as an upper limit for an instrument, then upper limits to the entrance linear field size of 1.5 m for a segmented design and 1m for a conventional design are derived. The latter number is also very close to the maximum for which a monolithic entrance window can be manufactured.

Staying with a conventional single-window design, and a 42m telescope with f-ratio between 8 and 16, a 1 m linear field size allows a maximum science field of view between 10 and 5 arcminutes. This can be increased/decreased proportionally for a smaller/larger telescope.

Wavefront Sensing
An advantage of a sparse array is that wavefront sensor pickoffs have large areas within which they can operate without vignetting the field. By distributing LGSs through the field rather than having them at the periphery, we can achieve substantially better performance over smaller individual regions. If the field is filled with a sparse array of detectors, the correction regions could be the individual detectors, or even sub-regions within detectors. This would be the imaging version of MOAO and would require a pixel scale around 25 milliarcsec. So a field somewhat better sampled than required for GLAO would seem a useful goal.

Conclusion
Given that the focal plane is likely to be the dominant cost in constructing a wide field camera for an ELT, it is certainly worth investigating optics which would allow BOTH a diffraction limited and seeing-limited field to be imaged.

4.10.4 Requirements and Pressures on Telescope, AO & Site

TABLE 15: REQUIREMENTS ON TELESCOPE, AO & SITE – Wide Field NIR Imager

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	600-2400 nm	High-z and mass assembly science cases require I to K photometry. I band is D, K band is D for high-z, C for mass assembly. YJH are C	C	
2	Telescope final focal ratio	>f/10	Optical relay, opto-mechanical implementation, tolerance to back focal distance	C	
3	Scientific Field Size (Diameter)	5-10'	Low density of targets	C	
4	Field flatness	No requirement	Can be dealt with, within acceptable limits	D	
5	Linear field size	<2-3m	Overall size	D	
6	Image quality	50 mas (fwhm)	Size of high-z objects, required sampling to resolve velocity fields in z<5 galaxies	C	
7	Adaptive Optics System	MOAO	Assumes GLAO in telescope & 2nd stage / MOAO in instrument. SCAO/LTAO possible initial fallbacks on smaller fields. LGS ultimately required	C	Major AO requirements
8	Stability of the focal plane scale	better than 10mas/hr	positioning IFUs on targets	C	
9	Background emission from telescope	Low	Affects K band performance	D	
10	Straylight from telescope	Low	No special spec	D	
11	Differential Refraction	Is what it is	Can be handled by re-positioning	-	
12	ADC	Required	IR dispersion > fwhm	C	
13	Zenith Distance Angle Range of operation	0-60^o	Standard specification	C	
14	Type of telescope focal station	Nasmyth or gravity stable (vertical opt. axis)	Design at large, integration, maintenance, operations.	C	
15	Back focal distance	>500 mm	Design of pickoffs and WFS, overall implementation	C	

16	Instrument attachment	tbc	rotator or decoupled	D	Gravity stable rotator?
17	Max Mass of Instrument (not rotating and/or rotating)	10-30 tons	Crude extrapolation from MOMFIS		Major interface driver
18	Max Volume occupied by the instrument	~100 m^3	Crude extrapolation from MOMFIS		Major driver on inst platform layout
19	Telescope pointing and guiding	Pointing: 100 mas, guiding: 10mas		C	
20	Telescope Chopping	not required			
21	Maximum brightness level of stars to study	N/A			
22	Calibration Requirements	FF, arcs, PSF, plate scale		C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	Service			
24	Typical Integration Time	tens of hrs	individual exposures 20-30 min (enough to be background limited between OH lines		
25	Special supply	LN2	LN2 for pre-cooling or for regular instrument cooling. Depends on infrastructure at site	C	
26	Various atmospheric properties of the site	Median seeing ~ 0.6"			
27	Latitude of the site		Targets from JWST and / or ELT. Multi-wavelength programmes, so best to be at latitudes of other major facilities. Observability of equatorial fields required	C	
28	Altitude of the site	>3000m	Colder, less atmospheric dispersion and differential refraction	C	
29	Percentage Photometric nights				
30	Percentage Clear nights			C	

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

4.10.5 Technology Readiness & R&D required

Need to check that a conventional optical design can achieve the required image quality and fields.

4.10.6 Cost and Complexity Issues

The instrument is envisaged as a reasonably simple design. More complex designs (eg. ONIRICA) could bring benefits in terms of lighter weight etc., but will carry their own risks. Cost will also be moderate. Based on focal plane costs a reasonable estimate is probably 16 M€ and 100 Staff yrs.

4.11 High Resolution NIR Spectrograph

The High Resolution NIR Spectrograph is a near diffraction-limited high-resolution spectrograph with maximum point-source sensitivity. It relies on medium-to-high Strehl ratios delivered by a SCAO system and achieves a resolving power of R=100,000 (goal >300,000) over the 1000-5000 nm range in a compact dual-arm design. The requirement for diffraction-limited image quality makes the spectrograph design mostly independent of telescope diameter and delivered f-ratio.

4.11.1 Instrument Modes

The High Resolution NIR Spectrograph is highly optimised for single point-source spectroscopy. The primary instrument mode is a 'long'-slit mode with full wavelength coverage and maximum throughput. In addition, an integral field spectroscopy mode with near diffraction limited spatial resolution over a 0.5x0.5 arcsec field but with limited wavelength coverage could be considered for line studies in extended objects.

Baseline AO system is a SCAO system working in NGS mode with the NGS equal to the science target. An LGS mode could be considered for faint science targets.

It is envisioned that IR high-resolution spectrographs of the ELT era shall provide full wavelength coverage in single exposures over large wavelength ranges to maximize the scientific return. Cross-dispersed echelle designs as already commonly used in the optical are required to achieve this goal.

In such a design, an additional 'low resolution' mode with a resolving power or R=10,000 can be foreseen, which is using the cross-dispersers as main dispersion elements. Considering the strong science cases for R=10,000 in the NIR (high-z Universe: sources of re-ionisation, GRB at z>10) it has to be seen if this important domain in resolving power can be better served by a low-resolution mode of a NIR high-resolution spectrograph or by a high-resolution mode of a NIR multi-IFU spectrograph. This decision has to be taken based on the maximum point-source sensitivity that can be achieved by either approach.

In the following we will concentrate on the high-resolution ($R=10^5$) case.

4.11.2 Science Drivers

The main relevant science drivers given in the science case for the European ELT [RD01] are:

- Exoplanets: direct detection of spectroscopic signatures $R=10^5$, 1.25 micron; [RD01] ch.3.1.1.2
- Protoplanetary Disks, molecular clouds $R=10^5$, 1-5 micron; [RD01] ch. 3.3.1
- Black holes in GCs R=20,000, at 2 micron; [RD01] ch.3.3.3
- High-redshift ISM $R=10^5$, 1-5 micron; [RD01] ch.4.1
- Resolved Stellar populations, Stellar abundance studies $R=10^4$-10^5, 1-2.4 micron; [RD01] ch.4.2
- Stellar Kinematic Archaeology $R\sim10^4$-10^5, FoV ~1arcsec; [RD01] ch.4.6
- Young Massive Star clusters R>40,000; [RD01] ch.4.9

4.11.3 Outline Specification

The main driver for the High Resolution NIR Spectrograph instrument design is the maximum point-sources sensitivity combined with large wavelength coverage while maintaining a reasonable instrument size. These requirements automatically lead to a cross-dispersed echelle design with near-diffraction limited AO feed. A goal for an average resolving power of R=100,000 was set for this study. To allow for an adequate sampling of the diffraction-limited input and an optimization of the design parameters (and materials/coatings) over the required 1000-5000 nm range, the instrument has been split in two arms, one for the 1000-2300 nm (blue), the second for the 2400-5000 nm (red) range. Corresponding spectrograph slit dimensions are 0.03x0.30 arcsec (blue) and 0.06x0.30 arcsec (red). For these slit widths a resolving power of 100,000 is achieved for diffraction-limited input at 1660 and 3500 nm, respectively. The full spectral range can be captured in both arms with 2k x 4k detector arrays of ~20 µm pixels in 50 (blue) and 40 (red) spectral orders. While a more efficient prism cross-dispersion appears still feasible in the blue arm, grating cross-dispersion appears mandatory for the red due to the minimum in spectral dispersion of infrared materials in this spectral regime. The diffraction limited input keeps the beam diameter (50mm) and therefore the size of the optics and the overall instrument comparatively small - independent of the chosen telescope diameter and f-ratio. However, f-ratios <10 lead to physical slit dimensions of <10 µm, which appear to be impractical. The operating temperature for the instrument is ~60K with a coolable mass of no more than 250 kg, which can be easily realized with standard cryo-coolers. The total instrument (and cryostat) volume is expected to be of the order of $1m^3$ with a total mass not exceeding 1.5 tons.

4.11.4 Requirements and Pressures on Telescope, AO & Site

The instrument outlined above is fully designed around a diffraction-limited input and therefore highly relies on the availability of AO. The baseline AO system for the instrument is a single-layer conjugated AO (SCAO) system delivering medium Strehl ratios over the 1000-2500 nm range. The performance of the SCAO system is the main driver for telescope parameters like f-ratio and back-focal distance. The presented instrument design does not allow for sensible seeing-limited operation. Based on this reasoning, High Resolution NIR Spectrograph does most likely not qualify as a potential first-light instrument for the ELT. Low emissivity of telescope and NIR sky are the main requirements imposed by the instrument. The requirements on the quality of the atmosphere are again driven by the requirement of the AO system to deliver medium Strehl ratios over large fractions of the operation time.

TABLE 16: REQUIREMENTS ON TELESCOPE, AO & SITE – High Resolution NIR Spectrograph

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	1000-5000 nm	to be split 1000-2300 nm and 2400-5000 nm Possibly two instruments?	C	
2	Telescope final focal ratio	>10	for slit width >10 µm. Mainly driven by AO requirements	D	
3	Scientific Field Size (Diameter)	1-5 arcsec	for target acquisition, science slit length ~0.1 arcsec	C	
4	Field flatness	not critical	cf. 3	N	
5	Linear field size	not critical	cf. 3	N	

6	Image quality	diffraction limited, medium to high strehl	to maximize point source sensitivity	C	
7	Adaptive Optics System	yes, SCAO type, SR =0.6 (H)	cf. 6. target can be NGS in most cases, single LGS could be desirable for fainter targets	C	
8	Stability of the focal plane scale	not critical	point source spectroscopy	N	
9	Background emission from telescope	low	mostly relevant in 2400-5000 nm regime for high sensitivity	C	Critical at up to 5000 nm
10	Straylight from telescope	not critical	point source, high-res spectroscopy		
11	Differential Refraction	not critical	point source		
12	ADC	yes	built-in to instrument, not critical if instrument has its own derotator	D	
13	Zenith Distance Angle Range of operation	0-60º	critical in connection with 7	C	
14	Type of telescope focal station	gravity stable, NAS	stability requirements for high-resolution. NAS preferred. CAS not impossible.	C	May be critical - needs study of flexure correction
15	Back focal distance		driven by AO system	C	
16	Instrument attachment	bench-mounted on NAS platform	cf. 14. Instrument internal derotator required, cf. also 12	C	
17	Max Mass of Instrument (not rotating and/or rotating)	<1500kg on platform	diffraction limited spectrograph: small dimensions (beam size <50mm)	N	
18	Max Volume occupied by the instrument	1 m^3	cf. 17	N	
19	Telescope Pointing	<1 arcsec	cf. 3. Tracking of additional velocities is required.	C	
20	Telescope Chopping	freq. depending sky, detector throw < 10 arcsec	could be relevant in 3000-500 nm regime	D	
21	Maximum brightness level of stars to study	very bright targets to be expected		D	
22	Calibration Requirements	internal calibration system		C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	visitor & service	Regular operations modes		
24	Typical Integration Time	15 - 60 min	high-res spectroscopy		
25	Special supply	cryo-coolers supplies	small mass to cool (<250 kg)		
26	Various atmospheric properties of the site	low sky emission for max sensitivity, others driven by AO requirements		C	
27	Latitude of the site	no technical requirements		N	
28	Altitude of the site	no technical requirements		N	
29	Percentage Photometric nights	not critical		N	
30	Percentage Clear nights	maximum		C	

[1] **Classification of requirement:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

A High Resolution NIR Spectrograph does not seem to be a candidate for a first-light instrument for two reasons:

- The required AO performance providing diffraction limited images may not be available early on
- The science cases for a resolving power of > 100,000 are somewhat specialised.

This assessment, however, would change if the High Resolution NIR Spectrograph instrument is conceived to also cover the spectral resolution range of 1000 – 50,000.

4.11.5 Technology readiness & R&D required

The baseline design for a two-arm cross-dispersed echelle NIR spectrograph does not require major R&D activities. The most critical items are the necessary R2-4 echelle gratings with low groove densities of the order of 20 l/mm and grating dimensions of some 50x200 mm. For replica gratings, the lowest groove densities which can be produced today are 20 l/mm with this technique. In case the free spectral range per order needs to be reduced, lower groove densities could be achieved using diamond turning techniques (tbc). With the given collimated beam diameter of 50 mm, a maximum size of lens optics of 150 mm diameters are expected (depending on the actual camera design) and appears feasible even for todays manufacturers of infrared optical materials like ZnSe and BaF_2 crystals. Buttable 2kx2k InSb (or HgCdTe?) 18-25micron pixel detectors with low noise and high QE are already in reach today. Detector mosaics with up to 4kx4k size appear to be feasible. Further, the cryogenic requirements of the instrument can be met with today's standard technologies.

4.11.6 Cost and Complexity Issues

High Resolution NIR Spectrograph is a simple single-mode instrument of medium-to-low complexity. A rough cost estimate based on experience with CRIRES suggests about 8 M€ in hardware and about 90 FTE.

4.12 Mid-IR Imager and Spectrograph

4.12.1 Instrument Modes

We base the following discussion on work done for T-OWL [RD03] and MIDIR in the ELT FP6 Design Study. MIDIR is a combined Imager and Spectrograph for the thermal/mid-infrared wavelength range. The baseline coverage is from 7 to 20 micrometers, with a strong incentive to include the shorter L and M bands, and a goal to extend the Q-band to 27 micrometers if the atmospheric properties of the site are good enough. MIDIR will provide imaging, low, medium, and high resolution spectroscopy, significantly expanding the phase space covered by current and future ground and space observatories.

4.12.2 Science Drivers

MIDIR on a 30-60m ELT will reveal the infrared Universe at a resolution comparable to what astronomers are used to from the Hubble Space Telescope in optical observations – but now at 10µm! This will be the dawn of a new era for mid-infrared astronomy, mainly enabled by three factors:

- large angular resolution provided by an ELT,
- the availability of large format, high performance MIR detectors,
- specific observing modes, not offered in space observatories.

Due to the high thermal background MIDIR will be optimised for (and will only deliver great results near) the diffraction limit. Hence, its main applications will be observations that require highest angular resolution, very high spectral resolution, or quick response times (< 1 day).

Science areas of particular interest are:

- Solar System,
- Proto-planetary Disks,
- Proto-stars,
- The Galactic Center,
- The IMF in Star-bursts,
- AGN at Low Redshift,
- Ultra-Luminous Infrared Galaxies,
- Gamma-Ray Bursts at very high redshifts,

The main "killer" science applications for MIDIR, however, will be:

- Galactic: the formation and evolution of planetary systems
- Local Universe: the luminous centres of galaxies
- Early Universe: Gamma-ray bursts and luminous AGN at very high redshifts

First sensitivity estimates (TBC) show that, at R=3000, MIDIR can reach a point-source sensitivity comparable to JWST/MIRI but at 6.5 times higher angular resolution - provided it is on an excellent site. Imaging will reveal structural details that cannot be resolved with JWST. The high resolution mode provides even superior sensitivity to unresolved lines, and additional information on the velocity fields in heavily obscured environments.

4.12.3 Outline Specification

From the science cases we derive the following instrument requirements:

- diffraction limited performance at N and (at least part of the) Q band
- coverage of the L and M bands is very desirable

with the following instrument modes:

- broad-band imaging
- low-resolution (R~200), long-slit spectroscopy
- medium resolution (R=3000), IFU spectroscopy
- high resolution (R=50,000) Echelle spectroscopy

Not all of these options, however, may be available at all wavelengths. A careful trade-off study to reduce the instrument complexity, is ongoing. The need for and feasibility of polarimetry is under study.

The field of view can be kept relatively small, with about two arcmins in imaging mode and a few arcseconds only in IFU spectroscopy mode. Part of the requirement for the larger field comes also from the possible need for chopping. For a large aperture at good a site time scales for chopping could be much relaxed. A study is needed to investigate what modes and strategies are valid options.

The resulting technical specifications are listed in a more comprehensive way in the table of requirements.

4.12.4 Requirements and Pressures on Telescope, AO & Site

TABLE 17: REQUIREMENTS ON TELESCOPE, AO & SITE – Mid-IR Imager and Spectrograph

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	7-20 μm (goal: 3.5-27 μm)		C	
2	Telescope final focal ratio	6-15		N	
3	Scientific Field Size (Diameter)	2 arcmin	chopping, optional 3.5 μm wide-field imaging	D	
4	Field flatness	N/A	re-imaging will provide flattening	N	
5	Linear field size	<100 mm	size of entrance window	C	
6	Image quality	diffraction-limited	requires SCAO in thermal IR	D	
7	Adaptive Optics System	SCAO; SR(L,M) > 0.3, SR(N,Q) > 0.7	provided either by a DM within an IR-optimized ELT, or internally to instrument	C	

8	Stability of the focal plane scale			N	
9	Background emission from telescope	not more than 3 telescope mirrors (goal), MIR-optimized coating and/or clean mirrors essential, telescope emissivity << 10%	some protected Ag coatings have absorption features in the mid-IR	C	Major impact on telescope and AO architecture
10	Straylight from telescope	no warm straylight baffles	The telescope should be designed that its background emission can be masked out. In the OWL design (Kevlar ropes & large gaps between M1 segments) this would have been a problem.	C	Conflict with visible wavelength baffling
11	Differential Refraction		see next item		
12	ADC	none within the telescope	can be better compensated within the instrument due to different material properties	N	Needs deployable ADC
13	Zenith Distance Angle Range of operation	0-60 degrees	limited by AO performance	N	
14	Type of telescope focal station	Nasmyth (or Cassegrain, TBD), M3-Mx optimized for the thermal IR or exchangeable		C	
15	Back focal distance	500mm		D	
16	Instrument attachment	fixed	Field (pupil) derotation internal if necessary	D	
17	Max Mass of Instrument (not rotating and/or rotating)	6t, not rotating		D	
18	Max Volume occupied by the instrument	3m (diameter) x 2m (height)	excluding electronics racks	D	
19	Telescope pointing and guiding	blind pointing better than 1" (1 sigma)		D	
20	Telescope Chopping	Chopping may not be feasible, but beam switching (~5”) must be possible at 0.5 Hz.	A study is needed to investigate what modes and strategies are valid options.	D	Special requirement
21	Maximum brightness level of stars to study	K = -2 mag		D	
22	Calibration Requirements	internal to instrument		C	
	IMPACT ON OPERATION, SITE				
23	Operation mode	service observing (queue scheduling)		C	
24	Typical Integration Time	0.001s < DIT < 10s, INT < 6hr		D	
25	Special supply	LN2		C	

26	Various atmospheric properties of the site	median condition: PWV < 2mm best condition: PWV < 0.5mm	C (D)	Critical
27	Latitude of the site	defined by sky coverage and science case	D	
28	Altitude of the site	as high as possible (temperature & transmission important) - see item 26	D	Critical
29	Percentage Photometric nights	see item 26	N	
30	Percentage Clear nights	see item 26	N	

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

A Mid-IR Imager and Spectrograph has several specific requirements on telescope and site:

Diffraction limited performance and AO This requires an adaptive optics system. Single-conjugate AO will be sufficient, and systems with about 500 actuators will be sufficient for the N and Q bands, even under average seeing conditions.

However, the performance of the Mid-IR Imager and Spectrograph depends critically on the thermal background emission from the telescope+AO system. Hence the first priority for Mid-IR Imager and Spectrograph would be a 2 or 3 mirror telescope with a deformable secondary mirror (DSM) which provides the AO correction. The second priority would be an infrared optimized telescope with up to 5 mirrors, which provides full SCAO correction for the thermal/mid-IR. However, it is VERY important to maximize the reflectivity of each surface. Calculations have shown that a 30 meter telescope with 3 mirrors with only 2% emissivity per surface will have the same N-band sensitivity as a much larger 42m telescope with 5 mirrors with 5% emissivity, each. Hence, the performance (initial coating and cleanliness) of the mirrors is of crucial importance. If, for some unfortunate reason, this requirement on the telescope concept cannot be met, the third priority for Mid-IR Imager and Spectrograph would be to have a simple 2 mirror telescope and a separate, instrument-specific, cryogenic AO system. The complexity of such an AO system may be comparable low, although it requires the development of large format, cryogenic deformable mirrors. The least attractive option, which would definitely compromise mid-IR science, would be a non-IR optimised telescope with more than 4 mirrors.

At any rate, wavefront sensing should be done in the NIR.

Excellent atmospheric properties: the feasibility of the science case and the competitiveness to JWST/MIRI depends largely on the thermal and transmission properties of the atmosphere/site. At L and in particular M-band, the performance is basically determined by the atmospheric transmission. At N-band the performance is basically determined by the temperature of atmosphere and telescope (although the width of the band depends on the transmission), while at Q-band the critical parameter is transmission again. The transmission of the atmosphere will determine if important, unique diagnostics (such as CO at 4.7μm in protoplanetary systems, or the molecular hydrogen line at 17.03μm) are accessible at all. For instance, at the long end of the M-band the sensitivity from Chajnantor is about one order of magnitude better than from a Paranal-like site.

Another, possibly very significant factor is the precipitable water vapour. The magnitude and timescales of its fluctuations require a more detailed study. In the worst case, these fluctuations may be the dominant component to image degradation after AO correction, and may require additional wavefront/tip-tilt sensing at N-band. However, this effect is expected to be much reduced at high altitudes.

Mid-IR Imager and Spectrograph could do useful science on day 1. There are four reasons why Mid-IR Imager and Spectrograph should be considered as a first light instrument:

- Mid-IR Imager and Spectrograph would provide diffraction-limited, wide-field images at 10μm at the same resolution as JWST in the NIR. Hence, the combination of NIR JWST images with MIDIR N-band images would provide a perfect match with significant PR value for first press releases.
- The biggest challenge for ELTs is arguably the required performance of the adaptive optics system to reach the diffraction limit - a very difficult task at shorter wavelengths. While an 8m telescope theoretically provides better/sharper images than a 2.5m, it has taken many years for the VLT to become competitive to HST in that regard. A similar relation will be between the ELT and JWST. Going to longer wavelengths overcomes many of these problems (including static phasing errors, vibrations, etc.).
- A Mid-IR Imager and Spectrograph may provide important additional information on the telescope structure and optics near the end of the commissioning phase, from the thermal point of view.
- Although Mid-IR Imager and Spectrograph will provide numerous options/modes, which can be tested and calibrated in the lab, its operation is expected to be rather straight forward ("point-and-shoot mode").

4.12.5 Technology Readiness & R&D required

MIDIR requires no fundamental new developments. Some areas require further developments but are based on existing technologies. That includes detectors, filters and electronics. However, several areas require further study:

- the manufacturing of the large Echelle gratings
- the cryogenic operation of deformable mirrors (possibly)
- the impact of water vapour fluctuations on the image stability and the possible need for a 10μm wavefront sensor.
- the need for chopping (to be addressed within the Small Study work)

4.12.6 Cost and Complexity Issues

The cost of Mid-IR Imager and Spectrograph will be dominated by manpower and, on the hardware side, by MIR detectors. Hence the total depends strongly on the number of channels realized in such an instrument, and the trade-off between complexity and science requirements needs further study. For the most complex (many channels) case we estimate 17 M€, and 250 FTE (incl. 20% contingency).

4.13 Sub-mm Imager

4.13.1 Instrument Modes

Sub-mm Imager is proposed as a sub-millimetre camera operating between wavelengths of 200 and 850 micrometer. It is envisaged as a dual wavelength imager with two separate focal planes of detectors (with "workhorse" wavelengths of 350 and 450 μm). In addition, a rotating waveplate polarimeter is proposed that can be inserted into the beam at the instrument cryostat window. One possibility is that Sub-mm Imager operates in a "hitchhiker" mode together with another instrument.

Operating modes include (simultaneous at 2 wavelengths):

- Mosaic mapping (series of CCD-style exposures)
- Scan mapping (scanning telescope over region of sky while continuously taking data)
- Polarimetry (using additional hardware - mosaic or scan-map)

Calibration modes include:

- Atmospheric extinction calibration (sky temperature measurement as function of elevation)
- Flux calibration (using "standard" astronomical sources)
- Flat-field (using external uniform black-body source)
- Dark frame (using cold shutter in front of detectors)

4.13.2 Science Drivers

The science drivers for Sub-mm Imager are derived from an extensive scientific case that concentrates on addressing the "Origins" questions of the formation and evolution of galaxies, stars and planets. The unique advantages of Sub-mm Imager are that simultaneous high angular resolution and large-area imaging are available from the same instrument for the first time. Examples include surveys of entire giant molecular clouds and fields of dusty galaxies at early epochs. Almost every area of astronomy would benefit from such an instrument. Some of the main science themes are:

- Measuring the star formation history of galaxies down to the Milky Way luminosity throughout the Universe
- Imaging the cold dust content of nearby galaxies
- Determine the clump mass function in star forming molecular clouds to sub-stellar masses
- Detecting debris disks down to dust masses less than that of our Solar System

Hence, the main science drivers for Sub-mm Imager are:

- To carry out deep imaging of selected areas well below current confusion limits
- To carry out wide-field surveys of the sub-mm sky (many square degrees of sky)

These dictate that we operate the instrument at the shorter wavelengths (200 and 350 μm) for best resolution and lowest confusion limits (this is also close to the peak wavelength of emission from cold pre-stellar cores and the high-z sub-mm background). A large field-of-view is needed to cover degree-wide (and larger) fields (e.g. Giant Molecular Clouds or galaxy fields).

4.13.3 Outline Specification

Wavelength range	200 - 850 μm
"Workhorse" wavebands	350 and 450 μm simultaneously
Field-of-view	at least 5 arcmin in diameter at each waveband
Focal planes	Two separate arrays of detectors
Imaging mode	Mosaic and scan map
Other modes	Polarimetry (using additional hardware)

Table 18: Specifications for a Sub-mm Imager

4.13.4 Requirements and pressures on Telescope AO & Site

TABLE 19: REQUIREMENTS ON TELESCOPE, AO & SITE – Sub-mm Imager

No.	Requirement	Value or Value range	Rationale	Index[1]	Major driver on telescope or AO systems
	OPTO-MECHANICAL TEL. PROPERTIES				
1	Wavelength range of instrument	850-200 μm	Shorter wavelength more competitive	C	
2	Telescope final focal ratio	f6	Needs to be de-magnified to allow a reasonable sized focal plane for detector arrays?		
3	Scientific Field Size (Diameter)	5(10) arcmin	Science field	C(D)	
4	Field flatness			N	
5	Linear field size	250 mm	Cryo window limit (seems reasonable as a compromise as to what is achievable and minimising themal loads)		
6	Image quality	<0.2 arcsec spot	Diffraction limit at 200 μm is ~0.8 arcsec	C	
7	Adaptive Optics System	N	May need to measure & compensate (in software) for sub-mm seeing. Is an active surface envisaged as standard? i.e. to take out thermal gradients? Might be essential if we are to observe during daytime.	C?	Option for daytime observing would be a critical driver of telescope design.
8	Stability of the focal plane scale		Not an issue for sub-mm spatial resolution		
9	Background emission from telescope	<10%	In sub-mm	C?	
10	Straylight from telescope		Not an issue (e.g. moonlight etc!)	N	
11	Differential Refraction			N	
12	ADC		Not necessary	N	

13	Zenith Distance Angle Range of operation	5-80º			
14	Type of telescope focal station	Gravity-neutral	Coolers cannot be tipped. Not sure this is entirely true. Really depends on whether we need a Dilution Refrigerator or not... Not impossible, but costly development for gravity variant		
15	Back focal distance				
16	Instrument attachment		No instrument rotator essential, but would be desirable		
17	Max Mass of Instrument (not rotating and/or rotating)	4-6 tonnes			
18	Max Volume occupied by the instrument	$8m^3$	From SCOWL study		
19	Telescope pointing and guiding	<0.3 arcsec			
20	Telescope Chopping				
21	Maximum brightness level of stars to study	no	Not necessary		
22	Calibration Requirements	None	Internal calibrator loads and/or load at window that can be removed. Cold (~1K) shutter a must.		
	IMPACT ON OPERATION, SITE				
23	Operation mode	Service	Hitchhiker (simultaneously with other instruments potentially, requiring dichroic)	D	Scanning modes may not be compatible with other instruments
24	Typical Integration Time	Hours	For large-scale scan maps		
25	Special supply	Custom pressurised He lines	For dilution fridges and pulse cool coolers	C	
26	Various atmospheric properties of the site	PWV<1mm(<0.5mm)	For sub-mm observing (200 µm observing)	C (D)	
27	Latitude of the site	<30	To allow ALMA follow-up; ideally, but not absolutely essential?		
28	Altitude of the site	>4km (>5km)	For low PWV	C(D)	Critical for science value, especially at 200 µm
29	Percentage Photometric nights	0			
30	Percentage Clear nights	0	Can observe through cirrus		
	ADDITIONAL REQUIREMENTS				
31	Spectral Resolution	NA			
32	Strehl ratio/ ensquared energy	Seeing limited			

[1] **Classification of requirements:**
C for critical to the realization of the instrument and/or its scientific goals,
D for desirable or preferred and
N for neutral

Sub-mm Imager could be operated during the daytime and/or during periods of poor optical/IR seeing. There are no requirements in terms of AO, but if the instrument is to be used during daylight hours some kind of active surface adjustment will be required to correct for thermal gradients (causing beam distortion). To correct for "sub-mm seeing" some form of wavefront sensors will be needed to measure the tilt of the wave across the aperture using, for example, the 183 GHz water line (such a scheme is planned for the Large Millimeter Telescope, LMT).

Operation at the shorter sub-millimetre wavelengths (200, 350 microns) from the ground requires an exceptional site! This means that a high-altitude site like the Atacama Desert (ALMA site) or a lower, but dry site such as Antarctica is required. Mauna Kea is not considered to be good enough for short wavelength sub-mm astronomy.

The instrument will be capable of doing excellent science from day one. The focal plane will be designed to allow upgrades (in terms of numbers and quality of arrays).

4.13.5 Technology Readiness & R&D required

SCUBA-2 is a similar instrument to the proposed Sub-mm Imager. The technology readiness of large superconducting detector arrays will be proven with SCUBA-2. The main R&D required in this area for Sub-mm Imager is to scale the technology to allow larger focal planes (Sub-mm Imager is envisaged as having two focal planes of at least 20000 detectors in each wavelength band c.f. 5000 for SCUBA-2). Alternative technologies (e.g. kinetic inductance detectors, KID) are also being considered, which may simplify many of the complexities. It should be noted that KIDs technology is in its very early stages compared to the superconducting arrays used in SCUBA-2.

4.13.6 Cost and Complexity Issues

Based on experience of the SCUBA-2 design we estimate that the cost of the instrument at around the 20 M€ mark (not including contingency). This is split roughly 12m on hardware and 8m on staff effort.

The main complexities are in developing larger arrays - at least 4 times the size of the SCUBA-2 arrays. This has other consequences in terms of focal plane layout, thermal design and the number of wires and volume of electronics. If a dilution refrigerator is needed to cool the arrays then this requires a fairly complex gas handling system and requires that the instrument not be tilted significantly, to maintain the phase boundary necessary for the dilution process to work.

4.14 Overview over instrument concepts and requirements

We have tried to summarise some of the instrument requirements in the form of diagrams and summary tables in line with the toolbox approach for this report. This should facilitate comparison of requirements resulting from the five different WGs. After a feedback loop with the other groups we plan a next step in which we will identify instruments which show large overlap in their requirements and which therefore could easily be implemented together.

It is important to raise a cautionary note on this list of instrument concepts and the requirements they set. In some cases they are not yet supported by any technical study. In the absence of proof of feasibility, one should be aware that the listed capabilities might be very difficult if not impossible to achieve, especially in a single instrument.

Table 20: Summary of Observing Capabilities

Name	Total Wave-length Range	Instantaneous wavelength coverage	Observing Modes	Spectral Resolution	Science FoV	Image Quality	AO Require ments	Object Multi-plexing
High Resolution Visual Spectrograph	400-700 nm goal 350-900 nm	Full range	Echelle Spectroscopy	150,000 additional mode 40,000	Req: 5 arcsec Goal 10 arcsec	0.5 arcsec FWHM	Seeing enhance ment desired - GLAO	Single object
Visual Imager	Goal 350 – 1050 nm	1, possibly two bands split by dichroic	Imaging	-	0.5/(D/F-ratio) eg 4x4 arcmin on 42 m f/12	Seeing limited	GLAO	
Multi-Object Visual Spectrograph	320 – 1000 nm goal up to 1500 nm	Higher (>~1000) resolution will require multiple grating settings	Medium Resolution Spectroscopy	700 -7500 goal 500 - 10000	> 6 arcmin	0.2 arcsec FWHM ~50 mas/pix	GLAO	> 50 ?
High Time Resolution Instrument	400-1000 nm goal up to 2000 nm	one, possibly two bands split by dichroic	High Time Resolution Imaging	Fixed by filter band widths	15 arcsec goal 60 arcsecs	Seeing limited	GLAO, tbc	-
Polarimeter	400-2300 nm goal up to 27000 nm	One band at the time	Imager, Low Res Spectrograph		> 10 arcsec		SCAO/X AO	Single object
Multi-Object NIR Spectrograph (small field, high spatial resolution)	800-2400 nm	very unlikely at high resolution	“Small” Field MO Spectroscopy	Low 4000 High: up to 20000	2x2 arcmin	FWHM 10 mas in H	MOAO	~20 pick offs FoV 0.4x0.4 arcsec at 5 mas/pix
Multi-Object NIR Spectrograph (wide field)	800-2400 nm	Difficult at high resolution	“Wide” Field MO, field spectroscopy	4000-10000	5-10 arcmin diameter	50 mas fwhm	MOAO	≥30 IFU FoV 1x1 arcsec, ~25mas/ pix fwhm

Planet Imager and Spectrograph	600 – 1800 nm, goal up to 2300 nm	Mode dependent	Imager, Area Spectroscopy, Polarimeter	low 15 mid 1000 high 50000	> 4 arcsec goal: 10 arcsec	Fully diffraction limited 4 mas/pix	SR=0.64 in R, 0.92 in H XAO	Single target
Wide Field NIR Imager	600-2400 nm	Filter dependent	Imager	-	LORES: 9 arcmin, 17 mas/pix HIRES: 2 arcmin, 3.7mas/pix	50 mas fwhm	MOAO	
High Resolution NIR Spectrograph	1000-5000 nm	1000-2300 nm (blue arm) 2400-5000 nm (red arm)	High Res Spectroscopy	100,000 goal >300,000	1-5 arcsec	Diffraction limited	SR=0.6 in H, SCAO	Single point source Plus ? IFU 0.5x0.5 arcsec
Mid-IR Imager and Spectrograph	7-20 µm goal: 3.5–27 µm	Mode dependent	Imager, Medium-Res Spectrograph	Low 200 Medium 3000 (IFU) High 50000	2 arcmin diameter	Diffraction limited	SR(L,M) >0.3; SR(N,Q) >0.7	IFU FoV dew arcsec
Sub-mm Imager	200-850 µm	Parallel band observing	Sub-mm Imager	-	5x5 arcmin	<0.2 arcsec spot	GLAO ?	-

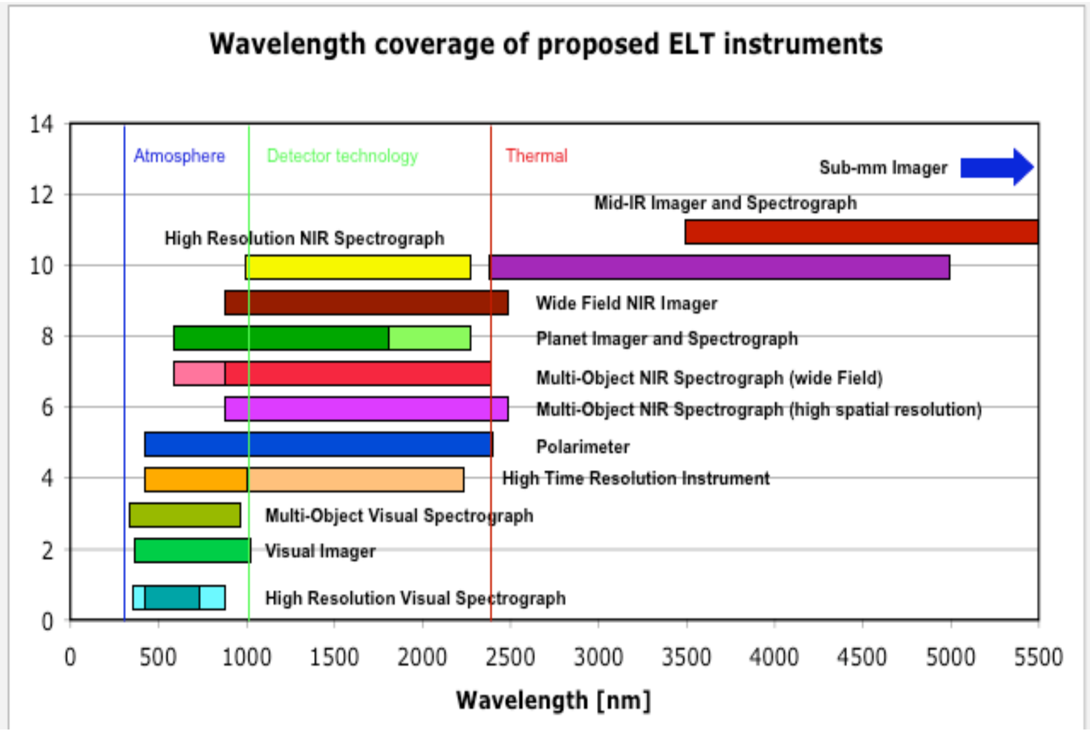

Figure 5: Schematic view of the wavelength coverage provided by the studied suite of instruments for an ELT. Note that the operating range of both the Mid-IR Imager and Spectograph and the Sub-mm Imager extended well beyond the range covered by the diagram.

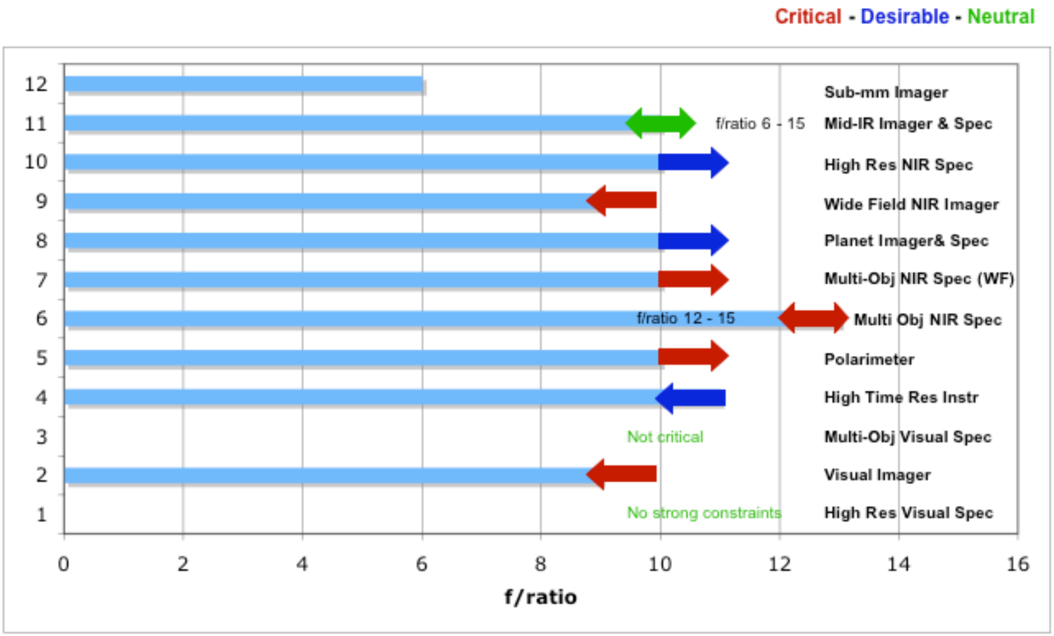

Figure 6: F/ratios required by the various instruments. We have used a color code to distinguish between critical, desirable and neutral requirements. Arrows indicate requirements specified as "larger or smaller than".

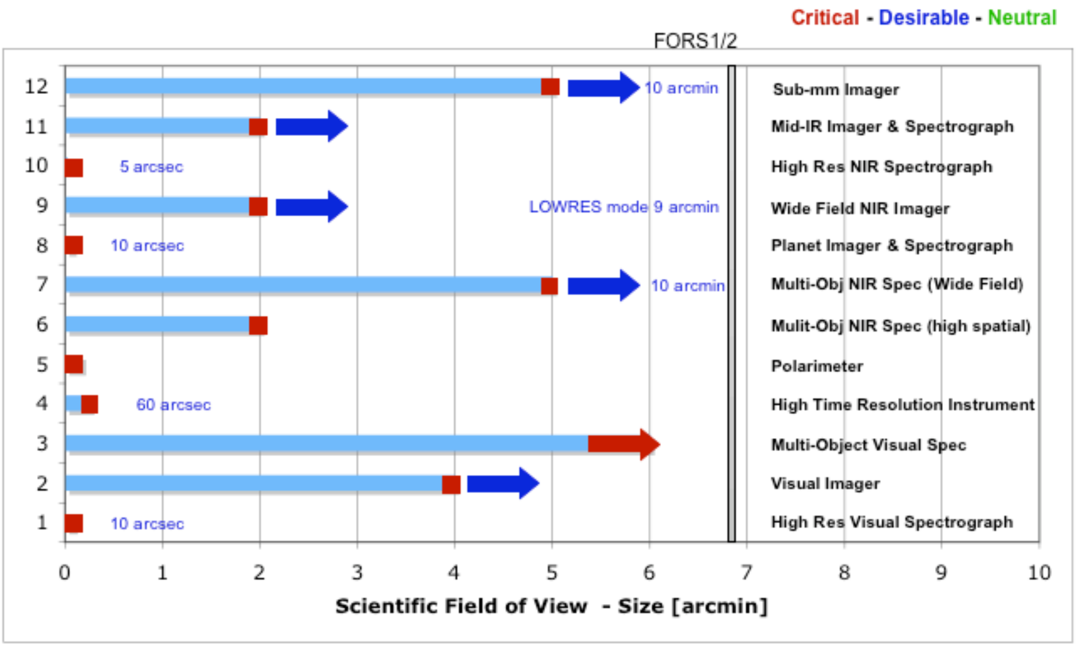

Figure 7: Required scientific fields of view for the suite of instruments studied. For some instruments a desired extended FoV (blue arrows) is given in addition to the critical requirement (red).

Table 21: AO Instrument Requirements

Instrument	Strehl Ratio	AO Requirement	Rationale
High Resolution Visual Spectrograph	-	-	No gain expected from AO in B, V and R bands. AO might however be required from telescope to deliver best seeing image quality (~0.4")
Visual Imager	-	-	cf High Resolution Visual Spectrograph
Multi-Object Visual Spectrograph	Not critical	-	cf High Resolution Visual Spectrograph
High Time Resolution Instrument	-	GLAO, SCAO	Diffraction limited imaging, S/N
Polarimeter	-	SCAO/XAO	High contrast imaging
Multi-Object NIR Spectrograph (high spatial resolution)	-	MOAO (MCAO)	Diffraction limit
Multi-Object NIR Spectrograph (wide field)	-	MOAO (MCAO)	GLAO plus MOAO, LGS required
Planet Imager and Spectrograph	V=0.4, R=0.64, J=0.87, H=0.92, star < 10 mag	XAO	Not useful without XAO
Wide Field NIR Imager	-	GLAO/MCAO or LTAO	Spatial Resolution
High Resolution NIR Spectrograph	H=0.6	SCAO	Maximise Point source sensitivity
Mid-IR Imager and Spectrograph	L,M > 0.3, N,Q > 0.7	SCAO	Increase sensitivity
Sub-mm Imager		?	Equired for datime observing ?

AO flavours: **SC:** single conjugate, **GL:** ground layer, **LT:** Laser Tomography, **MC:** multi conjugate, **MO:** multi object, **X:** extreme, high order SCAO

Table 22: Instrument Requirements: Atmospheric Dispersion Correction and Zenith Distance Angle

Instrument	ADC Required	ADC in instrument	Zenith Distance Angle
High Resolution Visual Spectrograph	Yes	Required	Up to 60 degrees
Visual Imager	Essential	Not necessarily	Up to 60 degrees
Multi-Object Visual Spectrograph	Essential	Required	Up to 60 degrees
High Time Resolution Instrument	Essential	Preferred (small field)	Up to 60 degrees
Polarimeter	Yes (tbc)	Not necessary	Up to 60 degrees
Multi-Object NIR Spectrograph (high spatial resolution)	Essential	Not necessary	Up to 60 degrees
Multi-Object NIR Spectrograph (wide field)	Required	Preferred	Up to 60 degrees
Planet Imager and Spectrograph	Required	Required	Up to 50 degrees
Wide Field NIR Imager	Required for HIRES, Yes for LOWRES	Not necessary	No requirement as long as ADC
High Resolution NIR Spectrograph	Yes	Preferred	Up to 60 degrees
Mid-IR Imager and Spectrograph	Required	Required	Up to 60 degrees
Sub-mm Imager	Not necessary	Not necessary	5 - 80 degrees

Table 23: Instrument Requirements: Focal Station

Instrument	Focal Station	De-rotator in instrument	Back Focal Distance
High Resolution Visual Spectrograph	Laboratory	Optional	No constraints
Visual Imager	Nasmyth, fixed to derotator	Not necessary	No constraints
Multi-Object Visual Spectrograph	Nasmyth, gravity invariant	Required	About 1.5 m
High Time Resolution Instrument	Nasmyth or Cassegrain, fixed to derotator	Not necessary	≤ 500 mm
Polarimeter	Cassegrain, fixed to derotator	Not necessary	> 300 mm
Multi-Object NIR Spectrograph (high spatial resolution)	Nasmyth, fixed to derotator	Not necessary	~ 300 mm
Multi-Object NIR Spectrograph (wide field)	Nasmyth gravity stable	Required if gravity stable	> 500 mm
Planet Imager and Spectrograph	Nasmyth gravity stable	Required	> 500 mm
Wide Field NIR Imager	Nasmyth, rotating or gravity stable	Required if gravity stable	No requirements
High Resolution NIR Spectrograph	Nasmyth gravity stable	Required	Depends on AO
Mid-IR Imager and Spectrograph	Nasmyth or Cassegrain, fixed to derotator	Not necessary	500 mm
Sub-mm Imager	Gravity neutral	Possibly software derotation	No requirements

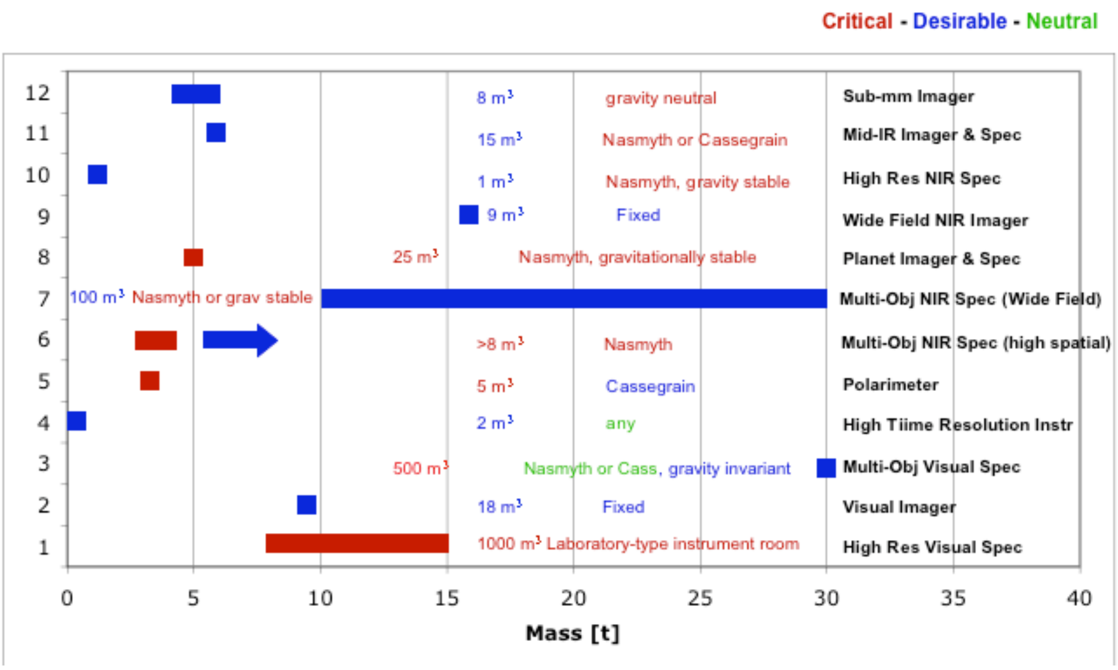

Figure 8: Mass, volume and required focal station for the ELT instruments. Requirements are again color coded in the standard manner.

Table 24: Instrument Requirements: Observing I

Instrument	Maximum Brightness of Target	Typical integration /exposure time	Observing Mode
High Resolution Visual Spectrograph	6 mag	20 – 30 min	Service
Visual Imager	> 20 mag	Depends on f/ratio	Any
Multi-Object Visual Spectrograph	Not critical	10 – 30 ks/mask, 30 min/exposure	Service
High Time Resolution Instrument	-1 mag	~ 4 h	Service
Polarimeter	> 0 mag	< 5 h	Service
Multi-Object NIR Spectrograph (high spatial resolution)	Not critical	1 - 2 h co-added	Service or Visitor
Multi-Object NIR Spectrograph (wide field)	N/A	Tens of h 20 – 30 min/exposure	Service
Planet Imager and Spectrograph	V = 3 mag	< 5 h, 1 – 10 s/exposure	Service or experiment
Wide Field NIR Imager	~ 20 mag	Minutes (HIRES) Seconds (LOWRES)	Any
High Resolution NIR Spectrograph	Very bright	15 – 60 min	Visitor and Service
Mid-IR Imager and Spectrograph	K = -2 mag	< 6 h 0.001 s < DIT < 1 s	?
Sub-mm Imager	Not critical	Hours	Service

Note that in many cases there is no strong requirement from the instrument concerning the observing mode. Visitor mode is certainly permissible for many observations. The desire for the best observing conditions and maximum observing and scheduling efficiency leads one to assume service mode as a standard mode.

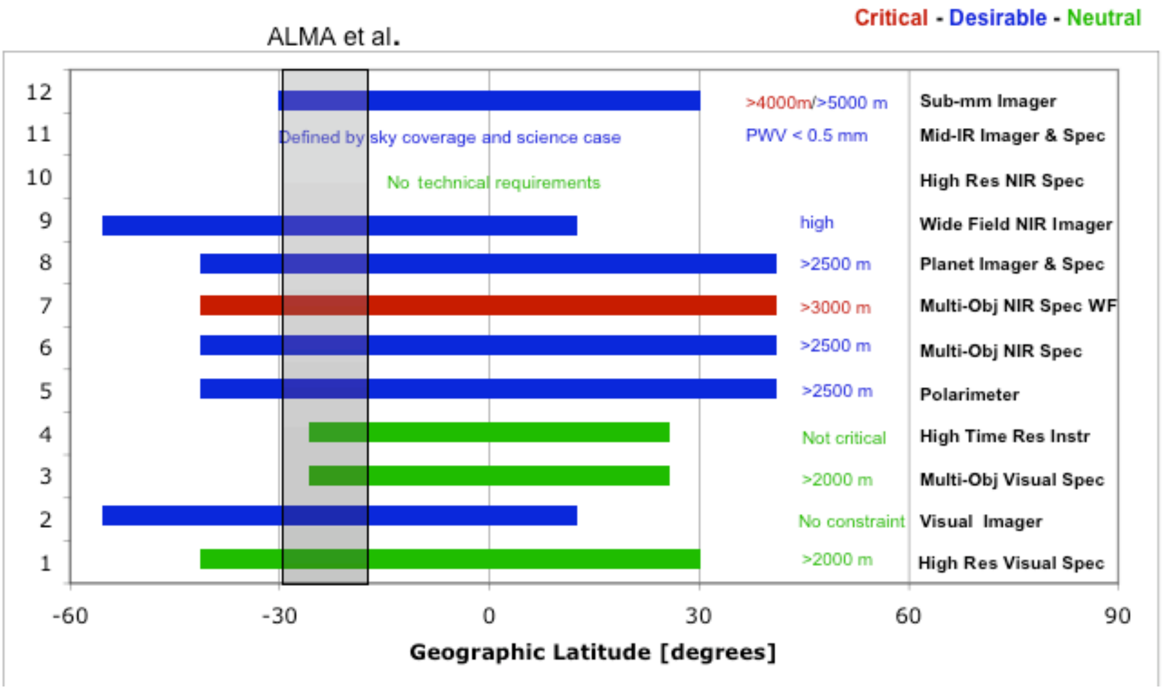

Figure 9: Instrument requirements on the site of the ELT

Table 25: Instrument Requirements: Observing II

The requirements given for site and atmospheric characteristics are not directly given by the instruments but are driven by the science cases and the need for efficient observations.

Instrument	Percentage of photometric nights	Percentage of clear nights	Median seeing [arcsec]	Properties of atmosphere
High Resolution Visual Spectrograph	Not critical	> 80	< 0.8	Low PWV, OH
Visual Imager	High	High	Best possible	seeing
Multi-Object Visual Spectrograph	> 10 ?	> 80	< 0.8	Good Transparency in Blue
High Time Resolution Instrument	Not critical	Not critical	Best possible	
Polarimeter	> 10	> 80	< 0.8	
Multi-Object NIR Spectrograph (high spatial resolution)	> 50	High		Low PWV, OH
Multi-Object NIR Spectrograph (wide field)	?	?	~ 0.6	
Planet Imager and Spectrograph	> 10	> 80	< 0.8	PWV < 2 mm
Wide Field NIR Imager	High	High	Best possible	1.) seeing, 2.) site
High Resolution NIR Spectrograph	Not critical	Maximum	defined by AO requirements to achieve SR	Low sky emission
Mid-IR Imager and Spectrograph	PWV	PWV	?	PWV: < 2 mm median, < 0.5 best
Sub-mm Imager	0	0		PWV: < 1 mm (0.5 mm)

It is important to note that values quoted in the "Estimated Cost" table are rough cost guesses, only. The source of each estimate is given in the corresponding instrument chapter. They are mainly based on the Concept Studies carried out for the OWL instruments (with the exception of the Multi Object Visual Spectrograph) or are based on extrapolation from existing instruments. They are not yet properly matched to a telescope of smaller diameter or to a different set of specifications which might result from the upgrade of the science.

Table 26: Instrument Requirements: Estimated Cost

Instrument	Hardware Cost [M€]	Manpower [FTE]
High Resolution Visual Spectrograph	25	100
Visual Imager		
Multi-Object Visual Spectrograph	~ 40	100 - 120
High Time Resolution Instrument	2.5	
Polarimeter		
Multi-Object NIR Spectrograph (high spatial resolution)		
Multi-Object NIR Spectrograph (wide field)	30 ± 10	200
Planet Imager and Spectrograph	15 – 23	150
Wide Field NIR Imager	16	100
High Resolution NIR Spectrograph	8	90
Mid-IR Imager and Spectrograph	17	250
Sub-mm Imager	12	8 M€

5 PHASED INSTRUMENT PLAN

5.1 Instrument Development Plan

In response to the fact that only 2 first light instruments were included in the OWL proposal the Review Panel recommended that 'Covering the parameter space will be key to the success of the facility and of its use as a science factory. It is the committee's opinion that the initial instrumentation plan should consider more instruments to meet substantially more of the science case requirements'. As concluded here, covering the total effective phase space of a 30-50m ELT would require about 12 instruments suggesting that some selection will be necessary anyway for the first generation and, most particularly, first light instruments. The main factors determining the instrument implementation plan are:

i) the science priorities
ii) synergy with other major facilities e.g. JWST, ALMA,VISTA, VSA, SKA, Darwin, TPF and others
iii) the technical/performance limitations linked primarily with the expected adaptive optics capabilities as a function of time
iv) the available resources - including qualified manpower, money and cash flow
v) the required commissioning time in view of the fact that the ELT is a single telescope.

Taking these factors in turn:

Science Priorities

Many of the highest priority science goals require imaging and multi-object spectroscopy in the red and near-infrared i.e ~ 800-2500 nm. These include the search and characterization of low mass exoplanets ,which requires the highest contrast imaging using XAO, and follow-up spectroscopic surveys of galaxies detected by JWST over ~ 5 arcmin fields and requiring Multi-object AO or at least Ground Layer AO for efficient pixel matching. Exoplanet imaging would be also be effectively complemented with high resolution spectroscopy for radial velocity measurements - probably in the optical where the highest accuracy is likely to be achieved and which would also be required for the exciting proposal to study the Cosmic Expansion. The selection on science priorities between optical (imaging and MOS), mid IR and sub-millimetre remains unclear and may ultimately depend on other factors such as the availability (unlikely) of AO in the visible, the dryness of the site and the size of the telescope e.g below about 40m the ELT would not be sufficiently competitive with a dedicated sub-mm telescope which may appear on a similar timescale.

Synergies with other major facilities

The value of having complementary observations of a given target from different facilities covering different wavelength regions is rather self-evident. The main considerations for the ELT in this context are site selection and how to achieve complementarity by providing the required instrumental capabilities.

Technical limitations of AO capabilities

The issue of adaptive optics has been touched upon above. Although SCAO may be available at first light, the adaptive optics flavours required for the highest contrast imaging and for correcting over large fields is not expected to be available for the first few years of operation and some e.g Multi-object AO may not prove to be feasible at all. As the VLT Planet Finder instrument based on XAO is now going ahead, however, it is possible that this technique could be available on the ELT at an earlier stage.

Resources

With regard to resources it is likely that both ESO and the community will have to be heavily involved in the technology development, design and construction of the instruments both to bring to bear the necessary skills and to limit costs. As a baseline we would propose something close to the VLT 1st generation instrument scheme with ESO covering the capital costs and institutes providing most of the manpower in return for guaranteed observing time. ESO, following the advice of its Scientific and Technical Committee, will issue calls for instrument proposals, establish an appropriate management and technical framework within which to develop the instruments, develop standards e.g software, control electronics and detector systems, probably provide integration facilities and probably develop specific instruments in-house or in collaboration with institutes. Given the larger size and engineering complexity expected of some instruments the role of industry may be larger than for e.g the VLT and should be taken into account in the cost estimates. It will also be necessary to provide more capability for testing instruments in Europe in order to reduce telescope commissioning time. As to the rate at which instruments could be built and taking again the VLT as a guide - development of its 1st light instruments started about 8 years prior to telescope first light. Telescope commissioning was made with a visible test camera and the first 4 scientific instruments (ISAAC, FORS1&2, UVES) were installed within ~ 1 year of the release of the telescope at the end of commissioning. Since then, new instruments have been installed at the rate of about 1/yr and there have been a number of upgrades already for the older instruments. At the moment, two new VLT instruments are at an advanced state of development in Garching and consortia exist for the development of four 2nd generation VLT instruments plus three 2nd generation VLTI instruments. Aiming for 5 or 6 first generation instruments would not be unreasonable therefore. Another factor which may limit the start-up of the ELT instrumentation, however, could be competition with the VLT itself for which instrumentation resources are currently planned until at least 2020. Assuming availability of a Cassegrain, coude and 2 Nasmyth foci the nominal number of simultaneously mounted instruments would be at least 4 and could be increased by providing multiple instrument foci, either using beam switching mirrors or instrument carousels. One key to having several instruments ready for first light is clearly to start early, say 2008-09 for 1st ELT light in 2017. However, this underlines the fact that the time for developing new technology, facilities, organizational structures etc is quite short and this may have a bearing on the nature of the 1st generation instruments.

Commissioning

Commissioning of instruments may be a limitation unless we significantly reduce the time/instrument below that used in many cases on the VLT. This issue does require much more effort to commission whatever is possible first in Europe. Another aspect of commissioning is that of the telescope itself which will require the development of quite advanced test cameras which could probably double as the first light science instrument(s).

5.2 First Light Instruments

Given the need anyway for a test camera, the most obvious 1st light instrument would be a near infrared camera, perhaps of the ONIRICA type. It would ideally provide a central diffraction limited field surrounded by a region with pixels as close to seeing limited as possible, giving a total field of view of around 30 arcsecs to 1 arcmin. This camera could test the basic telescope image quality, the performance of the 1st light AO system and produce early science with whichever flavour of AO that is - SCAO or LTAO. The possibility of including a basic medium resolution spectroscopic capability, perhaps using grisms, should be studied. The need or not for a visible test camera at 1st light should also be studied - it is not obvious what advantage over the near infrared it could bring but may be proposed out of familiarity. It should also be borne in mind that the visible red may be best covered with 'infrared' arrays (e.g down to 600 nm with the Rockwell 2RG) anyway and could therefore be included in the same camera..

Near Infrared MOS (MOMFIS/MOMSI) should remain as the second priority first generation instrument pending the final decision on telescope size and studies of MOAO. Ideally it would have both multi-slit and IFU capability and hence cover a large range of scientific questions.

Third priority could be a CODEX type (segmented pupil) visible spectrograph which would scientifically complement the exoplanet studies and open up the study of cosmic expansion and has the advantages of not needing AO (although GLAO would help) and its location at coudé where its installation would have least interference with telescope commissioning activities.

The mid-IR imager/spectrometer should probably be included in the first generation instruments both to open up new science and to commission the telescope in this wavelength range (emissivity, site). Its longer wavelength range would also make it less sensitive to possible problems with the early AO systems.

For the following instrument options priorities are less clear cut and also depend on the actual size of the telescope and the site:

If the telescope diameter ends up at the larger end of the range and if the site is exceptionally dry and at an appropriate latitude then consideration should be given to an early installation of a sub-mm camera (SCOWL/SCELT). As the main scientific goal is to perform surveys for ALMA, however, one consequence may be that it should be awarded a considerable block of observing time. Its use in daytime should also be considered.

If the telescope ends up at the lower end of the range, consideration should be given to a multi-object optical spectrograph, probably in place of the sub-mm camera if the site is also not exceptionally dry. It would be able to do most of the resolved stellar populations science cases in the Opticon study scaled down because the targets would have to be much closer than for a 50-100m telescope so AO would be less important. It would also be the only instrument that could study the intergalactic medium at z~3.

In line with the arguments above it is quite likely that the community could release sufficient resources to produce this set of instruments within a 10 years timeframe and to install and commission them on the ELT within the first two years following first light. They span the complete ELT wavelength range and provide enough scientific modes to cover a wide range of scientific interests. What would not be covered is wide field visible imaging and MOS, high time resolution visible imaging, polarimetry (although this could be partially included in the IR camera) and high resolution IR spectroscopy. At this stage this does not seem unreasonable. The use of the ELT in the visible at all is clearly a somewhat open question and one which may evolve as the telescope parameters (particularly diameter) become fixed and experience with AO increases. High time resolution and high resolution infrared spectroscopic studies still have to demonstrate themselves on smaller telescopes and expand their user communities

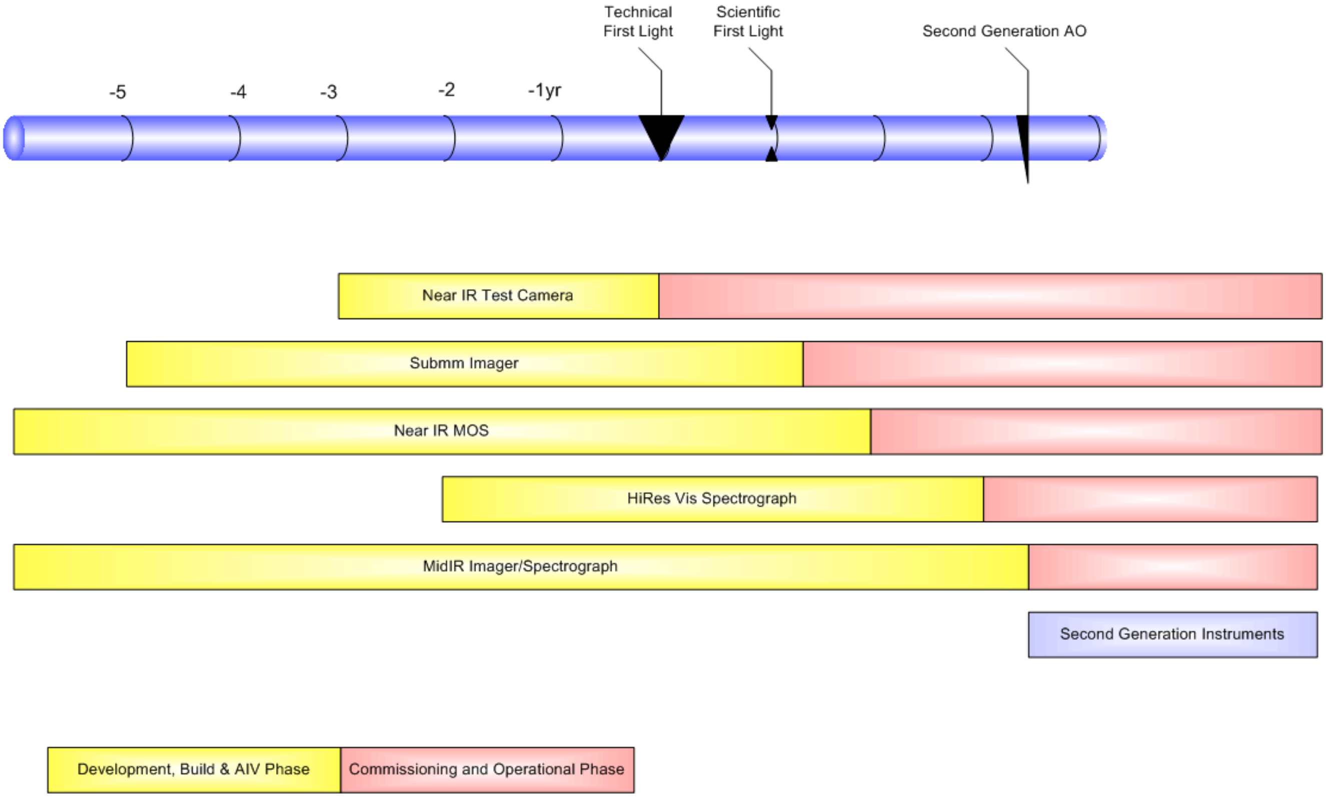

Figure 10: A possible phasing plan for instrumentation on an ELT. Time is given relative to technical first light.

5.3 Cost Model and Budget for Instruments

Following on from the comments in Section 5.1 on the instrument development plan, it is worth considering issues of whether current capacity in the European institutes and universities is adequate to build the instrument suite we aspire to, and whether the current cost model and procurement routes are appropriate.

More detailed estimates of instrument costs, and review of resource availability would be desirable in order to come to firm conclusions, but a first cut is adequate for some generalisations.

Over the last 5 years ESO had typically had four important external (mainly) instrument projects running plus 1-2 internal projects. Total effort used is around 100-130 person years per year. This includes some ramp up in the UK contribution (KMOS, VISTA). With potential for new ESO partners, involvement in the future could go up to say 140 person years/year. This should be adequate for development of four ELT instruments in parallel, although there could be a problem if ELT instruments overlap with VLT second generation instruments. A first estimate of resource requirements and availability will be included in the next version of this document.

As outlined previously, we assume the current Cost Model where ESO pays hardware costs and partners pay staff costs – receiving telescope time in return. There are strengths and weaknesses to this model in terms of cost control and dealing with make/buy decisions. More modular ELT instrument designs may prompt a logic towards more industrial procurement of instruments or subsystems. These issues are now being explored during development of second generation VLT instruments such as KMOS and MUSE. Such industrial procurement routes must be built in to the early design stages and developed in partnership with industry if costs and risks are to be managed. Changes to procurement methods may result in increased pressures on ESO budgets, depending on how industrial procurement is funded.

5.4 Verification and Test

On the VLT about 10% of the available time is invested in commissioning and other technical activities. While allotment of commission time for verification and test on the telescope is sometimes considered to be generous this has not been a problem since the VLTs have the luxury of availability of a large number of focal stations. However, this will not be the case on an ELT, and we will encounter very high daily operating costs and pressure on telescope availability. Hence if we want to keep commissioning times low and still bring 2 - 4 instruments into operation within the first two years we will need to place much more emphasis on Assembly, Integration and Verification (AIV) in Europe. The experience with commissioning runs at the VLT has shown that a substantial amount of time is spent to work on rather simple technical problems. A dedicated test facility could reduce these times drastically and commissioning time would then mostly serve for on-sky characterization of the instrument performance.

We recommend moving more towards space-type verification procedures - with consequent cost implications for ESO and partner organisations.

5.4.1 Recommended Philosophy for AIV

- Subsystem verification in representative environments
- Full end-end test in the laboratory with appropriate and agreed level of risk management
- Agreed process for requirements verification and waiver procedures
- Include flexure testing
- Adaptor rotator simulator
- Include environmental testing
- Simulation of telescope and AO PSF
- May need simulation of atmospheric turbulence for instruments with dedicated AO
- Focal plane simulator providing multiple point sources across the FoV
- Measurement of spectral response
- Measurement of throughput and detector QE
- Stray light and ghosting
- Simulation of the telescope software and network environment
- Verification of simulations and models
- Formal verification through standard systems engineering methodology
- Formal fault logging and rectification procedures

This should all be carried out to agreed standards, but with appropriate variations agreed for each instrument - for instance high-stability instruments may need testing in a simulated vibration environment. Some instruments such as a Sub-mm Imager may need EMC tests.

Simulation can never be fully representative, especially for a complex AO-based and segmented telescope. It will be necessary to make compromises to maintain reasonable costs for setting up facilities, and reasonable AIV timescales and labour costs. Of course, the real proof of performance only comes with actual measurement of know astronomical sources on the telescope

5.4.2 What can only be tested on the telescope?

- Operation with real hardware and control systems
- Real atmospheric variation
- Real astronomical sources
- Real adaptive optics systems
- Operation at altitude
- Operations over specified temperature range

Many aspects of instrument performance and operations can be investigated during AIV by closing the loop between "ground truth" from laboratory tests and the predictions provided by physical instrument models (see appendix 4) in an iterative manner. Commissioning will then serve to address the above points by providing on the telescope and on the sky verification of the performance.

5.4.3 Facilities needed for full end-end AIV in Europe

Depends on how many instruments are to be built in parallel, and on international funding and consortium-building constraints. Several laboratories are set up for flexure testing of instruments, with a range of capacities up to 10 tonnes. New laboratories are in planning stages, including at ESO. If two or more facilities are to be provided in Europe, it is essential that common standards for test facilities and simulation be developed. It would be hard to make much progress on this until a telescope concept is more solid, but it would be sensible to start developing standards and simulators very early in the system design phase, due to long lead times for new building and facility enhancement.

6 BASIC DRIVERS ON ELT DESIGN AND INSTRUMENT INTERFACE

6.1 Introduction

The detailed requirements set by the 12 instruments on the telescope, its operation, the site of the observatory and the associated AO systems are presented in section 4 and summarized in section 4.14. The requirements cover a very wide range of parameters which will be impossible to meet with a single ELT. Priorities between the different instruments have to be set to prepare an optimal instrumentation plan and to define the ELT-instrument interfaces. The ultimate choices have to be driven by scientific priorities and are outside the scope of this report. There is however a number of basic drivers on the ELT design, the instrument interface and the choice of the site which have been already identified from the experience of the instruments at 8-10m telescopes and the studies on OWL and other ELT instruments. These are addressed in the following three sections.

6.2 Optical Design

Two very relevant parameters of the optical design are the speed of the focal beam feeding the instruments and, once the telescope diameter is fixed, the resulting linear scale in the focal plane. The experience of the OWL studies has shown that a fast F/6 beam coupled with zero back focal distance (distance between the instrument/telescope interface and the focal plane) makes cryogenic instruments especially difficult to build. The instrument cryo-window will have to be inside the adaptor structure, preventing any AO sensor arm in the adapter to reach the central part of the field. Additional warm optics would be the consequence. One of the main motivations for a fast focal ratio at an ELT is the need to keep the linear field size (and hence dimension of the opening in the adapter and the cryogenic window of the instrument) relatively small. This problem was very relevant in the case of the 100m OWL telescope, it is somewhat alleviated by the smaller M1 diameter in the ELT now under study. A focal ration in the range F10-F15 appears as a good compromise between the two conflicting requirements. The back focal distance is an other parameter which can have devastating effects on the instrument design. Any instrument at any focus requires a minimum of 500mm for focal plane viewing devices and calibration units. In addition at least for some instruments at the classical Nasmyth and / or at the bended, gravity stable Nasmyth (see the discussion on the telescope platforms in the appendix 3) focus might well require more than 2000mm. This allows to extract beams with mirrors, folding them sideways or backwards without excessive extraction angles and to provide for an easy mechanical implementation.
Beam extraction can be for science targets e.g. in the case of a multi-object instrument using pickoff mirrors, or extraction of guide stars, be they natural or laser for telescope and AO control. While guide star extraction is usually handled at telescope level within the adapter, there may be situations where the science and technical fields are the same and where the implementation of instrument and adapter has to be seen globally.

The numbers of mirrors in the telescope optical train is important both for the effect on the thermal emission and for the overall efficiency of the optical train. A small number of mirrors are in principle an advantage but the complete thermal budget of the telescope plus instrument optics has to be considered. An efficient coating for the telescope mirrors is a strong requirement, as it is the possibility of in-situ washing of the mirrors which are most exposed to contamination. The design should allow for easy cleaning and coating of the smaller mirror surfaces in the optical train. This way mirrors M3 to M5 could be kept close to optimum conditions limiting the impact of their surfaces on e.g. emissivity. The temperature of the site is the other parameter to consider in the thermal budget.

The science field size will be eventually defined by the scientific drivers of the project, but will always be a trade-off with cost and practical implementation. There are many considerations (projected performance of the AO in the next decades, cost of the IR arrays with respect to the cost of the entire project) which suggest that imagers and spectrographs optimised for work at the diffraction limit will never be able to cover fields larger than 2'.

Larger fields (up to 5') will be most likely required from instruments working with a pixel sampling of 30-50 mas using AO systems like MCAO or MOAO. Even larger fields would be required by an instrument working down to V wavelengths and optimized for best/enhanced-seeing. The high priority of such an instrument has however not yet been specifically justified in the OPTICON science case for a European ELT and supported by a feasibility study.

It is important to note that the requirements from the adapter-rotator must also be considered in parallel to those of the instruments. In the adapter/rotator, sensors for active and AO optics, including those dedicated to the laser guide stars, do coexist and have to operate at a high degree of stability and reliability. The likely difference in focus of the laser guide stars has a major impact on the telescope-adaptor-instrument interface.

6.3 Choice of Focal Stations and Availability of Instruments on line

The VLT has four telescopes with a total of 12 foci (+ two for the coherent and incoherent combination of the beams) for on-line instruments. Eleven of them plus the combined interferometric focus will be fully occupied once all of the 1st generation VLT instruments are delivered. The ELT is likely to be a single telescope. The scientific pressure from the diversity of scientific programmes calls for the installation of the highest number of instruments on line or easily interchangeable. This is required also by the need to exploit the observing conditions with the optimal instrument. Now some of this variety may be accommodated in multi-mode single instruments, but not very much. For example, most VLT instruments already have multiple modes. Furthermore, multi-mode instruments usually require compromises (optical coatings, field sizes) which often result in a less than optimised instrument. A solution in this direction was provided by the OWL design which included 6 focal stations which were quickly addressed by a rotation of M6. The gravity-variant OWL instrument rooms do however represent an additional complexity for instrument integration and maintenance. Nasmyth foci with large platforms are an attractive alternative for large instruments attached to the adaptor-rotator or mounted directly on the platform, as the VLT experience has demonstrated. If sufficiently spacious, the Nasmyth platforms could host permanently at least two instruments. These could be selected by various schemes: a two-axis steerable tertiary mirror as proposed by TMT; a steerable mirror on the platform; or a rail track to position instruments into the beam. The exchange between the instruments should be made possible with small overheads and considered from an early design phase from the point of view of efficiency and safety.

From the point of view of the flexure under changing gravity conditions, a Nasmyth station is in principle less favourable than a Cassegrain one. Two solutions to avoid the rotation for large instruments at Nasmyth are possible: a derotator which feeds an instrument fixed to the platform or an additional 45 degree mirror feeding a focus with a gravity–invariant field rotation (see Appendix 3: A true gravity-stable instrument station). Each Nasmyth focus could then host three instruments: two on the standard platform and one at a lower level fed by the additional mirror. Alternatively, one could think of exchangeable instruments at the gravity invariant vertical port.

A Coudé type focus/location is also highly desirable for some applications. High Resolution Spectroscopy (possibly with ultra high time resolution photometry) is the only mode which is scientifically very attractive in the blue-visible wavelength range where the AO are not expected to produce any major image size improvement. A High resolution Spectrograph can exploit the huge photon collecting power of an ELT to obtain ultra-accurate spectroscopic measurements. The instrument study for a High Resolution Visual Spectrograph (see section 4.2) has shown that this is possible but requires a very large volume for the instrument and an ultra-stable environment from a thermal and mechanical point of view. This calls for an isolated laboratory outside the telescope structure fed by a combination of fibres and mirrors.

Consideration of the overall scientific productivity of the ELT (and its running costs) makes it worthwhile to debate novel operational approaches such as shared focal planes, and hitchhiker modes, although this generally works best in a facility such as a space telescope where the telescope and focal plane instruments have to be system engineered from day one as an integrated suite. We expect a phased instrument suite, and to be able to take advantage of novel ideas and technologies over upgrade paths, which would make a predetermined integrated instrument suite problematic.

6.4 Considerations on the Observatory Site

On the requirements from the instruments on the site, all instruments would obviously benefit from the highest number of clear nights and an excellent median seeing. There will be a mixture of imagers (which might call for photometric conditions) and spectrographs, which could tolerate variable conditions.

Of greatest importance will be the properties of the atmosphere of a given site related to the turbulence to be corrected with the AO systems. Different instruments rely on the correction of different layers over different fields. It will be crucial to combine the result of the site testing with AO correction simulations to arrive to a proper prediction of the instrument performance (and hence to assign priorities among the instruments).

With the majority of the instruments working at red and infrared wavelengths it is important to understand very well the OH emission characteristics of the site.

Finally, both the thermal IR and sub-millimeter instruments call for a site with a very low content of precipitable H_2O. Average temperature of the site is also a very relevant parameter in the overall thermal budget trade-off.

6.5 Overview

The following table summarizes for quick reference the basic conclusions of the previous sections from the first analysis of the possible instrumentation suite for the European ELT.

Table 27: OVERVIEW OF BASIC DRIVERS ON TELESCOPE, AO AND SITE

ITEM	REQUIREMENT	RATIONALE
Telescope Final Focal Ratio	F/10-F/15	All instruments would live with a FR in this range
Back Focal Distance	Up to 2000 mm	The large BFD is required from instruments which have dedicated AO but may also be dictated by laser delta focus. Other instruments would live well with 500mm. This is a parameter which requires system approach
Scientific Field (diameter)	2' (diffraction limit) 5' (pixel size 30-50mas)	From science and feasibility requirements (assumes no wide field , seeing limited instrument)
Focal Station	Place for at least 7 instrument "on line"	To have this minimum number of instruments on line (or to be automatically moved on line) is highly desirable from a scientific and operational point of view. See text for additional requirements and possible solutions
Gravity stable platforms	Minimum requirement of stable off-telescope laboratory. Large stable platforms very desirable	May be necessary to have gravity stable platforms to maintain reasonable instrument cost and complexity, but this is a system trade-off.
Thermal Infrared Observations	Reasonable compromise between the different parameters affecting thermal emission	Ideally instruments operating above 2 micrometer would like a 2 mirror telescope with the largest possible aperture in a cold site with low precipitable H_2O and at high altitude/low temperature. A reasonable compromise with other constraints which still offers unique performance has to be verified through simulations.
Telescope +AO System	At least 1 AO mirror in telescope	There is a general consensus that it would be advantageous to have at least one AO mirror in the telescope (conjugated to the ground layer?)
Sequence of implementation of AO systems	SCAO from the start, followed shortly thereafter by LTAO	Role of AO in securing the best seeing (0.1" at K ?) imaging quality from telescope and wind compensation has to be clarified. Availability of SCAO on bright sources from the very beginning of operation and multiple laser LTAO shortly thereafter.

7 CONNECTION WITH THE FP6 INSTRUMENT DESIGN STUDIES

The Framework 6 ELT Design Study work on ELT Instruments is being coordinated to fit in with the schedule for development of a reference design for a European ELT. The Small Studies will be completed by the end of June 2006, and the Point Designs will start in November, operating in parallel with Telescope and AO systems design. The aim is to iterate to a workable integrated instrument-AO-Telescope system during this period, by optimising cost-performance trade-offs.

It is important that we choose the most critical instruments as Point Designs, so that we really ensure that the telescope and AO designs are compatible with the science goals, and that cost and risk is shared between the systems in an optimal way.

The outputs of the Small Studies and debate in the ELT Working Groups will be used to guide Point Design selection in the period from June to November.

8 RECOMMENDED NEXT STEPS

We have developed a 'toolkit' of instrument options and system drivers. The next stage as we iterate to a workable and affordable ELT as a complete system will be critical. This is where the hard trade-offs must be made to ensure the inevitable compromises needed to reach stretching scientific goals at affordable cost and at reasonable risk. These risk/cost balances must be made in a systems manner, bearing in mind that it is the instruments which ultimately carry out scientific observations, and that the lifetime cost of ELT instrument program will approach that of the telescope. It is clearly important that design decisions made now are compatible with the programme of instruments we can expect to be developed during the ELT's lifetime. Of course, it is not possible to accurately predict where developments in astronomy and astrophysics will lead the development of a facility which could have a fifty year lifetime, nor the technology which may be available in the middle of the 21st century, but we owe it to future generations of astronomers to do the best job we can at 'future proofing' the European ELT.

Next steps:

- Further develop the science case for the range of telescope aperture from 30-60m, and develop a compliance matrix with the instrument and AO teams
- Trade-off study of the optical layout, including emissivity, polarisation, throughput and future AO development paths
- Trade-off study for instrument platforms with regard to flexure, image rotation, pupil rotation, adaptive optics, laser guide stars and maintenance
- Develop cost drivers for the instrument suite traded against other systems costs
- Ensure appropriate end-to-end test facilities are available in Europe
- Push towards a global development programme for critical instrument technologies

We expect these issues to be progressed by a combination of the FP6 small studies, reporting in the summer, leading to more detailed Instrument Point Design studies, which will be progressed in parallel and close interaction with development of the Telescope and AO systems reference design. We hope that the current Instrumentation Working Group can continue to contribute to the debate which must be held to resolve these issues and move to a European ELT project which can meet ambitious science goals in a timely manner.

Acknowledgement: We would like to thank the following individuals for their contributions to this report: Torben Andersen, David Crampton, Dainis Dravins, Chris Evans, Jim Hough, Pat McCarthy, Michael Redfern, Hans Martin Schmid.

9 REFERENCE DOCUMENTS

RD	Document Title	Authors	Issue	Date
[RD 01]	The science case for the European Extremely Large Telescope, 2005	OPTICON et al.	1	2005
[RD 02]	Euro 50 Design Study of a 50m Adaptive Optics Telescope	Andersen, T., Ardeberg A., Owner-Petersen, M.	1	2003
[RD 03]	OWL Instrument Concept Studies (CD-ROM)	ESO et al	1	2005
[RD 04]	OWL Concept Design Report: Phase A Design Review (Blue Book)	ESO	2	2006
[RD 05]	ESA-ESO Working Groups Report No. 1 Extra-Solar Planets	Perryman et al.	1	2005

10 ACRONYMS AND ABBREVIATIONS

Table of acronyms and abbreviations used in this document:

ADC	Atmospheric Dispersion Corrector
AGB	Asymptotic Giant Branch
AGN	Active Galactic Nucleus
AIV	Assembly Integration and Verification
ALMA	Atacama Large Millimeter Array
AO	Adaptive Optics
APD	Avalanche Photodiodes
CCD	Charge Coupled Device
CMOS	Complementary Metal Oxide Semiconductors
CPU	Central Processing Unit
DIT	Detector Integration Time
DM	Deformable Mirror
DSM	Deformable Secondary Mirror
EE	Encircled/Ensquared Energy
ELT	Extremely Large Telescope
FLAMES	Fibre Large Array Multi Element Spectrograph
FP	Framework Plan
FPGA	Field Programmable Gate Array
FoV	Field of View
GC	Galactic Center
GLAO	Ground Layer Adaptive Opics
GMT	Giant Magellan Telescope
GRB	Gamma Ray Burst
HOT	High Order Testbench
IFS	Integral Field Spectrograph
IFU	Integral Field Unit
IMF	Initial Mass Function
ISM	Interstellar Medium
JRA	Joint Research Activity
JWST	James Webb Space Telescope
KID	Kinetic Inductance Detector
LBV	Luminous Blue Variable
LGS	Laser Guide Star
LN2	Liquid Nitrogen
LTAO	Laser Tomography Adaptive Optics
MCAO	Multi-conjugate Adaptive Optics
MEMS	Micro-Electro-Mechanical Systems
MIR	Mid-Infrared
MOAO	Multi-Object Adaptive Optics
MOS	Multi-Object Spectroscopy
NGS	Natural Guide Star
NIR	Near Infrared

OWL	Overwhelmingly Large Telescope
PAE	Provisional Acceptance Europe
PSF	Point Spread Function
PWV	Precipitable Water Vapour
QE	Quantum Efficiency
R&D	Research and Development
RTC	Real Time Computer
SCAO	Single Conjugate Adaptive Optics
SKA	Square Kilometer Array
SNR	Signal to Noise Ratio
SPAD	Single Photon Avalanche Diode
SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research
tbd	To be determined
TLR	Top Level Requirement
TMT	Thirty Meter Telescope
UV	Ultraviolet
VLT	Very Large Telescope
VPH	Volume Phase Holographic
WFS	Wavefront Sensor
XAO	Extreme Adaptive Optics
ZDA	Zenith Distance Angle

Appendix 1: Instrumentation Considerations from the Euro 50 Study

Euro50 is a telescope concept for an adaptive optics based 50 metre Gregorian telescope. It is the conclusion of a ten years of evolution of a concept for an Extremely Large Telescope which originated from the Lund University Group led by Arne Ardeberg and Torben Andersen, who moved from initial ideas, back when the very idea of a 25-60 m telescope was regarded as rather outlandish, to a detailed and analyzed concept. This was presented for review in 2003, and is well summarized in Ref Doc 2. Instrumentation was not given a detailed treatment, but some useful general points were made and are summarized in this section.

Science Instrumentation for Euro50

A large background of expertise has been acquired building scientific instruments for the 8 to 10 m class telescopes. Instruments for these telescopes are difficult and expensive. One lesson learned from the previous generation is that the science instruments must be thought of and designed at the same time as the telescope and AO system. Moreover, they need to be part of an integral system consisting of the telescope, the AO system and the instruments.
Indeed the science instruments must be driven by the scientific programs that the community wants to address. Besides, an important consideration is that both diffraction limited and seeing limited instruments will be necessary. This comes from the fact that some science programs require large fields for seeing limited observations. For instance, cosmology programs require observations of several thousand galaxies, something that cannot possibly be done without a relatively large field of view. These programs require spectroscopy of faint galaxies at redshifts approaching the epoch of galaxy formation. At about 100 high z galaxies per square arcminute, instruments with 20 arcminute field of view could obtain several thousand spectra per frame. They do not require AO correction, thus can use those nights when the seeing precludes achieving good Strehl ratios.
The other group of instruments are those benefiting from the AO diffraction limited image both in the near and mid infrared. These instruments are no more difficult to build than similar instruments for 4 and 8 m telescopes with AO corrected beams.
The characteristics of the different seeing limited and adaptive foci of the Euro50 are shown in Table 3 on page 98 in [RD02] which is reproduced below. The diffraction limits for different wavelengths for the Euro50 are shown in 2.

Mode	Field	Achievable Field for Strehl ≥ 0.4	Scale arcsec/20 microns	No. of optical elements	Focus	Figure of Merit [1]
Seeing limited	8'		0.083	5	Primary	43m
Seeing limited	2'		0.016	5	Nasmyth	43m
Seeing limited (baseline)	*2'*		*0.006*	*2*	*Gregorian*	*50m*
SCAO, K-band	3'	30"	0.006	2	Gregorian	50m
MCOA, K-band	2'	1'	0.006	6	Gregorian	41m
MCOA, K-band	2'	1'	0.006	9	Nasmyth	35m
Improved Seeing	2'		0.006	5	Nasmyth	43m

[1] *(compared with 2 mirror telescope of same light collecting power)*

Table 2. Diffraction limit for the Euro50 at different wavelengths.

Wavelength	Diffration limit (1.22 λ/D)	Pixel size (λ/2D)
1 μm	0.005”	0.002”
2.2 μm	0.011”	0.0045”
3.5 μm	0.018”	0.0072”
10 μm	0.05”	0.02”
20 μm	0.10”	0.04”

If the instruments are to work in the diffraction limited regime, then the size of the instruments is independent of the size of the telescope, and the same instruments can be built for a 50 m as for a 10 m telescope with the same exit focal ratio. The 50 m telescope will provide increased spatial resolution but a smaller FOV. When seeing limited, however, for a fixed angle on the sky the distance in mm in the focal plane is proportional to the focal length of the telescope (i.e. the diameter multiplied by the f ratio), and thus the instruments get larger with the telescope diameter.

The large format arrays, whether near IR or visible, all have pixels sizes between 15 and 20 microns. On large telescopes, for seeing limited instruments, the focal ratio has to be significantly reduced so that the pixel size on the detector is well matched to the seeing. A reasonable and conservative rule is that there should be 3 pixels across the FWHM so for seeing of 0.6” this corresponds to a pixel size of 0.2”. On a 10 m telescope with a 15 μm pixel this needs a camera of about f/1.5, which is difficult but can be built. A 50 m telescope however would require a camera at about f/0.3 which cannot be built. The result is that a lot of pixels need to be used across a seeing profile, typically 5 times more than for a 10 m, significantly decreasing the FOV or requiring more detectors and larger optics.

A further consequence of the poor plate scale is that for seeing limited spectroscopy, the physical size of the slit becomes larger, this means that the size of the pupil, and hence dispersing elements, also become larger if the resolution is to be maintained. To a first approximation, the diameter of the pupil must increase proportionally to the diameter of the telescope. The volume, hence weight and cost, of the instrument will increase as D^3 and so the instruments for a 50 m will be over 100 times larger in volume than the equivalent instrument on a 10 m and they are already large.

The following summarizes the main characteristics for instruments between 0.35 and 28 μm for a 50 m telescope, including a discussion of the difficulties inherent to these instruments. The Euro50 is currently specified for use up to 20 μm wavelengths but the possibility of expanding the wavelength range to 28 or 30 μm is being studied.

Near-Infrared Instruments for the Adaptive Optics Regime

One of the main benefits from a 50 m telescope is the diffraction-limited imaging and spectroscopy. These instruments could be very similar to those on 4 m class telescopes and, as the corrected field of view will be relatively small, the instruments will not be that large.

Imaging

Currently the largest 1-2.5μm detectors are at 2k, although a 4k version seems to be within reach, so for the following discussion, it is assumed that a 4k detector will be available. In imaging mode, a 4k detector will give a correctly sampled FOV of 5” at 1 μm or about double that at 2 μm. The FOV is small enough that if only one detector is used, SCAO will suffice. For DCAO, the simplest solution would be to mount multiple copies of the same instruments (or use a number of detectors in the same instrument but then the camera optics becomes large).

Spectroscopy

Using a 4k detector at 4 pixels per resolution element gives 1000 resolution elements so that the entire K window can be covered at a resolution of 4500. This order of resolution with diffraction limited sampling will be easily available, even with GRISMs as in EMIR for the GTC.
An Integral Field Unit (IFU) would be an extremely powerful tool on a 50 m telescope. If an element size of 0.01" is chosen the FOV would be 0.6" x 0.6" assuming 1 element per column, although it must be noted that the optics will be a significant challenge.
There is interest in a multi-slit near IR spectrometer covering a sizeable part of the FOV available with multiconjugate AO. Problems with accurately centering the sources call for a slit size that is at least two or three times the diffraction limit, which facilitates the optical design of a possible instrument. For example, if the diffraction limit is 0.01", with three pixels across a slit size of 0.03", the FOV would be some 20" x 40" on a 4K detector and a resolution of 4000 should be achievable. This would be a very powerful instrument because with a resolution of 4000, the OH telluric lines would be resolved, thus increasing the sensitivity by about one magnitude over what would be attainable with low resolution spectroscopy. The cold multi-slit problem will be solved by that point. For instance EMIR on the GTC is producing a multi-slit cryogenic robot of a size comparable to what would be required for the near diffraction MCAO field at the Euro50.
As well as the traditional camera/spectrometer there may be interest in a high resolution (say R=100 000) cross-dispersed echelle spectrograph. Working near the diffraction limit, such an instrument would not need to be that large and would be very powerful given the large collecting area of the Euro50.

Near Infrared Instruments for the Seeing Limited Regime

Assuming a 4k detector with 18 μm pixels, a camera giving f/2 onto the detector will have a 2.5' fov, which is competitive with existing systems on 10 m telescopes. Such a system would probably need to be built solely as an imager, because an imager/spectrometer suitable for the K band would need a cryostat window over 1 m in diameter. However, an imager does not necessarily need the collimator to be cold, and so the window could be near the pupil, hence a lot smaller, say 10 to 15 cm. J-H spectroscopy could still be included however, although with maximum resolutions of about 500 to 1000 in a 0.6" slit.

Thermal Infrared Instruments

Thermal IR instruments (at 3 to 28 μm) will achieve diffraction-limited performance with a relatively simple AO system because far fewer actuators are needed than for the near IR. This can be done with the adaptive secondary so the emissivity of the whole system could be kept very low.
The main competitor for a 50 m telescope in this wavelength range would be the JWST, which currently is 6 m but will have extremely low backgrounds. The JWST will win hands down in area coverage whilst the 50 m would offer a far higher spatial resolution, potentially a factor 8 increase. In terms of sensitivity, the JWST will be more sensitive than a 50 m in imaging and low resolution spectroscopy (although a great deal depends on obtaining detectors with very low read out noise and dark currents, far better than currently exist). However, at resolutions between 1000 and 10000 the 50 m will match the JWST simply because the JWST runs out of photons.
The largest 2 to 5 μm detectors are 1k although 2k will probably appear within a reasonable future. A 2k detector would give a diffraction limited FOV at 3.5 μm of about 14". The same range of instruments as for the near IR could be built. In particular a 1-5 μm high spectral resolution instrument could be very interesting.
At 10 μm for ground based use, the largest detectors are 240x320 pixels giving a FOV of 6" x 5". A CanariCam style instrument including coronagraphy would be a simple starting point for 10 μm observations. Larger detectors are likely to be available but possibly only for lower backgrounds. In this case a mid IR medium to high-resolution spectrometer would be an obvious choice.

Seeing Limited Instruments for the Visible Range

It is inconceivable that a large telescope, such as the Euro50, will not have a full complement of visible instruments. For observations in the Gregorian focus and in the seeing limited Nasmyth focus, there are problems with the image scale (see Table 3 on page 98). A 15 µm pixel at the seeing limited Nasmyth focus will cover only 0.013” on the sky and in this case a 2k by 4k detector covers 25” by 50”. A further problem is that a large pupil is required to obtain any reasonable spectral resolution. However, there are scientific opportunities for seeing limited observations with the Euro50, and there is also the possibility of using those nights less favorable for high Strehl AO observations.

A simple Focal Reducer Instrument

There is a case for building a simple focal reducer although this is somewhat the brute force approach. The 2k by 4k detectors can form a mosaic of say 8 detectors giving a detector 8k by 8k pixels which in a seeing limited Nasmyth focus would cover 1.6’ by 1.6’. GRISMS could not be used in such an instrument, because they would be too large. However, large VPH (Volume Phase Holographic) gratings will certainly be feasible and they are very efficient. A 30 cm VPH grating would give resolutions of 2000+ and make an extremely powerful instrument. The optics, however, will be large and complicated, a 1.5 m collimating mirror will be required; however that is possible.
An interesting alternative would be to split the pupil into 4 or 6 sections each of which is fed into a separate instrument. It would be like observing with, say, 6 x 20 m telescopes working in parallel and all looking at the same field. Use of a smaller pupil allows increasing the pixel size by a factor 2 to 3, which means that the size of the grating for the same resolution can be reduced. Furthermore the size of the camera optics will be significantly reduced. If all of the instruments are configured in the same manner, the final sensitivity will be comparable with the single instrument. However there would be the option to configure each instrument separately.

Higher resolution spectroscopy

Higher resolution spectroscopy in the seeing limited Nasmyth focus would only be realistic behind an integral field unit. The simplest form would be a fibre IFU. A point source would illuminate a number of fibres, which are arranged along the slit. The energy from a point source is distributed among (possibly) hundreds of fibres, which are then arranged to form a line. See . As the slit width in mm is now far smaller, higher spectral resolutions can be obtained without the need for huge pupils and gratings. The aim would be to arrange the fibres such that the light from a point source covers consecutive rows on the detector. When reading out, these rows can be binned, significantly decreasing the total readout noise, readout time and amount of data to be saved.
Clearly one spectrometer can only take feeds from a few thousand fibres at most and so in order to apply the large number of fibres needed to cover a reasonable area in the focal plane, multiple spectrometers would be required. These spectrometers could all be the same but alternatively some could be optimized for lower resolutions and others for higher resolutions.

There would be a number of possible configurations for the fibres

- A pseudo long slit, where the fibres form a slit which is say 1” by 20 to 30”.
- Multiple IFUs. Each IFU is 1.5” x 1.5” and can be placed anywhere within the focal plane.
- A single IFU e.g. 7” x 4”

Obviously the area covered depends upon the number of fibres.

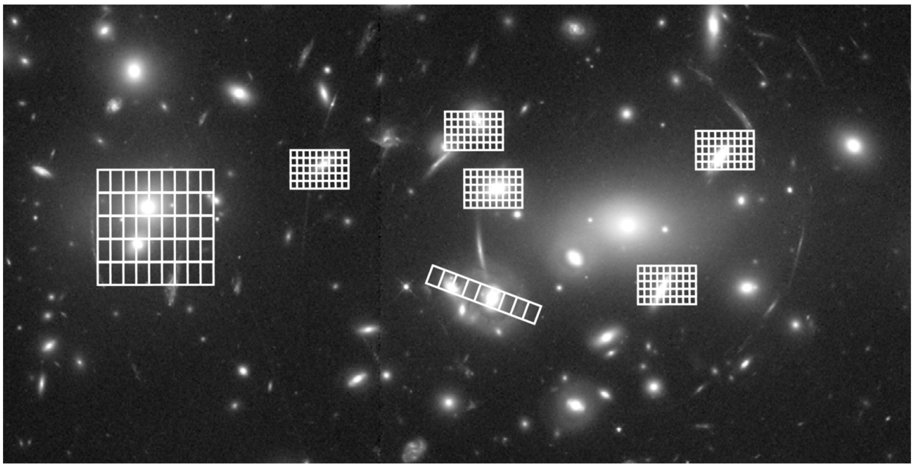

Figure A1-1. Different configurations for the IFU image slicer. There could be a pseudo long slit where the fibres are set in line, a set of mini IFUs where the different IFUs could be positioned throughout the entire field of view, and a large fibre bundle for high spatial resolution studies of sources. The different IFUs could feed different spectrometers. These could be identical spectrometers thus saving cost because of the economy of scale. A robot would be needed for placing the IFUs on the desired target across the whole field of view provided by the telescope. Underlying image: Hubble Space Telescope.

Prime Focus Observations

Observing in the prime focus seems highly attractive and should be possible in spite of the technological difficulties of placing instruments high above ground. Due to the plate scale, a FOV of about 8’ may be possible. If this can be combined with a fibre fed multi IFU system, this would provide a very powerful survey tool. It is probable that some stabilization system would be needed to overcome windshake, but this seems feasible to build.

It may also be possible to build a prime focus imager. For the corrected prime focus, a 15 μm pixel will cover 0.062” giving a field of 4x4’ with a 4k detector.

Acquisition and Guider Unit

Acquisition and guider units (AGU) would be necessary for each of the telescope foci which have instruments. It could however be possible to use the same AGU design for both of the DCAO foci (Gregorian and Nasmyth).

The acquisition and guider units should be able to patrol technical fields of view for guiding (always behind the atmospheric dispersion corrector). Acquisition could be facilitated by allowing access to the center of the fields of view, but acquisition followed by accurate telescope offsetting would allow for simpler units. They could be based on a simple arm with a pick-off mirror mounted on a rotator near the focal plane. The pick-off mirror could be moved radially, and so guide stars could be found anywhere within an annulus. The camera optics will have to be on a translation stage to compensate for the movement of the pick-off mirror and also to correct for field curvature.

Risks

Building science instruments for the Euro50 will be challenging, however possible. There are a number of risks that should be taken into consideration at an early stage. These are technological and managerial.

Technological Risks

Large numbers of focal plane detector arrays will be required to map only a few square arcminutes. If seeing limited visible instruments are to be built, they require many low read noise detector arrays. Handling the data and providing the necessary pipeline data reduction algorithms will require a well-planned strategy.
Large optics will be required. Even if strategies for reducing the size of the instruments are implemented (some of which have been described above), some large pieces of optics are still needed.
Advanced fibre technology is required. In particular the alignment of microlenses and fibres both at the entrance and exit ends of the fibres seems critical. Also, design and construction of a fibre positioner will be challenging, especially when located high up in the prime focus area. Also a fast correction mechanism for compensating windshake may be required.
Large size Grisms as well as VPH devices are needed. The latter can probably be produced with excellent efficiency so they will be the preferred option.
Cryogenically cooled thermal IR instruments. Even if these instruments are not extremely large, because they are diffraction limited by default, the diffraction limit at 20 µm is twice what it is at 10 µm. Besides, the detector arrays to be used at 20 µm require cooling at liquid He temperatures. This can be done with existing cryo-coolers, however for the optics and gratings bringing them down to about 10-20 K will probably require large quantities of liquid He.

Managerial Risks

Instruments for the Euro50 telescope will be very expensive; €20M to €30M will be a starting point for many of them. It is important that these costs are contemplated early in the planning stage.
There are not many institutes that can handle such large projects and it may be advisable to set up specific project offices for some of them. Indeed they will probably require managerial structures comparable to those of current 10 m telescope project offices.

Appendix 2: Explanation of the Table of Requirements

TABLE OF REQUIREMENTS ON TELESCOPE, AO & SITE

No.	Parameter	Explanatory Note
	OPTO-MECHANICAL TEL. PROPERTIES	These parameters address specific properties of the telescope or are instrument properties which have an effect on the telescope design
1	Wavelength range of instrument	In this first step, the widest desirable range has to be chosen
2	Telescope final focal ratio	Wide range F6-F15. No sense obviously in giving a precise value but indicate preference trend
3	Scientific Field Size (Diameter)	Specify if need to use part of the field for wav sensing. Whether you will use all field or access to selected targets within the field.
4	Field flatness	Is a potential advantage for the instrument or is it neutral?
5	Linear field size	Is there a max value set e.g. by the max dimension of the cryo window?
6	Image quality	To be specified whether diffraction limit has to be reached and at which wavelengths. Preferred metric: Strehl ratio, FWHM, EE .Requirements on PSF uniformity over the field
7	Adaptive Optics System	Related-overlapping with # 6. Refer possibly to type of AO system. Requirement on field for the wavefront sensors, sky coverage. Need for laser guide-stars. Can make useful work without AO?
8	Stability of the focal plane scale	Having in mind small field astrometry
9	Background emission from telescope	Depending of the wavelength range, regime of operation
10	Straylight from telescope	Is it going to be a possible problem for the instrument? E.g. it should not be so important for a single target high resolution spectrograph, but it is potentially important for instrument for planet detection or to do photometry over large field
11	Differential Refraction	To be specified if relevant for the instrument
12	ADC	Importance for the instrument and whether it is preferred to have it provided by the telescope optics or it could be _easily_ accommodated in the instrument.
13	Zenith Distance Angle Range of operation	Take 0-60 as offered unless special problems
14	Type of telescope focal station	Tell your needs in terms of stability, access, etc and if you want relate it to the classical Cassegrain, Nasmyth, coude stations. Justify preference. Address the possibility of sharing the focal plane (or the focal station) with other instruments
15	Back focal distance	Although not strictly a requirement from instrument, keep in mind associated AO
16	Instrument attachment	Specify whether to be attached to an adapter/rotator, or fixed on platform. Mention need of field rotation
17	Max Mass of Instrument (not rotating and/or rotating)	OWL had max 17 tons with 12 tons preferred on the platform-
18	Max Volume occupied by the instrument	OWL had 5mx5mx12m (and shape with respect to optical axis)
19	Telescope pointing	Accuracy in blind pointing, speed to reach position
20	Telescope Chopping	Frequency, stroke, AO in both beams?
21	Maximum brightness level of stars to study	This can have an impact on some of the telescope subsystems
22	Calibration Requirements	in the presence of AO, provided by instrument or facility

	IMPACT ON OPERATION, SITE	These are requirements from the instrument (and indirectly its presumed scientific targets) which have an impact on the operation mode of the observatory or the site choice
23	Operation mode	Visitor, service, long or short term experiment
24	Typical Integration Time	If applicable to the instrument
25	Special supply	eg. Liquid N2, He
26	Various atmospheric properties of the site	Median seeing, Water content
27	Latitude of the site	
28	Altitude of the site	
29	Percentage Photometric nights	
30	Percentage Clear nights	

Appendix 3: Instrument Platforms

A True Gravity-Stable Instrument Station

Conventional Nasmyth platforms are capable of holding heavy instruments but are NOT gravity-stable. In terms of dynamic flexure it is debatable whether they are better than Cassegrain. It is true that Nasmyth has the advantage of confining the gravity vector to act in a single plane orthogonal to the optical axis, so that stiffness is not required in the direction of the optical axis, while Cassegrain focus has a generally varying vector and needs stiffness in all directions. However, the rate of change of instrument angle with respect to the gravity vector is very severe at Nasmyth, especially when observing objects near zenith. A 180 degree instrument rotation causes a 2g change in the gravity vector, while at Cassegrain a similar rotation causes a change that is only fraction of this for objects near zenith.

Dynamic flexure is a constant concern and becoming a greater problem in most instruments as they get larger. It consumes a significant fraction of the overall design and test effort, requiring careful FEA, and generally adds significant mass to instruments in the form of trusses, thicker plates etc., and increases overall instrument cost and complexity substantially if active compensation is required as in for example Keck-DEIMOS or GEMINI-HROS On the VLT in the case of Hawk-I, redesigns were necessary to cope with flexure in the large mirrors, and flexure was a topic of considerable discussion with manufacturers. X-shooter has challenging flexure problems in keeping all three of its slits aligned. The flexure problems would be insurmountable in CRIRES if it did not use a field derotator. Flexure also means that elegant optical design solutions can sometimes not be employed – eg. the ONIRICA split optics design would probably suffer badly from flexure problems at Nasmyth.

On an ELT, flexure problems will be more difficult. Firstly, unless operation is at the diffraction limit with restricted fields of view, instruments will be much larger than VLT instruments. To first order, if a mechanical design is scaled up homologously, angular flexure increases linearly with size, while linear flexure (eg. decentre of a lens, or lateral movement of the focal plane) increases as size^2. So spectrometers requiring precise radial velocity stability, or imagers capable of high resolution imaging during long exposures for example, will become much more difficult. The problem is made worse by the fact that it is unlikely that we will be able to scale up directly from VLT-size instruments, since that means the mass would scale as L^3, resulting in very massive instrument. In practice weight savings will probably be needed – and this in turn will make flexure even harder to control.

These scaling laws for instrument flexure have been appreciated previously (Russell et al. Proc. SPIE 5492, Glasgow 2004) and have led to suggestions for a true gravity-stable “vertical Nasmyth” in designs for the Canadian VLOT, and the GSMT. (These have since merged into the TMT for which the design of instrument stations has not been specified.) By adding a stationary diagonal flat mirror at Nasmyth the optical axis becomes vertical and parallel to the gravity vector. Then instrument rotation does not alter gravity vector in the instrument. The instrument rotator/adapter would be essentially conventional, and possibly somewhat simpler since it would have to deal with an axial load only. At least one ELT optical design developed at ESO by B. Delabre shows this is perfectly feasible in 40-50m telescopes, with the elliptical flat measuring ~3m in the major axis, though this depends largely on field of view. A 3.4m back focal distance is also realised. The instrument could either hang off the adapter/rotator (allowing conventional WFS pickoffs) or sit on top of it. Another way of achieving gravity invariance is to use a derotator, and such a solution could be investigated for ELTs - however this does not appear so attractive at first sight since it requires three large moving mirrors.

A drawback of a vertical Nasmyth is that an extra mirror is needed in the optical train, adding to system emissivity. However, this loss of performance is relatively negligible, for the following reasons. Firstly, it is likely that an ELT will have >2 mirrors. Designs incorporating a single deformable mirror are likely to have ~5 mirrors + an entrance window in total, excluding the Nasmyth flat. All things being equal, an extra flat would therefore increase emissivity by a factor 1.17. Eg 10% emissivity would become 11.7%. This would be a very small effect in K band and negligible compared to the effects of average site temperature for example, or OH variability. On average it would be even less than this, since it is the average emissivity between mirror recoatings which determines average performance. A Nasmyth flat would be downward facing and could be well sealed; the primary would likely dominate the system emissivity. Furthermore, it is the best accessible mirror and could be replaced more frequently with a freshly coated spare if required. So the net degradation would be considerable less than 1.17.

A true gravity-stable instrument station would be a great bonus to instrument builders. Not only would costs and design times be reduced, and performance improved, but there would be the real possibility of simple “breadboard” designs based on cold optical tables and simple modular mounting assemblies, which would only need to be aligned once.

Appendix 4: Calibration of ELT Instruments

Summary:
Instruments for the ELT will be physically larger and heavier - in some cases by almost an order of magnitude - than instruments for the VLT. The scientific goals for ELT require that its instruments achieve levels of performance (contrast, stray light suppression, spatial and spectral resolution, stability) substantially beyond what is achievable today. As a result of these requirements the instruments will be very complex and technically demanding. In order to achieve the science goals it will be absolutely essential that excellent calibration is achieved for all scientific observations during standard operations. This will only be possible by having full understanding and full control over the physical configuration of the instrument. Furthermore the complex AO systems required for an ELT and its instruments will essentially be aiming to also calibrate the atmosphere by active sounding of its properties. The mode of operation for ELT observations has not been fully developed. It may differ substantially from current operations that are characterized by a roughly equal split between visitor and service mode. Some science goals of an ELT may be best served by allocating the telescopes for extended periods to a few projects, possibly only a single one. Such a methodology might be similar to the approach used for big experiments in laboratory and particle physics. Regardless of the exact operational approach adopted it is safe to assume that all scientific goals will be best served by making calibration an integral part of the instrument design and operations, already in the planning phase.

Baseline assumption:
The instrument should not be considered primarily an observational tool but a physical experiment for which we need to strive to eliminate or at least properly describe and understand all sources of relevant systematic and random errors.

Use of instrument physical modeling techniques:
The high complexity of ELT instrumentation and the need to fully control and describe the instruments physical properties over extended periods of time make it appear unlikely that the required performance can be achieved by applying standard empirical calibration methodology. Instead the approach of choice is to use instrument physical modeling techniques. In this the engineering information used to build the instrument is being used to describe its actual physical configuration and from that to assess its actual performance. ESO's Instrumentation division (INS) has recently enhanced its capability to develop models for its instruments. Note that ideally the physical instrument model should begin with the design phase. It will then accompany the development of the instrument through its phases of testing, verification and operations. An extensive interaction between the modeling and the laboratory verification is essential in order to achieve the full capabilities of the approach and to ensure that that excellent calibration can be achieved early on. It will be a key ingredient to maximize the performance of instruments and to minimize the effort required for routine operations.

One interesting aspect of instrument models is that they can be used to bring both the instrument and data reduction software to a more mature level before the instrument arrives at the telescope provided extensive testing is done during the laboratory integration phase, see also discussion in section 5.4. This would then result in less testing required during commissioning (and thereafter). Since the ELT is going to be a single telescope one would obviously like to keep the time required for instrument commissioning to a minimum.

Some science cases will require calibration of aspects that are not standard in observational astrophysics:

Calibration for intrinsically time dependent phenomena
Excellent calibration of each observations in exo-planet research will be vital not only because we will be studying features at low S/N ratios in many cases but also because the study of extra-solar planets involves intrinsically time dependent effects such as:

- Orbital motion
- orbital phase,
- rotation,
- seasons,
- atmospheric flows, weather, clouds, dust

Exotic chemistry of the atmospheres may result in unexpected properties and spectral features. High quality calibration will again be key to ensure proper identification of these features and to avoid pitfalls e.g. in identification of biomarkers.

Therefore the standard procedure of verifying critical observations by repeating them may or may no be useful since the relevant properties can be time dependent. In some cases changes as a function of time will be at the heart of the scientific result: e.g. common proper motion as result of physical connection or changes in relative position as result of orbital motion. In such cases calibration of each individual observation will be essential in order to derive a quantitative result.

Stability over very extended periods of time
Astrometric studies will need exceptional stability of calibration over many years. (cf PRIMA on VLTI). Similarly projects aiming for the highest accuracy in radial velocity (exo-planets, expansion of the universe with CODEX) will also need to be able to make quantitative comparisons over a decade or more. In these cases the understanding and mitigation of systematic errors is extremely important. Such projects may therefore benefit from dedicated calibration facilities studying these errors.

Influence of AO systems
For current ESO instruments using AO NACO (Shack Hartmann wavefront sensor) and SINFONI (curvature sensor) the recording of the data required for PSF reconstruction is a rarely used option. Currently, no good and general solution to PSF reconstruction is available. Similarly, deconvolution techniques are considered specialist applications that are not part of standard data reduction packages. For the success of VLT Planetfinder such tools will be very important and for ELT instruments they will be essential. One major limitation at this point is that the PSFs delivered by AO systems can not be well described by gaussian profile or alike and therefore can not be properly treated with existing data analysis tools. Valuable experience will be gained in the future from experiments on the VLT AO facility. Still, a significant effort in R&D will be needed to ensure that the full scientific content can be extracted from AO data in the future.

Conceptually the AO systems envisaged for the ELT aim to calibrate the influence of the atmosphere. Sophisticated data reduction tools should then make it possible to remove the signatures of the atmosphere from the data - similar to what is done today for instrumental effects. These AO systems with their LGSs perform an active sounding of the atmosphere over the telescope. For an ELT it is essential to know these properties both as a function of time and space. Only then can the influence on the observations be properly accounted for.

Appendix 5: Requirements on Site from Mid-IR

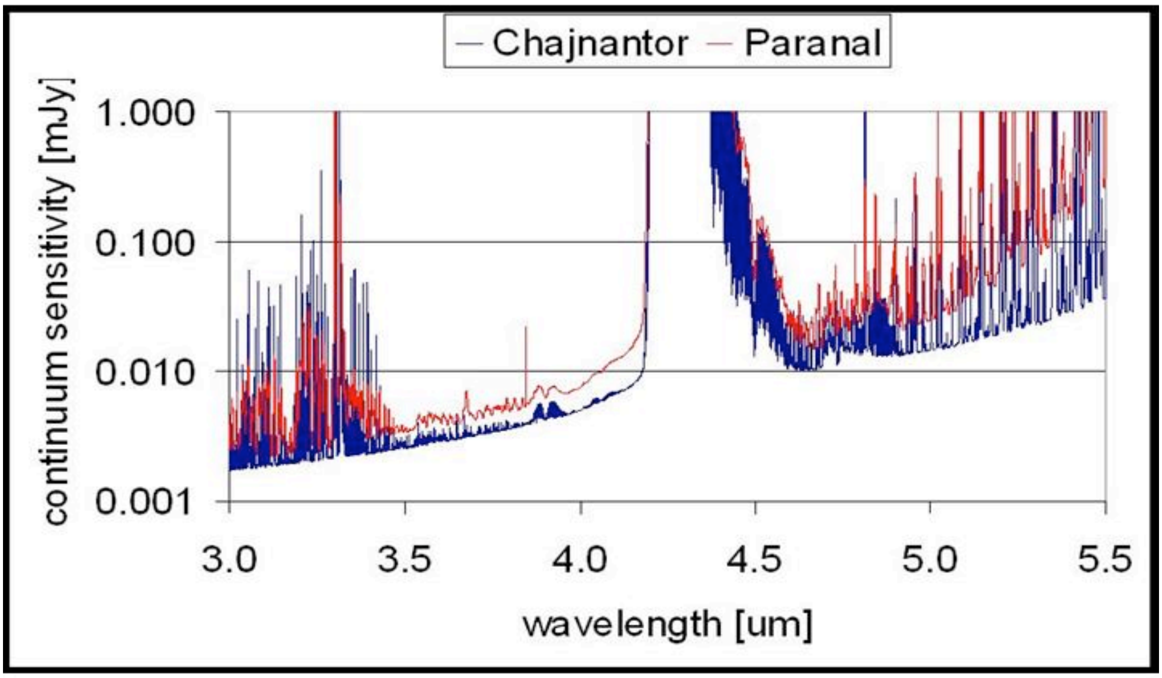

Figure A5-1: shows a comparison of the LM band continuum point-source sensitivities as a function of wavelength at R=3000. Note that the plot is in logarithmic units. The performance is always better by at least a factor of two up to an order of magnitude in areas where the transmission is bad. Placing the telescope on Paranal would essentially preclude such important science drivers as the evolution of protoplanetary systems where a lot of information is contained in the CO lines around 4.7 μm.

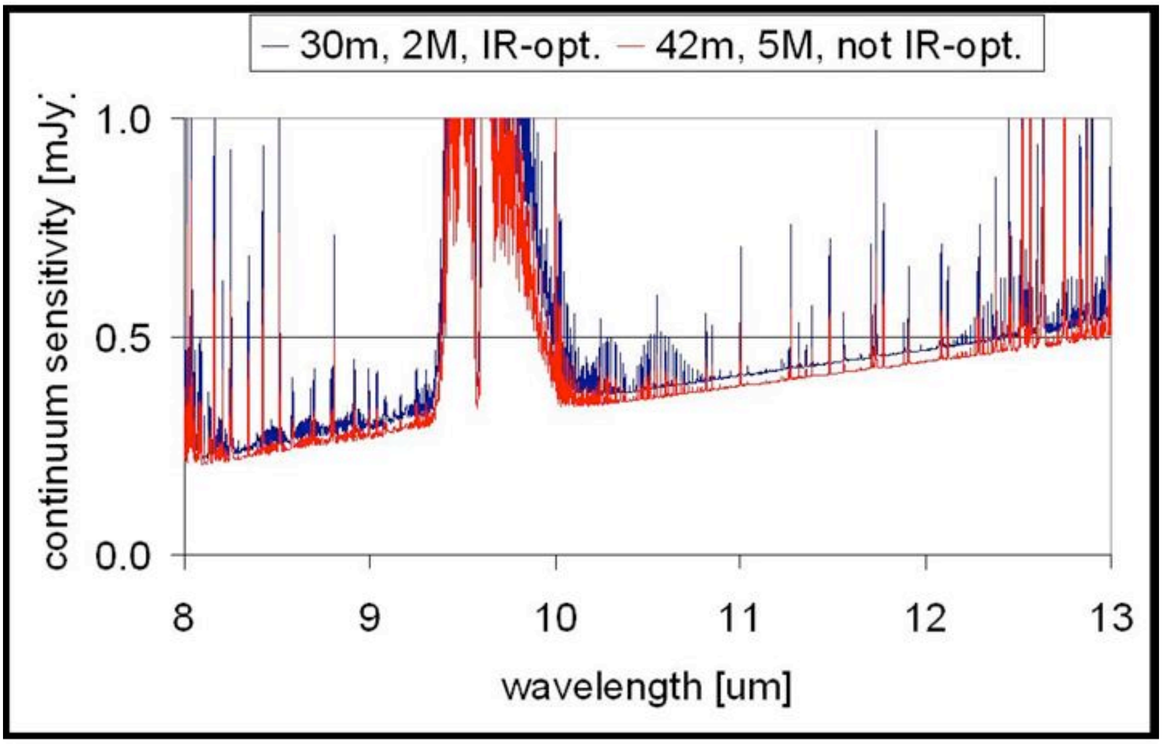

Figure A5-2: shows a comparison of the N band continuum point-source sensitivities between a 30 meter telescope with only two, IR-optimized mirrors (2% emissivity each) and a 42 (!) meter telescope with five, less-optimized or somewhat dusty mirrors (5% emissivity each). Despite its twice as large collecting area, the 42m telescope won't perform any better in terms of mid-IR sensitivity. In other words, the same mid-IR sensitivity would be much cheaper to achieve with optimally coated mirrors in a clean environment, in combination with a simple, frequent cleaning procedure. GEMINI has recently achieved 2% emissivity for the two mirror telescope, so these numbers are not unrealistic. However, many less carefully maintained telescopes can have emissivities of 20%, which would kill MIR science on an ELT, in particular if the number or warm mirrors is even larger.